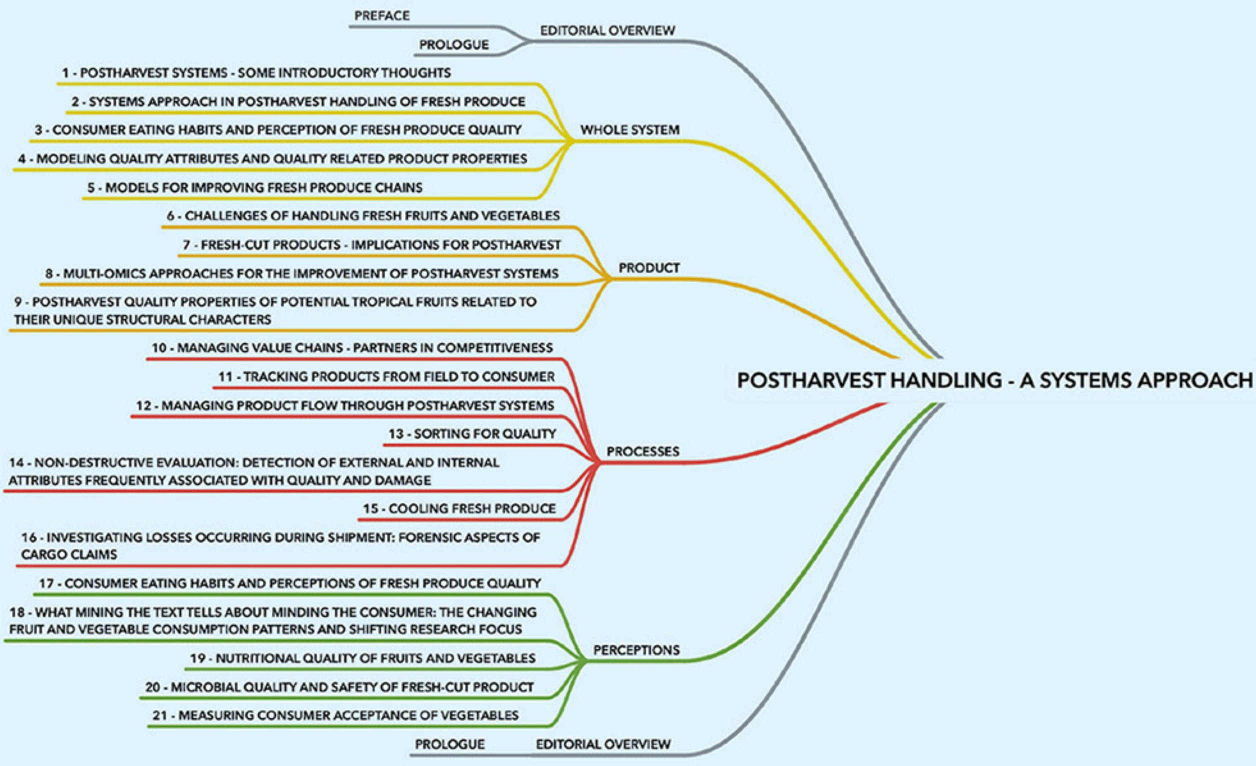
Fourth Edition

Postharvest Handling

A Systems Approach



Edited by

Wojciech J. Florkowski, Nigel H. Banks
Robert L. Shewfelt and Stanley E. Prussia

POSTHARVEST HANDLING

FOURTH EDITION

This page intentionally left blank

POSTHARVEST HANDLING

A Systems Approach

FOURTH EDITION

Edited by

WOJCIECH J. FLORKOWSKI
Department of Agricultural and Applied Economics, College of Agricultural and Environmental Sciences, University of Georgia, Griffin, GA, United States

NIGEL H. BANKS
Mount Maunganui, New Zealand

ROBERT L. SHEWFELT
Department of Food Science and Technology, University of Georgia, Athens, GA, United States

STANLEY E. PRUSSIA
College of Engineering, University of Georgia, Athens, GA, United States

ELSEVIER

ACADEMIC PRESS
An imprint of Elsevier

Academic Press is an imprint of Elsevier
125 London Wall, London EC2Y 5AS, United Kingdom
525 B Street, Suite 1650, San Diego, CA 92101, United States
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom

Notices

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

ISBN: 978-0-12-822845-6

Publisher: Charlotte Cockle
Acquisitions Editor: Nina Bandeira
Editorial Project Manager: Fernanda A. Oliveira
Production Project Manager: Vijayaraj Purushothaman
Cover Designer: Christian J. Bilbow

Typeset by MPS Limited, Chennai, India

Contents

2

Product

6. Challenges in handling fresh fruits and vegetables 167

Robert L. Shewfelt and Stanley E. Prussia

7. Fresh-cut produce quality: implications for postharvest 187

Silvana Nicola, Giacomo Cocetta, Antonio Ferrante and Andrea Ertani

8. Multiomics approaches for the improvements of postharvest systems 251

Pietro Tonutti, Claudio Bonghi and Stefano Brizzolara

This page intentionally left blank

List of contributors

Matt Adkins Zespri International Limited, Mount Maunganui, New Zealand

Deepak Aggarwal Department of Engineering, Sam Higginbottom University of Agriculture, Technology and Sciences, Allahabad, India

Nigel H. Banks Mount Maunganui, New Zealand

Arthur Frank Bollen Zespri International Limited, Mount Maunganui, New Zealand

Claudio Bonghi Department of Agronomy, Food, Natural Resources, Animals and Environment (DAFNAE), University of Padova, Padua, Italy

Jacobus Bouwer Koos Bouwer Consulting, Cape Town, South Africa

Amy Bowen Vineland Research and Innovation Centre, Vineland, ON, Canada

Stefano Brizzolara Institute of Life Science, Scuola Superiore Sant'Anna, Pisa, Italy

Bernhard Brückner Leibniz-Institute of Vegetable and Ornamental Crops, Großbeeren, Germany

Giacomo Cocetta Department of Agricultural and Environmental Sciences - Production, Landscape, Agroenergy - DiSAA, University of Milan, Milan, Italy

Ray Collins School of Agriculture and Food Sciences, The University of Queensland, Brisbane, QLD, Australia

Carlos H. Crisosto Department of Plant Sciences, University of California, Davis, CA, United States

Magalí Darre Research Laboratory in Agroindustrial Products (LIPA), National University of La Plata, La Plata, Argentina

Bart De Ketelaere Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, KU Leuven, Leuven, Belgium

Benjamin Dent School of Agriculture and Food Sciences, The University of Queensland, Brisbane, QLD, Australia

Angel Dizon Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, KU Leuven, Leuven, Belgium

Malcolm C. Dodd Department of Horticultural Science, Stellenbosch University, Stellenbosch, South Africa

Jean-Pierre Emond The Illuminate Group, Tampa, FL, United States

Andrea Ertani Department of Agricultural, Forest and Food Sciences - DISAFA, University of Turin, Turin, Italy

Elazar Fallik ARO—The Volcani Institute, Department of Postharvest Science, Rishon LeZiyyon, Israel

Antonio Ferrante Department of Agricultural and Environmental Sciences - Production, Landscape, Agroenergy - DiSAA, University of Milan, Milan, Italy

Wojciech J. Florkowski Department of Agricultural and Applied Economics, College of Agricultural and Environmental Sciences, University of Georgia, Athens, GA, United States

Alexandra Grygorczyk Vineland Research and Innovation Centre, Vineland, ON, Canada

Maarten L.A.T.M. Hertog Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, KU Leuven, Leuven, Belgium

Zoran Ilic University of Priština-Kosovska Mitrovica, Faculty of Agriculture, Lešak, Serbia

George A. Manganaris Department of Agricultural Sciences, Biotechnology and Food Science, Cyprus University of Technology, Lemesos, Cyprus

Silvana Nicola Department of Agricultural, Forest and Food Sciences - DISAFA, University of Turin, Turin, Italy

Bart Nicolaï Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, KU Leuven, Leuven, Belgium

Sompoch Noichindra Division of Agro-Industrial Technology, Faculty of Applied Science, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand

Cristian M. Ortiz Research Laboratory in Agroindustrial Products (LIPA), National University of La Plata, La Plata, Argentina

Annelies Postelmans Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, KU Leuven, Leuven, Belgium

Stanley E. Prussia College of Engineering, University of Georgia, Athens, GA, United States

Wouter Saeys Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, KU Leuven, Leuven, Belgium

Rob Schouten Horticulture and Product Physiology, Wageningen University and Research, Wageningen, The Netherlands

Robert L. Shewfelt Department of Food Science and Technology, University of Georgia, Athens, GA, United States

Anna L. Snowdon University of Cambridge, Wolfson College, Cambridge, United Kingdom

Gabriel O. Sozzi National Council of Scientific and Technical Research (CONICET), Buenos Aires, Argentina

István Takács Keleti Faculty of Business and Management, Institute of Economics and Social Sciences, Óbuda University, Budapest, Hungary

Pol Tijskens Horticulture and Product Physiology, Wageningen University and Research, Wageningen, The Netherlands

Pietro Tonutti Institute of Life Science, Scuola Superiore Sant'Anna, Pisa, Italy

Tim Van de Looverbosch Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, KU Leuven, Leuven, Belgium

Pieter Verboven Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, KU Leuven, Leuven, Belgium

Ariel R. Vicente Research Laboratory in Agroindustrial Products (LIPA), National University of La Plata, La Plata, Argentina

Kerry Walsh Central Queensland University, Rockhampton, QLD, Australia

Chalermchai Wongs-Aree Division of Postharvest Technology, School of Bioresources and Technology, King Mongkut's University of Technology Thonburi, Bangkok, Thailand; Postharvest Technology Innovation Center, Ministry of Higher Education, Science, Research and Innovation, Bangkok, Thailand

Niels Wouters Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, KU Leuven, Leuven, Belgium

Preface

Forty years ago, we started our quest. Two department heads at the University of Georgia, Brahm Verma and Tom Nakayama, conceived the idea of an interdisciplinary team and hired us to bring it to fruition. The University of Georgia experiment station, located in Experiment, Georgia, brought us together. Stan came to the Agricultural Engineering Department and soon developed two dreams:

- build a mobile lab to follow produce from the farm to its destination and
- develop a research program based on systems thinking.

Eighteen months later, Rob arrived in Food Science with a mission to:

- work with fruits and vegetables and
- partition that effort between basic and applied studies.

The department head of Agricultural Economics, Joe Purcell also hired Jeff Jordon who joined the team. Bill Hurst brought his extension contacts to the team. With them we were able to follow peas and greens from the fields to processing plants. Jeff told us to forget the processed vegetables. The money and research opportunities were in fresh.

Interdisciplinary research is exciting. It drew in many collaborators from within and outside the station in Experiment. Interdisciplinary research is also hard. Disciplinary perspectives create barriers that are hard to overcome. Arguments raged. Feelings were hurt. We dealt with concepts from fields we didn't understand. Concepts we did understand divided us. The same terms had different contexts in different disciplines. Those concepts were the ones that sent up the barriers that threatened to break us apart. Colleagues at national meetings failed to appreciate our ideas.

After a few successes, Jeff pushed us to write a book. He negotiated the contract for the first edition of *Postharvest Handling*. The three of us received a USDA Superior Service Award as an interdisciplinary team. By the time we wrote and published the book, partnerships and friendships had broken apart. Jeff became the first casualty and moved on. Too much disagreement; too much tension!

Despite the conflicts and endless meetings that seemed to go nowhere, the two of us stuck together. We believed in each other's visions. We marshaled resources from within the station. Our department heads and college administrators found us meager funds. Federal grants for this work were nonexistent, but we prevailed. The first edition generated international contacts that resulted in authors from around the world for subsequent editions.

Another economist, Wojciech J. Florkowski joined the effort at Experiment. His research collaborator from Germany, Bernhard Brückner, visited us in Georgia and took a similar direction in postharvest research. Bernhard and his director, Rolf Kuchenbuch, proposed organizing an international conference. It convened in Potsdam, Germany (1997). In turn, Wojciech organized the second international conference in

Griffin, Georgia, United States (2000). Conferences followed in Palmerston North, North Island, New Zealand (2001); Wageningen, The Netherlands (2003); and Bangkok, Thailand (2006). Bernhard helped edit the second and third editions. Wojciech took the lead in editing the second, third, and fourth editions of this book.

Stan studied the systems approach on a 12-month study leave in England. Rob traveled to Australia to research cantaloupe flavor. Stan stayed at the experiment station branching out into models and simulations of postharvest handling. Rob left for the main campus to teach food science and study fresh flavor of selected fruits and vegetables.

We offer this edition of the book to emphasize how far our vision has come. Nigel H. Banks, a new editor from New Zealand, has joined us in our quest and points out in the introduction how far the systems approach has gone and yet needs to go.

Rob L. Shewfelt
Stan E. Prussia

Prologue

Wojciech J. Florkowski, Nigel H. Banks, Robert L. Shewfelt and Stanley E. Prussia

We present the fourth edition of *Postharvest Handling—A Systems Approach*. What started as a new paradigm for conducting research on postharvest systems for fresh fruits and vegetables has evolved into a series of revised editions. Each revised edition, including this one, contains updated chapters written by the same contributors, together with chapters on new topics. We have also welcomed a number of new contributors over time in our sustained attempt to apply the systems approach to fresh fruit and vegetable value chains.

Improving postharvest value chains requires systems thinking to assimilate plant physiology of the fresh produce and technological advances with management decisions at each link of a chain. From the outset the proposed approach required more than a disciplinary focus. The systems approach is implied and occasionally explicit in the chapters. In the current edition, we include a new chapter outlining the background of systems thinking and methodologies. The chapter familiarizes a reader with the basic concepts and provides general guidelines how to read and think about the challenges of fresh fruit and vegetable postharvest handling.

Each chapter can be read without getting acquainted with any other chapter. Yet, frequently, we placed a reference to other chapters for those wishing to learn more about a specific topic. Awareness of intertwined connections in postharvest handling and the implications of actions taken or denied at one link for any other link in value chains is a first step toward systems thinking.

Much has changed in a short time since the third edition was published, which is very important for fresh fruit and vegetable consumption. Fresh-produce consumption has maintained pace with growth in the global population: per capita consumption remains low and losses remain high. The distribution of growth in consumption is uneven. The body of research linking disease prevention and health maintenance to eating fruits and vegetables has accelerated. Fresh fruits and fresh vegetables are the original functional foods.

International trade in fresh fruits and vegetables expanded and continues to grow driven by evolving consumer demand and ability to purchase. Despite the unprecedented availability of fresh produce, the global epidemic of obesity has continued and dramatically increased since the publication of the third edition. Like never before, there is a need for continuing research on postharvest to assure availability and accessibility of fresh fruits and vegetables worldwide.

For the fourth time, this edition of *Postharvest Handling—A Systems Approach* brings a team of contributors scattered across the globe, all driven by the common interest in improving the value delivered to consumers. The continuation of this effort testifies to the relevance of the subject and the proposed approach.

This page intentionally left blank

PART 1

Whole system

This page intentionally left blank

CHAPTER

1

Postharvest systems—some introductory thoughts

Nigel H. Banks
Mount Maunganui, New Zealand

1.1 Encounters with postharvest systems

The core of the editorial team for the Postharvest Systems series of books (Stan Prussia and Rob Shewfelt joined by Wojciech J. Florkowski) shaped the early exploration of systems concepts in the context of postharvest technology. In this volume you will find their latest thoughts on

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00001-4

postharvest systems. You can also dive into a curated collection of contributions of current thought leaders in the space that they opened up through the intervening three and half decades.

What do you think of when you talk with others about the systems approach to postharvest knowledge? When I first read of the concept in the context of postharvest handling (Prussia, Jordan, Shewfelt, & Beverly, 1986), it was a strong consolidating discovery—a true aha moment:

> "This is the expression of what I have been reaching for!"

The systems approach they described in that paper and linked publications was a unifying principle. It formed the core of my teaching practice for the 12 years I was at Massey University. And, as I shaped my various research programs, it guided all of the more useful work that I did there and since.

This first chapter of the new "Postharvest Handling" sketches some basic concepts used by systems thinkers in the field of postharvest technology. It explores these tools in the context of practical postharvest systems. Finally, it will challenge you with some thoughts on emerging paradigm shifts in some key areas of postharvest technology. Its goal is to set you up to gain the most from your reading of Postharvest Handling—2021.

1.2 Concepts in postharvest systems

1.2.1 What is a system?

A system, any system, comprises coherently organized parts that interact to achieve something (Meadows, 2008). A postharvest system delivers harvested fresh products to their consumers. In commercial and social systems like postharvest systems, what is achieved is the system's "purpose." This function is usually dependent on much more than just the parts—the system's physical content and even its processes. The essential extra ingredient is the system's organization—its pattern. Typically, outputs from one component part are arranged to become inputs to the next part in a deliberate sequence. What emerges is a supply or value system—one that takes remotely harvested product and delivers it in the format of a safe, nutritious, convenient, accessible, and valued product to consumers (Fig. 1.1).

In my mind, systems are useful as maps rather than territory. When we indulge in systems thinking or systems research, we go out into the physical world to characterize componentry and behaviors of systems as best we can. Take a single physical packhouse. It is one example of the diverse array of facilities that function as packhouses in disparate locations around the globe. Its "packhouse-ness" makes it well suited to delivering packhouse

FIGURE 1.1 In each progressive step through a postharvest system, the component subsystems are arranged sequentially. Together, they form what is often described as a supply or value chain. Each subsystem can be considered worthy of investigation and characterization; each can be considered to be a system in its own right.

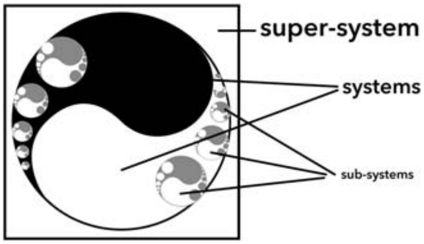


FIGURE 1.2 A supersystem encloses a system. A system encloses subsystems.

services. In a similar way we can draw the boundary for our own interest around multiple steps in a supply or value chain and consider it as a system—a postharvest system. But the words and diagrams we deliver—what we peddle as tools for use by postharvesters—are maps. None of our maps will correspond one to one with the world. If we achieved one-to-one correspondence, we would have duplicated a piece of the universe—not particularly helpful. Our goal as postharvest systems thinkers is to design, engineer, and manage behaviors of high-performing postharvest systems.

Different participants in the system may conceive of its purpose in different terms. Thus the purpose of a postharvest system for growers is to reward them for delivering high-quality fresh produce to consumers. For packhouse owners, its purpose is to secure a return on investing in a facility that provides services for networks of growers and networks of distributors, retailers, and consumers. For consumers, its purpose is to deliver them safe, fresh, defect-free, and nutritious produce that will last longer than the interval between purchases. In this sense the purpose of a given system depends strongly upon sources of meaning for the observer.

Ultimately, there is just one system: the Universe. Every system ever studied is a subsystem of the Universe. For convenience, investigators put boundaries up around subsystems and consider them as systems in their right (Fig. 1.2). Postharvest systems are subsystems of food systems—impermanent, shifting networks of enormous reach, connection, and complexity (Parasecoli, 2019).

The purpose of the system boundary is to define the area of interest. Things within the system boundary are part of the system; they are of interest. Those outside the system boundary are beyond the scope of consideration. Boundaries work tidily for closed systems. A can of baked beans, considered on a timescale of weeks or months or even years, is a closed system. Nothing moves in or out. Inside, the contents are stable—there is no life in here. Contrast this with harvested fruits and vegetables. They are bursting with life. They are bursting with quality. And they are supremely prone to decline in quality. They are beautifully vital. They are intrinsically health giving. They are valuable. All because they are so labile. Postharvest systems, like all systems based upon biology and sociology (Capra & Luisi, 2016), are far from equilibrium.

1.2.2 Postharvest systems are open systems

Postharvest systems achieve organized outcomes. They deliver sorted, segregated, packaged, and market-appropriate products to consumers in selected, sometimes very distant

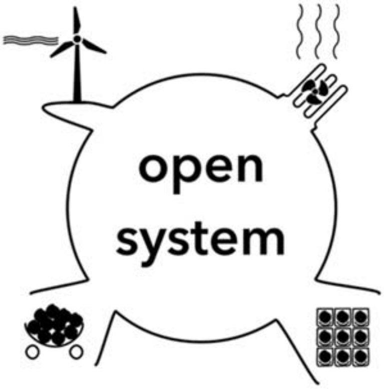


FIGURE 1.3 Postharvest systems are open systems.

FIGURE 1.4 The systems manager or researcher walks the line between holism and reductionism, making maximum use of what each has to offer.

locations. A postharvest system consumes resources that enter across the invisible system boundary (Fig. 1.3). It uses those resources, and internal patterns and processes. It delivers outputs, fulfilling its purpose. From one view of the system boundary, resources taken in may include energy, information and data, wash water, chemicals, packaging materials, and knowledgeable and skilled people. From another view of the system boundary, outputs from the system include prepared and packaged products, delivered to appropriate markets at appropriate times, information and data, worker pay packets, waste water, and packaging waste. Postharvest systems are open systems.

1.2.3 Holism and reductionism

The systems approach walks the line between holism and reductionism. It takes in and synthesizes information from both perspectives to develop understanding (Fig. 1.4).

The reductionist approach dominates the traditional scientific method. Systems investigators explain behaviors of the whole as functions of its component parts. This builds insight into bottom-up causal behaviors within the system. In a perspective that sees systems as part of a multidimensional network, reductionism looks inwards to explore them.

As an example, take the color change of immature tomatoes from green to red during maturation and ripening. From a reductionist view, changes in levels of green and red pigments in the fruit drive this change in appearance. Chlorophyll declines, reducing greenness; synthesis and unmasking of carotenoid pigments boosts redness (Ilahy, Tlili, Siddiqui, Hdider, & Lenucci, 2019). To manage fruit color for the market, a reductionist explores the influences of factors on these processes. These factors may include the impacts and interactions of cultivar with maturity at harvest, fruit mineral composition, postharvest temperature, oxygen, carbon dioxide, ethylene levels, and time. All are susceptible to interventions by managers of the system. And most of them will interact, to an extent that defies comprehensive characterization. Managing commercial degreening uses robustly tested and developed best practice. The operations team will also use a collection of rules of thumb to deal with atypical outcomes.

With a holistic view, one seeks to know and understand a system as an integrated network of processes. The holistic approach is often to the fore in social and commercial investigations of systems. Systems-orientated investigators search outwards into context to understand system behaviors. Feedback loops from system processes can drive nonlinear behaviors. These contrast with the straightforward linear causalities sought by the reductionist manager. For example, ethylene produced by a single advanced maturity fruit may advance ripening of all other fruit within the same pack. Other packs of identical fruit but lacking the advanced maturity fruit may behave quite differently. This is an example of classic "nonlinear" behavior. It occurs when the outputs of one process feed back to influence the same or a related process in the system. It can result in radical shifts in behavior that may be qualitatively different from other outcomes in the system. Thus ripening behaviors of fruit populations with diverse maturities may differ greatly from those of uniform maturity. Uniformity of a crop population of fruit at harvest depends upon a host of variables:

- date of planting relative to the season,
- soil type/cultivation method,
- canopy management (pruning practice, size of plant, density and shading effects, position in canopy relative to sinks, and sources of nutrition for the growing product),
- fertilizer and pest and disease control practices,
- date of harvest relative to the season and previous crop growth,
- factors affecting recent preharvest temperature history of the crop (geographical region, elevation, local climate, ongoing weather events, degree of shelter, or protection from the elements).

By definition, cultivars behave differently from others of the same species in response to all of these features.

With all of these factors influencing maturity at harvest, the role of managing behavior of a postharvest system is fraught with complexity and unpredictability. Walking the line between reductionism and holism, this applies with the intrinsic quality of the crop—that built into the product at the time of harvest. It also applies to the host of interactive influences that come into play after harvest:

- immediate management upon removing the product from the plant (physical damage, insolation/shade, temperature management, infection control),
- delays through a packhouse/into cool storage,
- efficiency of grading out defects and excessive variation in maturity,
- rates of heat production by the product as functions of cultivar, fruit size, maturity/physiological time, temperature, and other environmental conditions (e.g., oxygen, carbon dioxide, and ethylene levels within the store and within individual packs),
- starting temperature profile of crop items within the pallet, which might vary with time of day,
- number of items per pack,
- packaging materials,
- heat transfer associated with convection and conduction within the packs,
- heat transfer characteristics of the crop items themselves, of packaging materials, and of packs with zero, one, two, or three faces exposed,
- number and size of cartons per pallet,
- tightness of pallet stacking,
- shrouds placed over pallets,
- external air temperature, velocity/turbulence as functions of heat load on the store/cooler, and set point temperatures,
- effects of radiant heat transfer,
- storage environment (cool store, shipping container),
- wider environment (insolation as a result of a ship moving from low to high latitudes).

As before, all of these influences are susceptible to interventions by managers of the system. And most of them will interact to an extent that defies comprehensive characterization. Despite this, postharvest engineers have made numerous attempts to model outcomes from postharvest systems. Such models can yield immensely helpful tools for both growing understanding and for making management decisions. The combined systems approach is required for constructing these models. It explicitly recognizes that variation in evolution of many of the above variables can lead to qualitatively different outcomes. It yields explanations that arise from looking up or down among levels within a system. As I have come to appreciate with a sense of awe through extensive rubbing shoulders with systems managers and modelers, they learn to tread the dotted line in Fig. 1.4. They learn the skill of leaning on the tools of both holism and reductionism. And then they use of all these to build batteries of approximate knowledge that they will use in characterizing their system.

1.2.4 Systems thinkers use approximate knowledge

I went to Massey University believing that it was the role of academics to chase down the truth. Furthermore, I believed that applied academics like technologists had made the further commitment of making this work in the world of commerce, of chasing down useful truth. Truth, as it turned out in the real world, was a little more evasive than I had expected. But I was fortunate to collaborate on models of many postharvest systems with engineers who opened my eyes to the awesome discoveries available through pragmatic use of appropriate models. They skillfully picked their way through dozens of potential models for different processes. They selected those that felt robust and had good fit. Then they set about gathering numbers for the parameter values we needed. Again, generic values from analogous situations often yielded remarkably helpful and verifiable predictions. The key to making this work was the modeler's instinct that helped to separate processes and interactions that could be approximated from those that needed further exploration. Modelers intuitively know that it is impossible to empirically characterize any absolute truth. Their solution is simple: they settle for approximate knowledge. Unknowingly, this is what every one of us does in every model we have of the world, its systems and its processes. The critical thing for modeling and managing systems is recognizing those elements of our models that can be approximated from existing knowledge and those that require further empirical study.

1.2.5 Information and learning

High-performing postharvest systems are likely to have a responsive information system (Fig. 1.5). This information system is a repository of key information about the components and drivers of value for the product. It supports marketing, quality assurance, and postharvest operations. Delivering upon brand promises requires standardization and consistency of all aspects of quality and the logistics of supply. A postharvest system's information system is home to the information that supports the ability of a brand to delight consumers.

Self-organization (Fig. 1.6) is a common feature of complex systems throughout the natural world (Capra & Luisi, 2016; Meadows, 2008). Since postharvest systems include

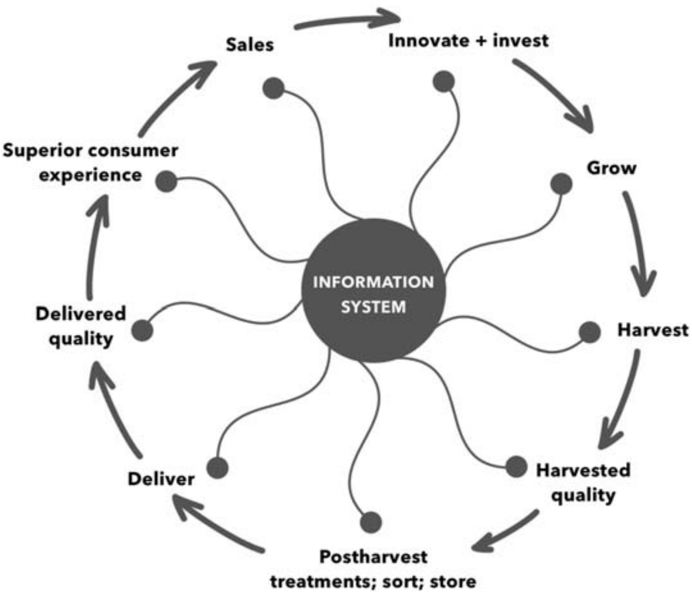


FIGURE 1.5 Flows of resources (outer flows: product, physical, financial) and information (inner flows) in the marketing and quality assurance system of a fresh produce supply system.

FIGURE 1.6 Self-organization is a standard feature of postharvest systems.

human participants, there is ample opportunity for systems to know themselves, to research, and to improve themselves.

There is a wonderful section in Zen and the Art of Motorcycle Maintenance (Pirsig, 1974) in which the central character, Phaedrus, is working with a student. He is helping her overcome a block in her creative writing. Repeatedly, Phaedrus invites the student to enter the space of the topic she is writing about: macro through everyday experience through micro (supersystem through system through subsystem). Eventually, when he invites her to present detail at the level she can relate to, the dam breaks and her creativity bursts forth. For a system to be functioning close to its optimum, those involved in the system's knowledge of itself have a special responsibility. They need conceptual insight into key mechanisms of the system. They need to be able to relate to the levels at which interventions can work. And there needs to be efficient throughput of product at all positions in the network. Then the system can enter flow.

When your system is stuck, not working, or broken, try this:

- Look outwards (holism): what in the environment, the context, needs to change for the key mechanisms of the system to thrive?
- Look inwards (reductionism): what component parts need to be designed better and related better for the system's mechanisms to tick with real fluidity?
- Do both at once: how are feedback loops from outer network structures affecting the functioning of inner componentry?

Progressive postharvest systems monitor and adapt to all aspects of their environment. Their information systems meet two key functions:

- They inform participants about performance relative to current best practice. This supports exemplary handling using existing insights.
- They monitor, learn from new experience, and innovate in the process of solving contemporary problems.

FIGURE 1.7 Learning and evolution in postharvest systems develops through repeated cycles of two broad steps. Step 1: Build and implement a new solution. Step 2: Learn through reflecting upon performance of the system and imagining potential solutions to its shortcomings.

FIGURE 1.8 Virtuous cycle in performance of production and postharvest systems that rewards investments in delivering superior product that is preferred by customers.

"Learning systems" of this kind continually learn how to better meet new conditions. Then they adjust their behaviors, building successive new versions of themselves as learning progresses (Fig. 1.7).

Postharvest systems can innovate more rapidly when they enter what is termed a "virtuous cycle" (Senge, 2006) that rewards participants for improved behaviors (Fig. 1.8). Developing a new measurement technology and associated metric of success helps to establish such virtuous cycles.

Effective marketing and quality assurance systems that create this responsiveness require that participants right through the system (growers, marketers, consumers, technologists and quality, operations, and logistics managers) work in a coordinated way to:

- identify what makes a great eating experience;
- devise a measurement and rewards system for the key attributes of product that delivers a great eating experience;
- develop ways to grow and deliver superior product;

FIGURE 1.9 Learning with a brand: with each cycle of purchase and consumption, the consumer's level of trust in the brand promise is modified according to experience. Source: *Simplified from: Andani, Z., & MacFie, H. J. H. (2000). Consumer preference. In R. L. Shewfelt & B. Bruckner (Eds.),* Fruit and vegetable quality *(pp. 158–177). Lancaster, PA: Technomic (Andani and MacFie, 2000).*

- achieve and maintain high transparency concerning value, so that fairness can be seen to be dominant and trust emerges (Cadilhon, Fearne, Giac Tam, Moustier, & Poole, 2007; van der Vorst, da Silva, & Trienekens, 2007).

Once the postharvest system has these features, it is then equipped to develop the positive feedback loop that comprises the virtuous cycle that can deliver extraordinary returns (Fig. 1.8). The presence of a brand can further strengthen development of a virtuous cycle. For all participants in the supply system, a brand can function as a "virtual telescope" that connects them to other parts of the system, providing simplified information about a shared perspective on what is important to all who identify with the brand, supporting rapid decision-making on values-based issues and building reputation throughout value chains (Florkowski, 2000).

For consumers, a brand helps them make purchasing choices in the context of an overload of information as they make fresh fruit purchases (Fig. 1.9).

1.2.6 Evolution in what system participants value in fresh produce

In a high-performing postharvest system, participants are attuned to each other's needs. Each recognizes a greater good for the system as a whole:

- Growers cultivate and harvest crops that are valued by consumers, delivering a high value for themselves and others with low impact on the environment.
- Packhouses and distribution centers favor consumer-preferred products, using grading and storage practices that balance perceived value to consumers with responsible levels of food loss and environmental impact.
- Consumers purchase safe, nutritious products that support health for themselves, local or distant growers, and global ecosystems.
- Marketers work throughout the postharvest system to communicate information that achieves better outcomes for all participants. They play a critical leadership role in success of the supply system as a whole. The essence of this success is often captured in a brand that reflects the important points of difference of the system and its products.

There is rapidly growing awareness of the health-giving nature of a diet rich in fresh fruits and vegetables. As this awareness continues to grow, it is likely that preferences in fresh produce will further evolve. It is a well-known business maxim that what gets measured gets managed. Thus technologies for measuring newly valued aspects of quality will likely be developed. Information available to consumers on origins (ethical sourcing; organic production) and taste (flavor intensity) will be supplemented by information on new attributes of quality. This might include evidential health claims and verified freedom from pesticide residues.

1.3 New paradigms in postharvest systems

As Rogers (1983) outlined in his classic text on innovation, spread of technologies and new ideas follow an S-shaped curve of adoption. This may take months, years, or decades to become complete. On the other hand, for an insightful individual or team, the scales of not-seeing can fall from the eyes in a moment−conceiving a new paradigm, a new way of seeing, can occur at the speed of thought. This section challenges you to explore the horizon out in front of you, or deep within the system that most concerns you. There you may find a chink of light that signals the impending fall of a scale. As beautifully characterized by Kuhn (1962), areas with an abundance of conflicting observations may provide fertile hunting ground for paradigmatic shifts. The challenges presented below are not predictions. Rather, they are observations on areas that indicate there is no shortage of possibility for revolutionary change over the coming decade or two—all happening on your watch.

1.3.1 New perspectives on nutrition

There is a trivial story reported by a kids TV program that I recall from my youth. The show introduced a teenage boy who had apparently been eating absolutely nothing but baked beans on toast since he was 6 years old. He was puzzling nutrition experts who believed that he should be suffering from multiple deficiency disorders. Whether or not the story was true, it has from time to time made me ponder the real value of the foods we eat. The intervening more than five decades have provided us with an explanation of how such a diet could, at least potentially, be viable—and perhaps how we all avoid diverse nutritional deficiencies despite less than fully rounded diets. As individuals, we are in the process of recognizing that we are not individual at all. Rather, every person on this planet is a walking colony comprising one human and trillions of microorganisms. What we feed this colony has profound impacts upon its functioning, behavior, health, and longevity (Sinclair & LaPlante, 2019). Microbes impact both central and diverse aspects of our physiology and psychology. Whether we are depressed or euphoric, skinny or obese, or healthy or diabetic depends significantly upon what we eat and hence what we feed our microbiome.

Ongoing discovery of the fundamental importance of the microbiome in human health seems to indicate that the most critical purpose of the food we eat may be to nourish the hundreds of microbial species that comprise our microbiome. What the bugs make of the food may be more important to us than the contents of the food itself. If that is true, what will that do to our perceptions of quality in the fresh produce we consume? To the health claims we may wish to make or assess? To the metrics will we want to apply to assess that quality? Has the postharvest paradigm of the past five decades obsessed over completely the wrong dimensions of quality? While there is much debate about the relative merits of different macronutrients and food types on human health span and longevity, it is now widely agreed that high plant content diets with a focus on green leafy/high color vegetables supports a healthy microbiome, a healthy body, and a long life (Lustig, 2021; Sinclair & LaPlante, 2019). But these succulent and fragile fruits and vegetables have a much shorter storage life than low-moisture content grains. There has never been a more valuable time to be a postharvester, skilled in maintaining quality in fresh produce. Quality is a thousand issues with consequences that reach much further and deeper than we have ever imagined.

1.3.2 New perspectives on trust

Flows of information, money, and materials connect systems throughout the man-made world. Communities have learned that food miles comprise the small story in food provenance. Social meaning has emerged as an important reward of local food supply. And COVID has challenged global value chains that connect poor rural growers with lucrative distant markets. Distance is an issue—at a level of impact that we are only just beginning to glimpse.

Blockchain is emerging as a technology that could radically transform exchanges of information and money in postharvest supply systems. Why? Blockchains enable information systems to be distributed, transparent, immutable, and democratic (Motta, Tekinerdogan, & Athanasiadis, 2020). The nonerasable nature of blockchain transactions provides a robust basis for developing trust throughout a diverse supply network. This applies to verifying provenance of harvested crops. It applies to openly communicating transaction values as product moves all the way through the supply system. It applies to transmitting far more complex information on crop safety, crop quality, and compliance on ecological and work practice standards or food miles than has ever been possible before. Agunity (2021) is exploring this potential with a blockchain and app-based communication platform to trade, train, market, and connect remote rural users in developing countries with distant markets. Could brands be replaced or, alternatively, greatly augmented and enhanced by such information transfer?

1.3.3 Delivering to world food needs

Capacity of the world's food production system needs to grow by upwards of 50% to meet food needs of the projected global population of 10 billion people by 2050 (Searchinger et al., 2018). Decline in ecosystem diversity and stability is threatening the world's ability to further grow food output (Eisenstein, 2018). Around the world, about 35% of food produced is lost in postharvest systems (Flanagan, Robertson, & Hanson, 2019). Quantity is an issue—at a level of impact that we are only just beginning to glimpse.

Brown (2009) suggested that unless we cut greenhouse gas emissions by 80% by 2020, increasing instability of climate would threaten food production systems around the world. At the time of writing this chapter, despite a short dip in greenhouse gas emissions driven by COVID-19, greenhouse gas emissions are now actually higher than they were a decade ago (UNEP, 2020). The world is on track for a catastrophic temperature rise of more than 3°C this century. Global climate is indeed already less stable. And to make matters worse, much worse, it is clear that what is now being described as the "climate emergency" is being driven by much more than just high levels of carbon emissions. Rather, it is the product of wholesale ecosystem abuse and collapse on a global scale over many decades (Eisenstein, 2018). Demand for food is driving much of this abuse (Barber, 2015; Hoffman, Koplinka-Loehr, & Eiseman, 2021). Postharvesters have the opportunity to mitigate demise of the global ecosystem upon which we all depend. By reducing food loss and waste. By ensuring that grower and consumer perceptions of required product attributes are better aligned. And by devising and implementing solutions to postharvest challenges that achieve less impact upon ecosystems distributed across the world.

1.4 Conclusion

Systems thinking helps to characterize how systems function in response to:

- behaviors of their component parts,
- emergent properties that are hard to predict from behaviors of the component parts,
- the wider context in which the system operates.

The global food system is immensely complex—hard to predict and still harder to manage. Dealing with fresh whole foods such as labile fruits and vegetables is at the most challenging end of that food system. But the burgeoning epidemic of chronic illness across the world provides ample incentive to improve access to fresh fruits and vegetables everywhere. Postharvesters with strong systems thinking and management skills will be central to this endeavor. In this volume you will find specific and general, deep and high-level insights into the ways that postharvest systems function and behave. If you are a postharvester, this volume can open new ways for you to influence the health-, wealth-, and food-focused social and commercial exchanges among the peoples of the world.

References

Agunity. (2021). Australian startup using blockchain in agriculture to solve developing world farmers' low incomes <https://www.agunity.com> Accessed 11.11.21.

Andani, Z., & MacFie, H. J. H. (2000). Consumer preference. In R. L. Shewfelt, & B. Bruckner (Eds.), *Fruit and vegetable quality* (pp. 158−177). Lancaster, PA: Technomic.

Barber, B. (2015). *The third plate — Field notes on the future of food* (p. 496) Penguin Books.

Brown, L. R. (2009). *Plan B 4.0: Mobilizing to save civilization*. http://www.earth-policy.org/books/pb4. Accessed 11/11/21.

Cadilhon, J. J., Fearne, A. P., Giac Tam, P. T., Moustier, P., & Poole, N. D. (2007). Business-to-business relationships in parallel vegetable supply chains of Ho Chi Minh City (Viet Nam): Reaching for better performance. In P. J. Batt &

J. J. Cadhilon (Eds.), *Proceedings of the international symposium on fresh produce supply chain management*. Food and Agriculture Organization of the United Nations, Regional Office for Asia and the Pacific, Publication 21.

Capra, F., & Luisi, P. L. (2016). *The systems view of life: A unifying vision* (p. 510) Cambridge University Press.

Eisenstein, C. (2018). *Climate: A new story* (p. 320) North Atlantic Books.

Flanagan, K., Robertson, K., & Hanson, C. (2019). *Reducing food loss and waste: Setting a global action agenda*. https://www.wri.org/publication/reducing-food-loss-and-waste-setting-global-action-agenda. ISBN: 978-1-56973-964-8. Accessed 11/11/21.

Florkowski, W. J. (2000). Economics of quality. In R. L. Shewfelt, & B. Bruckner (Eds.), *Fruit and vegetable quality* (pp. 227−245). Lancaster, PA: Technomic.

Hoffman, M. P., Koplinka-Loehr, C., & Eiseman, D. L. (2021). *Our changing menu: Climate change and the foods we love and need* (p. 264) Comstock Publishing Associates.

Ilahy, R., Tlili, I., Siddiqui, M. W., Hdider, C., & Lenucci, M. S. (2019). Inside and beyond color: Comparative overview of functional quality of tomato and watermelon fruits. *Frontiers in Plant Science*. Available from https://doi.org/10.3389/fpls.2019.00769, Accessed 01.05.21.

Kuhn, T. S. (1962). *The structure of scientific revolutions*. United States: University of Chicago Press, ISBN 9780226458113.

Lustig, R. (2021). *Metabolical: The lure and the lies of processed food, nutrition, and modern medicine* (p. 416) Harper Wave.

Meadows, D. H. (2008). *Thinking in systems: A primer* (p. 240) Chelsea Green Publishing.

Motta, G. A., Tekinerdogan, B., & Athanasiadis, I. N. (2020). Blockchain applications in the agri-food domain: The first wave. *Frontiers in Blockchain*. Available from https://www.frontiersin.org/articles/10.3389/fbloc.2020.00006/full, Accessed 03.05.21.

Parasecoli, F. (2019). *Food* (p. 228) MIT Press.

Pirsig, R. M. (1974). *Zen and the art of motorcycle maintenance: An enquiry into values* (p. 418). New York City: William Morrow and Company. The "Pirsig Brick" excerpt is available at https://www.drury.edu/academics/undergrad/core/pdf/readings/Pirsig.pdf Accessed 13.04.21.

Prussia, S. E., Jordan, J. L., Shewfelt, R. L., & Beverly, R. B. (1986). A systems approach for interdisciplinary postharvest research on horticulture crops. In: *Georgia Agricultural Experimental Station research report no. 514*. Athens, GA.

Rogers, E. M. (1983). *Diffusion of innovations* (4th ed., p. 519)The Free Press.

Searchinger, T., Waite, R., Hanson, C., Ranganathan, J., Dumas, P., & Matthews, E. (2018). https://files.wri.org/s3fs-public/creating-sustainable-food-future_2.pdf. Accessed May 2021.

Senge, P. M. (2006). The fifth discipline. The art and practice of the learning organization (p. 445) London: Random House.

Sinclair, D. A., & LaPlante, M. D. (2019). *Lifespan: Why we age − And why we don't have to Thorsons* (p. 432) Atria Books.

UNEP. (2020). *Emissions gap report 2020*. United Nations Environment Programme. ISBN: 978-92-807−3812-4. https://www.unep.org/emissions-gap-report-2020. Accessed 05.05.21.

van der Vorst, J. G. A. J., da Silva, C., & Trienekens, J. H. (2007). Agro-industrial supply chain management: Concepts and applications. In: *Agriculture management, marketing and finance occasional paper 17*. Rome: FAO.

CHAPTER

2

Systems approaches for postharvest handling of fresh produce

Deepak Aggarwal[1], *Robert L. Shewfelt*[2] *and Stanley E. Prussia*[3]

[1]Department of Engineering, Sam Higginbottom University of Agriculture, Technology and Sciences, Allahabad, India [2]Department of Food Science and Technology, University of Georgia, Athens, GA, United States [3]College of Engineering, University of Georgia, Athens, GA, United States

Abbreviations

3Ls	Low per capita consumption of fruits and vegetables, Loss and waste, Low farm income
3Rs	Reduce reality, Refute hypotheses, Replicate results
CSP	critical systems practice
FAO	Food and Agriculture Organization
FFVV	fresh fruit and vegetable value
FLW	food loss and waste
FSC	food supply chain
ILE	interactive leadership experiences
MIT	Massachusetts Institute of Technology
NIFA	National Institute of Food and Agriculture
SOSM	system of systems methodologies
SSM	soft systems methodologies

Start with consumers. *Heaton (1981)*

Mr. Kell Heaton gave those words of advice to us in 1981 as we were organizing an interdisciplinary team of researchers at the University of Georgia, Griffin campus. Kell's wisdom remains as valuable today as it was shortly before he retired as the supervisor of the food processing pilot plant in the Food Science and Technology Department. His insight was based on taking a systems approach to the handling of fresh fruits and vegetables. Most efforts at the time focused on increasing farm production. Growers then tried to

DOI: https://doi.org/10.1016/B978-0-12-822845-6.00002-6

push their fresh produce through "supply" chains. Most likely, Kell realized that "chains" only work correctly when pulled; not when pushed. In simplest of terms, fresh fruits and vegetables are pulled through supply chains by money from consumers.

The interdisciplinary team at the University of Georgia mentioned earlier grew in the early 1980s to include researchers in food science, engineering, economics, and horticulture and a food science extension specialist. Most of the chapters in the first edition of "Postharvest Handling, A Systems Approach" (Shewfelt & Prussia, 1993) were written by team members and their collaborators at the University of Georgia. Many authors in this fourth edition are international. Kell would be pleased; this fourth edition has a separate section with five chapters focused on consumers.

This chapter starts by showing that past approaches have not substantially increased fruit and vegetable per capita consumption, lowered losses, nor increased family farm incomes. Evidence is given that improvements are difficult to make because fresh fruit and vegetable value (FFVV) chains are not systems as defined by systems principles. Three complimentary ways for learning about complex postharvest handling situations are presented; the scientific method, the engineering approach, and systems thinking. Then, a system of systems methodologies is presented that provides a framework for interventions to increase per capita consumption, lower losses, and improve family farm incomes.

Thinking "outside the box" will most likely result in new approaches for addressing these and other postharvest issues. Many references are provided for additional studies on each topic presented.

2.1 Status of postharvest handling

Advances in postharvest physiology and technology over recent decades have failed to yield desired improvements related to three global issues listed as 3Ls:

- Low per capita consumption of fruits and vegetables
- Loss and waste remain high
- Low income for family farms

2.1.1 Low per capita fresh produce consumption

The 5 A Day for Better Health Program for the Centers for Disease Control and Prevention was unsuccessful at increasing consumption of fresh fruits and vegetables (Centers for Disease Control and Prevention, 2005). Americans were attracted by the convenience and cost of processed foods compared with fresh produce.

2.1.1.1 Best efforts are failing

After more than 25 years of admonitions to eat less processed food and eat more fresh fruits and vegetables, per capita consumption of fresh produce is not increasing in the United States. Unfortunately, total fruit and vegetable consumption in the USA declined from 299 pounds/person to 272 pounds in the decade from 2003 to 2013

(Lin & Morrison, 2016). Much of this decline is associated with lower consumption of head lettuce, orange juice, and potatoes. Potatoes are still the vegetable Americans consume in the largest quantity, followed by tomatoes (see also Chapters 3, 17 and 21).

Fruit and vegetable intakes in the United States are still extremely low even after national campaigns to increase per capita consumption (see also Chapters 19 and 20). The "2015−2020 Dietary Guidelines for Americans" (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2015) has comprehensive nutritional information presented in colorful graphics that are easy to understand. The percentage of consumers with intakes below the goal is extremely high for both the vegetable (*87%*) and fruit groups (*75%*). The ninth edition for 2020−25 (U.S. Department of Health and Human Services and U.S. Department of Agriculture, 2020) shows even lower consumption for both vegetables (90%) and fruit (80%) (See also Chapter 18).

2.1.1.2 Consumers are not satisfied with the flavor of fresh produce

Sweet corn is a success story in the United States. Through genetic improvement, improved horticultural and postharvest practices, flavorful sweet corn is now consistently available from distant growers over a long season. Other examples of successful long availability season is sweet cherries shipped from Chile kiwifruit shipped from New Zealsnd to the United States. Many fruits and vegetables would benefit from similar improvements, especially in developing countries.

Another global issue is that climacteric fruits are typically harvested at less than optimum maturity, resulting in low flavor. The greater firmness helps to reduce bruising during handling and transport compared to more mature, softer fruit. Tomatoes and peaches represent particular challenges during handling. Harvested too soon, they reach acceptable firmness but lack flavor at distant destinations. Harvested too late they become unacceptably soft by arrival at distant markets. Tropical fruits like bananas are harvested green and treated with ethylene prior to marketing. Flavor is acceptable for most markets.

2.1.2 Losses remain high

Estimates indicate that over 30% of food produced around the world is lost or wasted from production to consumption (HLPE, 2014). A chart in a report by the UN Food and Agriculture Organization showed that over 50% of the harvested fruits and vegetables were lost or wasted in five of the seven global regions (FAO, 2011). Complex issues surround unnecessary global loss and waste of fruits and vegetables that have resisted improvement over several decades. New approaches are needed to reduce loss and waste.

2.1.2.1 Definitions for food loss and waste

Not every fruit or vegetable that is harvested is consumed (see also Chapter 7: Fresh-Cut Products—Implications for Postharvest and Chapter 11 and 16). The difference between harvest and consumption is food loss and waste (FLW). In general, food loss occurs prior to arriving at market and food waste occurs at the market or in the home

(HLPE, 2014). Loss is associated with technical inadequacies of a handling system. Waste is attributed to lack of management by a retail outlet, foodservice operation, or the ultimate consumer.

2.1.2.2 Global food loss and waste

Each fresh fruit or vegetable eaten by consumers progresses through a unique "value chain" that represents the natural resource and monetary inputs before and after harvest (See also Chapter 10). Whenever an item is lost or wasted, the accumulated value of these inputs is lost (Shewfelt, 2017; Zeide, 2019). Minimizing losses is a major challenge in sustainability of a postharvest value chain (Alamar, Falagán, Aktas, & Terry, 2018; Berja, Capone, Debs, & Bilali, 2018; Falagán & Terry, 2018; Parfitt, Barthel, & Macnaughten, 2010). A classic report illustrates how postharvest losses accumulate in food pipelines (Bourne, 1977).

Fruit and vegetable losses are higher in developing countries due to inadequate postharvest technology (FAO, 2013). Lack of refrigeration, inadequate equipment in the field, poor roads from field to market, and other limits in infrastructure are major contributors to these losses. Food waste is higher in more wealthy nations (FAO, 2013). Food waste at retail or in foodservice operations results from failure to purchase by consumers. Shrink, expressed as a percentage, represents the monetary loss incurred by the retailer. Shrink is 100% for any item discarded and partial in terms of sales at discount. Disfigured or decaying fruit presents an opportunity to reduce waste by offering it in precut form. One cause of waste at home results from purchasing more food than needed for consumption.

2.1.2.3 Implications of losses for fresh produce value chains

It is troubling to realize the same global regions that have over 50% loss and waste of fruits and vegetables are the same regions of the world with the greatest food shortages (FAO, 2011). Modest investments in infrastructure by the grower or produce cooperative could reduce losses, but capital is not always available. High waste at the consumption link is the most harmful economically and ecologically despite some attempts to utilize waste (Meng, Klepacka, Florkowski, & Braman, 2016). Studies (using systems approaches) of value chains for industrialized Asia, where loss and waste are substantially lower than all other regions of the world, are needed to learn what could be adapted to improve other regions of the world.

New ways are being developed to calculate FLW. FAO (2019) reports the use of a Food Loss Index. Also in development is a Food Waste Index. Data to this point are inadequate to develop conclusions. Such indices will have hig value when applied as part of a systems approach. Wilson (2013) notes "We invest 95% of our resources into producing food and only 5% into postharvest preservation." (World Food Preservation Center® LLC).

2.1.3 Low income for family farms

Most of the world's poor are located away from big cities and depend on subsistence agriculture (FAO, 2014, 2018). Only a small portion of the selling price at market returns to them through value chains (see also Chapter 10). Data from 2018 showed that farmers in the United States received 8.0% of the amount customers paid for food purchased at both grocery stores and eating out purchases (USDA Economic Research Service, 2020).

2.1.3.1 Importance of family farms

Over 90% of farms are run by an individual or family. Farm families occupy about 70%–80% of farmland. Family farms produce about 80% of the world's food (FAO, 2021).

2.1.3.2 International recognition

The United Nations adopted 17 Sustainable Development Goals for 2016–30 (FAO, 2015). The first goal is "No Poverty." Efforts are underway for a decade of focus on family farming (FAO and IFAD, 2019).

2.1.4 Systems thinking offers help

Existing approaches are failing to adequately improve postharvest handling of fresh fruits and vegetables. Low per capita consumption persists and is trending lower. Loss and waste remain unsustainably high in all regions of the world. Low incomes to family farmers result in widespread poverty. Systems thinking (as described in Sections 2.2.5, 2.3.4, 2.4 and 2.6) offers help to improve all 3Ls.

2.1.4.1 Low percapita consumption

What steps are needed to increase fresh fruit and vegetable consumption in the United States? Developing a better understanding of why American consumers prefer processed foods over fresh produce is a start. Key components to increasing purchase and consumption include:

- establishing the price/quality relationships that entice shoppers to select fresh produce,
- learning the inadequacies of current items available in the market,
- determining the cost and convenience of fresh foods relative to processed foods,
- designing handling techniques to deliver fruits and vegetables at peak quality, as defined by the consumer,
- assessing optimal harvest maturity to navigate handling, and
- developing breeding stock of selections that provide superior quality and withstand handling.

To be successful, such efforts will not be sequential. Rather they need integration, cross-fertilization of ideas, and frequent feedback between investigators.

2.1.4.2 Loss and Waste

Possible avenues of research to reduce loss and waste of fresh fruits and vegetables include:

- learning the forms of items sold that lead to the greatest waste in the home,
- analyzing fresh delivery patterns and inventory management in retail and foodservice operations,
- identifying key steps in each distribution channel where loss and waste are most likely to occur,
- developing techniques that minimize loss and waste in the most vulnerable steps, and
- devising economic incentive programs to actors in the chain who can lower loss and waste.

Once again, the greater the integration of these avenues of analysis, the greater the chance of success.

2.1.4.3 Low family farm incomes

Increasing low incomes among fruit and vegetable growers in rural areas around the world could start with assessing the limitations and benefits of:

- establishing price floors at the point of sale and to the growers,
- microfinancing for growers with proven track records,
- finding other forms of employment for disadvantaged growers,
- consolidating growers into cooperatives to command more equitable pricing,
- improving infrastructure, particularly rural roads, between the growing area and market, and
- providing appropriate technology and advice about its use to minimize loss and maximize return to the farm.

Note that these and other ideas to decrease rural poverty interact. Studies of individual efforts may obscure interactive effects. Success in decreasing poverty among growers should also help reduce food loss between farm and market.

2.2 Fresh fruit and vegetable value chains

FFVV chains start and end with consumers. At the same time, they start and end with farmers. Chains start with money flowing from consumers to the businesses in each chain and finally to farmers (see also Chapter 10, 11, and 12). All the money for the businesses in FFVV chains comes from consumers. Product flows in the opposite direction through business links in chains until a consumer eats the item. Fruits and vegetables must *consistently* taste good and have other desired attributes if the businesses in the chains expect to maintain or increase sales (see also Chapters 6–8 and 10–15).

2.2.1 Value chain description

The visual model for a fresh produce chain in Fig. 2.1 shows money and information that should flow from the consumer to the producer through other business links. Meanwhile, *value* is added as product flows the opposite direction. This concept was used by Prussia,

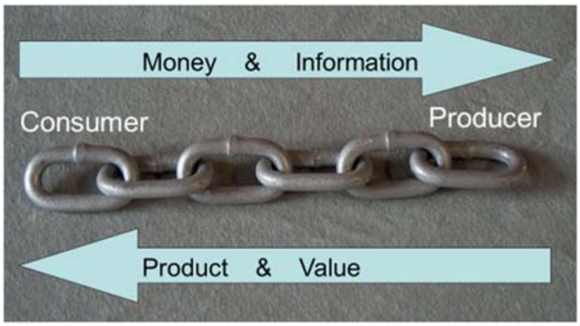


FIGURE 2.1 Visual model for a fresh produce chain.

Florkowski, and Lynd (2004) at an international symposium in Mexico. The English title of the presentation was "Producer Push or Consumer Pull?" Others have used terms such as "market pull" (Accorsi, Bortolini, Baniffaldi, Pilati, & Ferrari, 2017; Day-Farnsworth & Miller, 2014). Traditionally, growers have poor results when they try to push their produce through a chain. Limited information usually flows from the consumer to each link in the chain, especially to the packer and producer. Value is added to the product in many ways as produce flows through business links from producers to consumers. A question remains about how much information on the needs and desires of consumers actually flows along with the money from consumers to decision makers in fresh produce chains.

As an individual fruit or vegetable travels from the orchard or field where it is grown to a consumer where it is eaten, it can be exposed to a number of environments and circumstances (see also Chapter 16 and 18). These paths are known as a supply or value chain and are discussed in many different ways in different chapters in this book. The quality and condition of each individual fruit or vegetable when it arrives at its point of consumption depends on its maturity at harvest, delicacy or roughness of its treatment during handling, the storage conditions to which it is exposed, and the cumulative length of time from harvest to consumption (Gogo, Opiyo, Ulrichs, & Huyskens-Keil, 2017; Mampholo, Sivakumar, & Thompson, 2016; Prusky, 2011).

Value can relate to each individual fruit or vegetable, or to a unit such as a consumer pack, a master pack with several consumer packs, a pallet, a lot (batch), a truck load or larger units like a ship. For example, strawberries are typically removed individually by hand from the runner (vine) and placed into a pack that is eventually purchased at a retail grocery store. Strawberries need to remain on their runner until ready to eat; they do not ripen after harvest like peaches, mangoes, tomatoes, or other climacteric fruit. So, value is added to the pack when the harvester picks only individual berries that are mature (preferably no white color), clean, free of defects and meet other standards. The value of each pack is increased when it is transported from its point of growth and delivered to its point of purchase. Proper handling of the master pack (cool chain, careful handling, expedited delivery) is required to reduce the rate and amount of senescence (the condition or process of deterioration with age).

Other crops that go to packinghouses have value added to larger containers (fiberboard boxes, returnable plastic containers, etc.) in similar ways by separating debris and undesirable items and by sorting individual items for quality attributes and placing them into batches (grades, lots) with similar characteristics. Sorting improves the quality of the lot, not the individual item (see also Chapters 12–15). Value can be added to climacteric fruit as it travels through a chain by controlling the rate of ripening by adjusting storage time, temperature settings, ethylene levels, and using other technologies.

2.2.2 Terminology for chains

Along with using care when referring to systems, we also need to correctly identify postharvest chains. They should be plural because there are multitudes of different chains for fresh produce. Even for a specified category like peaches, it is incorrect to say "the peach chain" because each shipment often passes through different business links. Different links (grower, packer, trucker, distribution center, food purveyor, foodservice provider, cafeteria) form each chain (see also Chapter 6). Different retailers can negotiate different purchase orders to different shippers. Orders for a convenience store would have a different purpose or function for a value chain compared with orders by a foodservice provider for peaches decorating a table at a wedding banquet. Food operations extend beyond restaurants to cafeterias, caterers, fast-food outlets, and any other business that markets food for consumption away from home (FAO, 2019).

Taking the uniqueness of purchases to the extreme can be illustrated as follows. Each peach eaten by a student in a school cafeteria has a unique history along the chain of events necessary to deliver it to that student. Different attributes result from different genotypes, orchard location, age of tree, pollination date, weather events, maturity at harvest, delays in cooling, locations along the pack line, position in the box, location of the box in the truck, travel environment and duration, carefulness of material handlers at the distribution center and transport to the school cafeteria, and conditions during display.

Improved quality likely leads to more consumption. Sufficient money from consumers must flow to the business links that make an investment to improve quality. For example, growers need a higher price per box if they increase thinning to ship larger fruit. Likewise, if packers are required to ship fruit that is more mature, then funds would be needed for upgrading packaging methods and for improved handling equipment used for transporting fruit from the orchard to the packinghouse. In most chains, there is imperfect feedback for increasing quality or reducing loss (FAO, 2019).

2.2.3 Systems

Checkland and Poulter (2006) discuss the concept of systems. They insist the term "system" as used in everyday conversations or news articles is not appropriate. For example, the criminal justice system, national food system, or the health-care system does not meet the requirements of a system. Even what we refer to as postharvest systems in previous editions (1993; 2009; 2014) of this work do not qualify as sysems.

Terms related to systems are more difficult to define than we expected. A systems approach can include both a systemic (sys-'tem-ic) approach and a systematic (sys-te-'matic) approach. (Lane, 2018) stated "...both a systemic and a systematic approach can be encompassed within a systems approach, by an aware practitioner."

"Systems thinking" is the term that is becoming more prevalent than the term "systems approach." Many authors who discuss systems thinking have their own definition. For now, we offer this short, new definition:

> Systems thinking can be viewed as a framework for learning about complex inter-relationships among parts that form a whole system with properties different than any of its parts.

A designed system has an owner who established its purpose(s) (Lane, 2018, p. 51). A boundary separates the parts inside a system from the environment outside the system. The design and organization of the parts give the whole system unique properties that none of the parts have on their own. The parts have logical flows of information, material, and energy among themselves. Parts can also interact across their system boundary with systems in the surrounding environment. Only the system itself has final authority to make changes. Outside systems can influence a system, but cannot change it. Individual parts of a system can also be systems (subsystems) as defined here.

2.2.4 FFVV chains are NOT systems

The previous discussion on systems is now applied to FFVV chains. They fail to meet the requirement for being a system. Links of a chain are systems.

2.2.4.1 Properties of a system

Wilson and Morren (1990) specify nine properties that a putative system must possess to qualify as a system. FFVV chains fail to meet three of these properties.

Property 3 A system (S) is a system if it: "Has a mechanism of regulation (a process of decision making and resource allocation) that reflects the purpose, responds to information, and governs performance." FFVV chains do not have a process of decision-making and resource allocation that responds to information. For example, consumers cannot require a percentage of their purchase cost be allocated for the changes necessary to deliver more mature peaches.

Property 7 A system (S) is a system if it: "Can be distinguished from the suprasystem or environment (E) in which it exists by a boundary that represents the interface between an S and an E; and clearly distinguishes things that are under the S's control from things that are not controlled and to which the S must be adapted or accommodated." Individual FFVV chains do not have a boundary enclosing it, nor a a person, business, board of directors, or other authority that controls all the links in that chain. Even vertically integrated companies (like Zespri, Chiquita, Del Monte, Dole) cannot control handling and storage of product in homes or in restaurants, cafeterias, and other institutional food preparation and serving businesses.

Property 9 A system (S) is a system if it: "Has some guarantee of continuity, stability, with the capability of returning to a stable state (or qualitatively acceptable changed state) when disturbed and/or resisting forces emanating both from within the system itself (e) and from its environment (E)." FFVV chains lack a guarantee of continuity, stability, with the capability of returning to a stable state. Many business links frequently contract with different business links (like changing growers, packers, transporters, etc.) (see also Chapter 11).

Failure of fresh produce chains to satisfy three of the nine properties necessary to be a system means they are not systems as defined by Wilson and Morren (1990) and by Checkland and Poulter (2006). Therefore it is a misnomer to call any fresh produce chain a "system." Chains also fail to meet the definition of a system specified by a distinguished leader of systems thinking (Ackoff, 1999).

2.2.4.2 Links as systems

However, individual links in a fresh produce chain can be viewed as a system with clear ownership, defined boundaries, expected continuity, and characteristics that satisfy all nine requirements. For example, autonomous packinghouses are systems that can be influenced by other links in a chain but are not subject to any final authority by retailers, foodservice providers, or even consumers. Knowing that none of the innumerable fresh produce chains that exist is a system, means there are *no* "postharvest system" at the local, regional, national, or global level.

Realizing that fresh produce chains are not systems helps to understand why decades of efforts have not increased per capita consumption of fresh produce, reduced food loss, nor improved the livelihoods of farm owners. Most likely, grant funding is scarce for projects that seek to improve entire chains because there is not an identifiable person or group that represents entire chains like there would be if they were systems. A possible approach is for a group of systems thinking experts to evaluate fresh produce value chains and make recommendations for moving forward. Food and Agriculture Organization (FAO) is a likely candidate for conducting such a project.

2.2.5 Systems thinking applied to chains

Examples of systems thinking are evident in reports related to food security initiated by the United Nations (FAO, 2019; HLPE, 2014). These reports by the HLPE (High Level Panel of Experts) and the FAO relate to reducing FLW by improving communications, understanding latent loss, and considering economics of chains.

2.2.5.1 Communications

One of the reasons given (HLPE, 2014) for adopting a "food chain approach" is a "lack of coordination" in chains. Communications necessary for coordination are difficult because FFVV chains are not systems, as discussed in Section 2.2.4. "However, incomplete information about their own food loss and waste decisions, as well as those made by other actors in the food supply chain [sic], may prevent actors from taking fully rational decisions on the optimal level of food loss or waste" (FAO, 2019).

2.2.5.2 Latent loss

Losses that "occur at a different stage than where losses effectively appear" (HLPE, 2014) can be called latent losses. "For instance, some part of [food loss and waste] FLW happening at retail and consumption stages can be traced back to causes at harvest or even preharvest stages" (HLPE, 2014). Systems thinking is needed to investigate and to determine the actual cause of the losses (see also Chapter 18).

2.2.5.3 Economics

Family farmers could benefit the most from a shared distribution of costs due to waste inherent in a chain from farm to market. Economic incentives by actors up the chain could lead to reduced waste at the farm. FAO (2019) Lowering consumer losses and waste can hurt earlier links in a chain. By reducing consumer waste, less crop is needed and farmers receive lower incomes (FAO, 2019). Farmer income can also be hurt by decisions of retailers by lowering the price they are willing to pay.

FAO (2019) recognizes the need for farmers and others to be paid for their investments to improve. Systems thinking offers fresh approaches for addressing global postharvest handling problem situations that have resisted improvements for several decades.

However, Jackson (2019) recognizes the challenges when trying to improve chains with multiple links. If each link seeks to maximize returns, then value in the chain as a whole will not improve. Individual actors will not receive compensation for adding value (see also Chapter 11).

2.3 Learn the unknown

Most learning by students at all levels involves information already known. Likewise, most knowledge gained by adults is information that had been learned previously by others and passed on through books, magazines, newspapers, videos, social media, and other modes of communication. The scientific method is the best-known way to obtain knowledge that was unknown in the past. However, it is not the only way to learn the unknown. It has limitations (Checkland, 1999).

2.3.1 Visual model with three ways to learn the unknown

Table 2.1 is a visual model that represents three ways of gaining knowledge that was *un*known before starting an inquiry. The table follows the pattern of conceptual models described by Checkland (1999) when using soft systems methodologies (SSM). Verbs emphasize actions that can be accomplished by users of a learning system. Not included are prerequisites like language, logic, math, and discussions on epistemology. The purpose of the diagram is to encourage discussions on possible improvements for presenting ways to learn new knowledge.

The first column in Table 2.1 is based on describing the scientific method using three words that start with the letter "R" as originated by Checkland (1999). The diagram in Table 2.1 is arranged so that each column can be read as a sentence. The first column can be read as; "To learn the unknown with the scientific method we research scientifically using 3-R's to Reduce reality, then Refute hypotheses, and Replicate results." The second column is from Prussia and Birmingham (2000). The remaining column is new for this chapter.

TABLE 2.1 A conceptual model for learning the unknown that uses verbs as described for conceptual models in soft systems methodologies.

To	Learn the unknown		
With	The scientific method	The engineering approach	Systems thinking
We	Research scientifically	Design knowledgeably	Simulate holistically
Using	3Rs	3Ds	3Ss
To	Reduce reality	Desire improvements	Select methodologies
Then	Refute hypotheses	Develop designs	Simulate systems
And	Replicate results	Deploy innovations	Share insights

2.3.2 The scientific method—research scientifically

Tremendous progress has been made by using the scientific method to learn publicly verifiable knowledge of unknowns in the world and the universe. Notable examples are discovery of deoxyribonucleic acid (DNA), gravity, electricity, and vaccines. In addition, the theory of relativity, the uncertainty principle, and quantum mechanics shaped many advances in the twentieth century.

Roger Bacon stated the need of independent verification and for basing the scientific method on observations, experimentation, and hypotheses in a repeating cycle already in the 13th century. Sir Francis Bacon is credited with introducing the scientific method we use today. Isaac Newton developed the basis for classical physics. Karl Popper described the concept of falsification to include the null hypothesis. Thomas Kuhn proposed the concept of replacement to include the use of paradigms.

Checkland (1999) identified three major defining characteristics of science. The activities commonly associated with the scientific method are described under the appropriate verb in the next sections. A postharvest example from research by the authors is given for each verb.

2.3.2.1 *Reduce*

Reduction is necessary to simplify the complexity in a messy world to the point that variables can be controlled. Reduce includes:

- make observations in the real world,
- do a literature review, and
- ask and define questions.

Growers are often encouraged to cool fresh produce *as soon as possible* after harvest. Delays in cooling are inevitable because it is not technically feasible to cool within seconds or minutes after harvest. We followed the scientific method to give answers to growers for several cultivars of blueberries and peaches because such research with regard to specific cultivars was lacking but had immediate practical application (Aggarwal, Prussia, Prussia, et al., 2003; Aggarwal, Prussia, Florkowski, & Lynd, 2011).

Possible postharvest studies were reduced to the effect of time and temperature on blueberry and peach firmness and mass for selected cultivars. From the literature the research team knew that most fruits have exponential rates of change for physical characteristics. We determined to learn rates of change for seven blueberry and nine peach cultivars grown in Georgia.

2.3.2.2 *Refute*

- Develop a hypothesis that is testable, falsifiable, and realistic.
- Design experiments to test the hypothesis.
- Collect and analyze data.
- Accept or reject the hypothesis.

Our hypothesis was that losses of firmness and mass over time for different cultivars of blueberries and peaches would be exponential and depend on storage time and temperature (see also Chapter 4). Within one hour of hand-harvesting, 25 individual fruits from the cultivars were randomly placed into 4 different chambers with controlled temperatures and humidity. Firmness and mass were periodically measured nondestructively with calibrated instruments for 2 weeks. Regression analyses found the best fit for curves. The exponential hypothesis was accepted for temperature but not for time.

2.3.2.3 *Replicate*

- Test multiple samples during experiments.
- Repeat experiments.
- Publish results so others can repeat the experiment.

Experiments had 25 blueberries for each cultivar and temperature treatment combination. Measurements were nondestructive so we could use the same individual fruits over the duration of the test. Results were published so others could benefit and repeat the experiments. (Aggarwal, Prussia, Florkowski, & Lynd, 2003; NeSmith, Nunez-Barrios, Prussia, & Aggarwal, 2005; Nunez-Barrios, NeSmith, Chinnan, & Prussia, 2005).

2.3.2.4 *Summary and comments for research scientifically*

Ackoff (1999) describes a limitation of the scientific method resulting from reduction. There is no step for understanding a whole system from studies of its parts. Scientific Research has enabled scientists to learn about the realities of the universe. Scientific Research has produced many useful results but is limited to learning about what exists. It is reductionist and lacks a step for integrating results back into reality.

2.3.3 The engineering approach—design knowledgeably

The second column of Table 2.1 can be read as: "To learn the unknown with the engineering approach we design knowledgeably using 3-D's to Desire improvements, then Develop Designs, and Deploy Innovations."

Patents obtained by using the engineering approach show that something unknown was learned using a way other than the scientific method. This is evidence that the engineering approach is a way to learn the unknown in addition to the scientific method.

Simon (1996) states that engineering provides synthesis, but science emphasizes analysis. "Science is about what is, design on the other hand is about what ought to be." (Ackoff et al. (2010)) (Table 2.2).

Prussia and Birmingham (2000) developed a description of the engineering approach using three words starting with the letter "D" by following the pattern of Checkland's three words starting with the letter "R" to describe the scientific method. The following description of each activity is followed with a postharvest example.

2.3.3.1 *Desire improvements*

Design engineers assume the attitude that "there must be a better way." Rather than accepting what *does* exist, they tend to visualize what *could* exist. Design engineers then synthesize ideas for improvement.

TABLE 2.2 Comparisons of the scientific method and the engineering approach.

Research scientifically	Design knowledgably
Reduce	Synthesize
Study what *IS*	Design what will *BE*
Research to learn	Learn if the design works

- The engineering approach is much more than "the application of science."
- Engineers design what never existed before.
- Until it is tested, it is *unknown* if it will work or serve its intended purpose.

The firmness of fruits and vegetables is an important quality attribute at all links of fresh produce value chains. Human judgment of firmness is not reliable. The standard instrument to measure fruit firmness is the Magness–Taylor device that measures the force needed to penetrate the product with a plunger with specified dimensions. The measurement is destructive, so only a small sample can be tested to represent the batch or lot. A nondestructive test would enable testing of individual fruits and vegetables. As described earlier in the scientific study of blueberry and peach storage, nondestructive tests also enable repeated measurements on individual items over time to improve the statistical evaluations.

2.3.3.2 *Develop designs*

- Understanding scientific and engineering principles helps to design knowledgably.
- Thinking creatively and "outside the box" encourages innovation.
- Engineering analyses evaluate feasibility.
- "Invention" could replace "Genius" in Edison's famous quote "Genius [Invention] is one percent inspiration and ninety-nine percent perspiration."
- Design cycles can include understand, observe, define point of view, ideate, prototype, test, reflect (Lewrick, Link, & Leifer, 2020).

An idea for measuring fruit firmness "hit" me (S. Prussia) when having my eyes tested for glaucoma (excess pressure inside the eyeball). An early laboratory prototype was designed, built, and tested. It released a puff of air through a nozzle placed near the item tested (Fig. 2.2). The deformation of the object was measured with a laser displacement sensor. The output voltage was measured with an oscilloscope. A second-generation prototype the size of a desktop computer was built that used a laptop computer to display and store the voltage measured.

2.3.3.3 *Deploy innovations*

- Presentations at professional meetings.
- Publication of peer-reviewed articles.
- New designs can be patented.
- Companies can obtain rights to manufacture products using the new design.

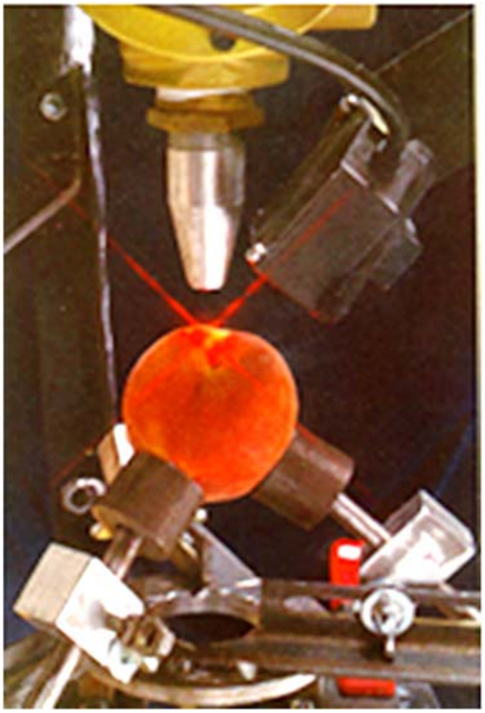


FIGURE 2.2 Laser-puff instrument for measuring fruit firmness.

Results of the study on the improved laser-puff food firmness detector were published in peer-refereed journals (Hung, McWatters, & Prussia, 1998; Prussia & Hung, 2001). Additional research studies were enabled because firmness could be measured nondestructively. The University of Georgia obtained a patent for the "Laser-puff firmness detector." A small business bought the patent (Prussia, Astleford, Hewlett, & Hung, 1994).

2.3.3.4 Summary and comments on the engineering approach

This description of engineering differs from science; meaning they are not the same way of learning the unknown. Integration of Scientific Research and Engineering Design is needed to improve learning of the unknown. Engineers need to increase the use of the scientific method when evaluating designs. Scientists would benefit from an improved understanding of engineering design when they develop new apparatuses and products.

Three books on design engineering are mentioned here. *The Design Thinking Playbook* is intended to help individuals, teams, and organizations combine design thinking with systems thinking and big data analytics (Lewrick, Link, & Leifer, 2018). Design takes existing knowledge and develops tools to solve a problem or introduce a new reality (Müller-Roterberg, 2020). Lewrick et al. (2020) compile 50 methods and tools beneficial to design thinking. Guidance is given for when and how interdisciplinary design teams can apply the tools during the seven-phase design process presented in the book.

2.3.4 Systems thinking—simulate holistically

The third column of Table 2.1 can be read as, "To learn the unknown with systems thinking we simulate holistically using 3-S's to Select models, then Simulate systems, and Share insights." Reductionism focuses attention very narrowly. Systems thinking takes a holistic approach to see the bigger picture Science narrows research to determine cause and effect. Systems thinking expands the horizon and looks for multiple causes (Jackson, 2019). Thinking in terms of a system requires synthesis and seeks to understand the interactions of different parts of that system. Science describes structure of its subject to produce knowledge. Synthesis reveals why something functions as it does to provide understanding (Ackoff, 1999). The systems thinking that resulted in the Peach Game (described in Chapter 5) was published before the modeling started (Prussia, Florkowski, Sharan, Naik, & Deodhar, 2001).

2.3.4.1 Select a model or methodology

Models range from scale model airplanes, to simple mathematical equations, to large computer simulation models. These models are generally concrete with clear outcomes, but systems thinking can lead to more abstract outcomes. They can be formed through:

- *Hard systems thinking*: Hard systems relate to projects with known goals with approaches like; linear programming, dynamic programming, queuing theory, inventory management, system dynamics, Markovian chains, Monte Carlo simulations, computer simulations.
- *Soft systems thinking*: Soft systems include people with differing worldviews. For SSM, "Soft" implies the inquiry does not have a predetermined "hard objective" such as to "double sales in two years" (see also Chapter 5).

Hard systems relate to systematic treatments. Soft systems are systemic (Meadows, 2008).

A hard systems model (computer simulation) was selected by the postharvest research team at the University of Georgia who used the scientific method to obtain equations for predicting blueberry and peach mass and firmness as described in Section 2.3.2. Microsoft Excel was selected to simulate postharvest changes as a function of time and temperature. The use of Excel software was desired because it allowed combining results from all cultivars of blueberries (seven) and peaches (nine) into one user-friendly decision support program. Also, the postharvest team wanted a graphical display of the changes in firmness and mass for selected times and temperatures for critical postharvest decision points.

2.3.4.2 Simulate systems

Much of the time needed to complete a project with a focus on systems thinking is necessary for the simulation activities. In the same way, much of the time for the scientific method is for formulating and testing hypotheses and for the engineering approach the most effort is usually for developing designs. Each type of model requires different processes for simulating systems.

2.3.4.2.1 Types of simulation models

The following short list of model types includes selected tools that are the most relevant for models discussed in Chapter 5, which also provides details for these and other types of models available for simulating systems.

- Math—Solve algebraic equations, differential equations, matrices, complex variables, series equations, and other approaches.
- Visual—Construct plots, schematics, survey maps, diagrams, dynamic animations, time-lapse, and slow-motion videos.
- Physical models—Build scale models of vehicles, buildings, cities, organic chemical bonds, DNA molecules.
- Computer simulation models—Examples are in Section 2.4.1 and Section 2.4.2.
- System dynamics—Both quantitative (Meadows, 2008) and qualitative (Senge, 2006) model are explained in Chapter 5. Checkland and Poulter (2006) describe soft systems methodoloty as a way to organize thinking around a process. It provides a defined protocol to learn about the system being studied.

2.3.4.2.2 Simulating blueberry and peach firmness and mass

The development of a simulation model for predicting quality changes in fresh fruit represented a transition from the scientific method described in Section 2.3.2 to systems thinking. Equations for predicting changes in mass and firmness of blueberries and peaches were entered into Microsoft Excel spreadsheets. Visual Basic provided an interactive graphical user interface that covered details of the spreadsheet. The simulation model enables users to evaluate the benefits of reducing delays in cooing—in general, the loss of mass and firmness during storage for 1 h at 34.2°C = 1 day at 2°C (See Chapter 5 for more details).

2.3.4.3 *Share insights*

The simulation is not complete until it is communicated to others.

- Demonstrate simulations to individuals, workshops, and other groups.
- Post software programs on websites.
- Mail memory devices with the programs to users or send through the internet.
- Present results at professional and other meetings.
- Publish results in peer-reviewed journals and other publications.
- The fresh produce simulator program for Excel is available from the authors.

Users of the blueberry and peach postharvest simulations were able to visualize the importance of cooling delays in the field. Users enjoyed trying extreme conditions, such as 50°C in the trunk of a car for one hour. Insights learned by applying a systems approach were shared through publications. Users were reminded to think about the entire chain, especially the consumer in the context of postharvest quality of fresh blueberries or peaches (Aggarwal, Prussia, Prussia, et al., 2003; Aggarwal, Prussia, Florkowski, & Lynd, 2004a).

Insights learned from systems thinking were also shared at specially arranged seminars and roundtable workshops. The fresh produce simulator helped participants better understand fresh produce value chains. Soft Systems Methodology (Prussia, 2000; Rohs, Prussia, Beristain, & Cortez, 2002) was also taught through active participation at meetings.

2.3.4.4 Summary and comments on systems thinking

Systems thinking is a third way for learning the unknown. The diagram in Table 2.1 is a model of a learning system. Systems at least one level higher and one level lower must be learned understand to the system between them. Workshops described earlier showed the value of interactions with business leaders. Results and benefits of systems thinking for the interdisciplinary postharvest research team included:

- Focus on consumers is needed to help the producer.
- Postharvest chains are not systems; a multitude of chains exist; each link can be a system.
- We had unusually frequent opportunities to interact with business leaders and the people performing postharvest tasks.
- Preharvest conditions, maturity at harvest, and latent damage are critical factors.
- The sum of our publications was greater than the sum expected from individual researchers.
- Systems thinking helped to prioritize individual research projects.

2.3.5 Summary and comments for learning the unknown

The scientific method reduces reality to learn cause-and-effect relationships. It is one of three ways to learn the unknown. The engineering approach produces innovative designs that were previously unknown. Systems thinking enables learning the unknown by modeling complete systems. Systems thinking broadens the perspective of the scientific method of the engineering approach. Systems thinking permits a better understanding of how parts within a system interact and provides potential solutions to complex problems not available to the other two alternatives. Its limitations are that it focuses mainly on the whole system, not details.

2.4 Examples of systems thinking

Postharvest research in recent decades has resulted in remarkable improvements for measuring quality attributes, sorting, packaging, understanding and modeling physiological responses, extending shelf life, and learning consumer responses. Still lacking is research on helping business and organization leaders and managers integrate and implement these technological and physiological advances into the complex realities of FFVV chains. Consequently, the 3Ls (Low per capita consumption, Losses and waste, and Low farmer income) have shown little overall improvement.

Numerous efforts for improving postharvest handing for fresh fruits and vegetables have focused on plant physiology (science) and technology (engineering) along with some economic analyses. Surprisingly, few business colleges have studied fresh produce chains. This section gives examples of systems thinking by some FFVV businesses, describes needs for research integration, and presents needs for simulations and games for FFVV chains. Then a section on learning from other sectors provides some examples that could be adapted for FFVV chains.

2.4.1 Examples for FFVV chains

Systems thinking has increased over the last decade in major business sectors, academia, organizations, and international agencies. Systems thinking is starting to be noticeable in books, publications, and other communications for agriculture, food processing, and (slightly) in value chains for fresh fruits and vegetables. Chapter 1 gives an overview of systems thinking while Chapters 2, 5, 6, 10 and others give more details. This book as a whole is an example of systems thinking.

2.4.1.1 Commercial business examples

Some companies are vertically integrated to different degrees. The degree of integration depends on the number of links in their value chains that are under their control (integrated) or the percent of product that flows through integrated chains that they own. Integration of value chains enables companies to implement systems thinking to improve the entire chain. However, the most integrated chains do not have final control over retail outlets, foodservice companies, and consumers at home.

Several examples of fresh fruit providers illustrate the actual integration. Dole owns its growing operations in Central America and is vertically integrated from harvest to retail (Dole Food Company, 2021). Fresh Del Monte Produce Incorporated is also vertically integrated, distributing fresh and fresh-cut fruits and vegetables on company-owned ships (Fresh Del Monte Produce, 2020). Chiquita is a major vertically integrated distributor of bananas and other fruit (Chiquita Brands International, 2021). Zespri International Limited is the world's largest marketer of kiwifruit. They own or control many links in the value chains for growing and marketing kiwifruit. Zespri was formed as a cooperative of kiwifruit growers in New Zealand. To supply fruit year-round, they have licensed growers in Italy, France, Japan, South Korea, Portugal, and Greece (Zespri, 2020).

2.4.1.2 Need for research integration

Advances and innovations in value chains will accelerate as researchers share results and integrate their perspectives. For example, a grower-initiated value chain that shares knowledge obtained through genetics, crop production, and processing is used to invest in consumer-focused research (Teese, Currey, & Somogyi, 2019). Chapter 10 describes another group of Austrailian growers vertically integrated with suppliers and distributors. Systems thinking provides benefits by showing the need for sharing quality expectations and willingness to pay back through the value chain. Unfortunately, some links in most chains are unwilling to share such information due to proprietary considerations or other reasons.

Galanakis (2019) reviews losses and waste for many food chains and recommends ways for improving them using systems thinking. He emphasizes the need for collaboration in optimizing FSCs.

Acedo (2019) describes a major success story for improving fresh produce quality, reducing postharvest losses, and improving incomes for small farms in several countries in Asia and Southeast Asia. They intuitively used systems thinking from the beginning by drawing *value chain maps* of products and actors *starting* from the final markets to farmers. Their value chain analysis included loss assessments that prioritized loss reduction measures. The main causes of losses involved insufficient attention to handling techniques, proper packaging, and optimal storage conditions.

Further research emphasized breeding, production, and postharvest techniques to increase shelf life. Improved cultivars were introduced for several crops based on yield, quality, shelf life, and other traits. Postharvest technologies suitable for smallholder farmers, including low-cost evaporative cooling, hydrocooling, modified atmosphere packaging, ethylene controls, and natural fungicide treatments, were evaluated.

Best practices were identified and training manuals were prepared in several languages for use in hands-on training programs using tech demos, field days, and agri-trade fairs. Family farmer groups were organized and packhouses were built that enabled quality assurance activities and served to coordinate chain management. Postharvest losses were reduced and grower income increased.

Two publications that advance systems thinking in agricultural research are the *Journal of Food Distribution Research* (JFDR, n.d.) and *Agricultural Systems* (Agricultural Systems, n.d.). The latter journal limited content about business links because it requires a "substantive biological component" to publish research involving supply chains. Further information on systems research is available from public organizations, institutions, agencies, and nongovernment organizations from many countries that publish relevant information for FFVV chains. For example, agencies such as USDA (National Institute of Food and Agriculture) and United Nations FAO are rich sources of information.

2.4.1.3 *Need for simulations and games for FFVV chains*

The Peach Game (Aggarwal et al., 2004a) and the Postharvest Quality Simulator were developed at the University of Georgia. Peach Game players assume the role of a retail produce manager ordering boxes of fruit through a value chain from a grower to a retailer. The introductory level has a known demand plot and a 2-week delay for delivery from growers to arrival. The game ends if stocks are depleted. A bank balance serves as the score. Other levels enable changes in variables like reducing delays to 1 week, which improves scores and shows the structure of a system is more important than the processes.

Researchers in Italy expanded on the Peach Game using an object-oriented simulation language, Extend, to develop management simulation models that allow testing of diverse logistic and transport solutions (Busato & Berruto, 2006). Their FruitGame simulates decisions required for boxes of strawberries, zucchini, and tomatoes moving through the links in a value chain from grower to market. By tracking each box factors like quality traits and shelf life can be monitored.

Accorsi and Manzini (2019) provide valuable examples of system-dynamic methodologies incorporating sustainability variables within food chains. Issues modeled for different phases of an FSC are described. Physical flows of food from farm to consumer and important parts of the network contributing to the food ecosystem are tracked. They emphasize the need for governance and control by policymakers in chains. However, one of the arguments that fresh produce value chains are not systems is based on their lack of any person or group with authority to control (or rule over) all the links in the chain. Valuable results can be obtained from models that treat chains as if they are systems by learning what flows of information, materials, and energy that are needed to improve performance.

Meinke (2019) discusses the power of agricultural systems thinking in the context they are "complex, adaptive systems." He projects increased use of these techniques in the future to improve management of chains.

Accorsi et al. (2017) explain their gaming simulation tool that was developed within Labview integrated development environment. They *start with market demand* to simulate value flows that started with the agricultural/production stage and progress through distribution/transport, storage, consumption, and waste/disposal stages. This game aims at enabling the users/planners to experience the effect of a decision on a given link of the network to the whole food ecosystem. Such a method is called gaming, because the users/planners play the levers of the network and experience the impact of their choices on the overall sustainability of the FSC as a whole ecosystem. Current programs are described on their website (FSC, n.d.)

Besides computer-based simulation games, a board game was developed for selling and buying of tomatoes in a marketing chain with links for growers, cooperatives, wholesalers, retailers (Van Haaften, Lefter, Lukosch, van Kooten, & Brazier, 2020). Researchers and representatives from the chain participated in the development of the interactive game. Players could request cards with information about the link in the chain they had selected to play. Volumes traded were determined by rolling dice. Players had a limited time to negotiate the volume and price for their deals. The researchers concluded, "Involving stakeholders from the field in the design, development and execution of the gaming simulation (sessions) enables explication of tacit knowledge from participants, independent of the field of application."

If more were available, gaming-type dynamic simulations would stimulate intense user interactions for large populations of users. Real-time interactions with dynamic simulations could also add complexity at levels typically encountered by managers. Chains could be simulated as if they are systems so we can better understand interactions and communications.

2.4.2 Learning from other sectors

Links in produce value chains are businesses and organizations that would benefit from business management trends that have been successful in other economic sectors such as automotive, electronics, and consumer goods. Individual chains could benefit from evaluating them as if the chain is a system, to learn what activities and lines of communications are needed to improve. Special attention is needed for improving communications into and from all links in a chain and for compensating for the lack of control in chains because they are not systems.

Sterman (2020) suggests that the complexity of commercial operations is difficult to describe or model in a classroom. Simulation games illustrate the depth of complexity and provide insight that a verbal explanation cannot. The Massachusetts Institute of Technology (MIT) Sloan School of Management provides open access to its management simulations free of charge (MIT Sloan, 2021). Another source of free simulation software is available from Simio (2021).

Forio is a company (in partnerships with MIT and other business schools) that develops custom and many ready-to-run simulations, including one that simulates the management of a global supply chain. Activities include:

- Create a cost-effective and flexible supply chain.
- Evaluate forecasting methods, including understanding the pros and cons of consensus forecasting.

- Build a production plan based on a probabilistic demand forecast.
- Distinguish between a forecast and a production plan.
- Weigh the relative importance of results and process performance measures.

A comprehensive book on SIMIO is available (Law, 2014). Another book describing simulation (Smith, Sturrok, & Kelton, 2018) includes details for using the simulation package SIMIO. Winners of student competitions included simulations of supply chains for an international manufacturer and processing operations at a hybrid seed company. The SIMIO website gives an example of applying the digital twin as a validation tool to evaluate operation strategies in restaurants. Another suggested application is to evaluate how the implementation of Industry 4.0 will benefit supply chain planning. FFVV chains could benefit from simulations based on software such as SIMIO.

Popular video games that simulate farming operations are Farming Simulator (Farming Simulator, 2021) and SimFarm (Electronic Arts, 2021). They enable players to experience producing and selling their agricultural products in the adjacent town. Players could add to their valuable learning experiences if the companies developed similar simulations for marketing fresh produce through multiple FFVV chains.

2.5 Critical systems thinking

One technique cannot solve all problems. (Fig. 2.3). If we only have one way to learn the unknown, then we use whatever way we know even if the results are not satisfactory. Better results can be expected if we or a team are prepared to use all of the ways for learning; the scientific method, the engineering approach, and systems thinking as described in Section 2.3.

A new plateau of thinking about FFVV chains is possible by adapting ideas from a book by Jackson (2019) titled *Critical Systems Thinking and the Management of Complexity*. It has four parts in addition to an introduction and conclusion: I. systems thinking in the disciplines, II. the systems sciences, III. systems practice, and IV. critical systems thinking. The next sections discuss parts III and IV.

FIGURE 2.3 If a hamer is all I have, then everything looks like a nail. Source: *Photograph by S. E. Prussia.*

2.5.1 System of systems methodologies

Jackson (2019) defines *methodology* as "The guidance given to practitioners about how to translate the philosophy and theory of an approach into practical application." This concept differs from a *method* that will always deliver a particular outcome if it is used properly. He argues for the practice of using both methodologies and methods simultaneously to improve performance within a system or organization.

The first section of this chapter describes the need to improve FFVV chains. If the existing approaches are not working, then Jackson (2019) recommends using different methods. For example, replace the hammer in Fig. 2.3 with a screw driver. Complex situations like FFVV chains need many types of tools as discussed in this section.

2.5.1.1 The system of systems methodologies diagram

The diagram in Fig. 2.4 displays 11 methodologies in specific positions. The diagram is adapted from the original one by Jackson (2019). The two axes are described by Jackson (2019, p. 158). The *y*-axis for SYSTEMS represents a continuum from simple to

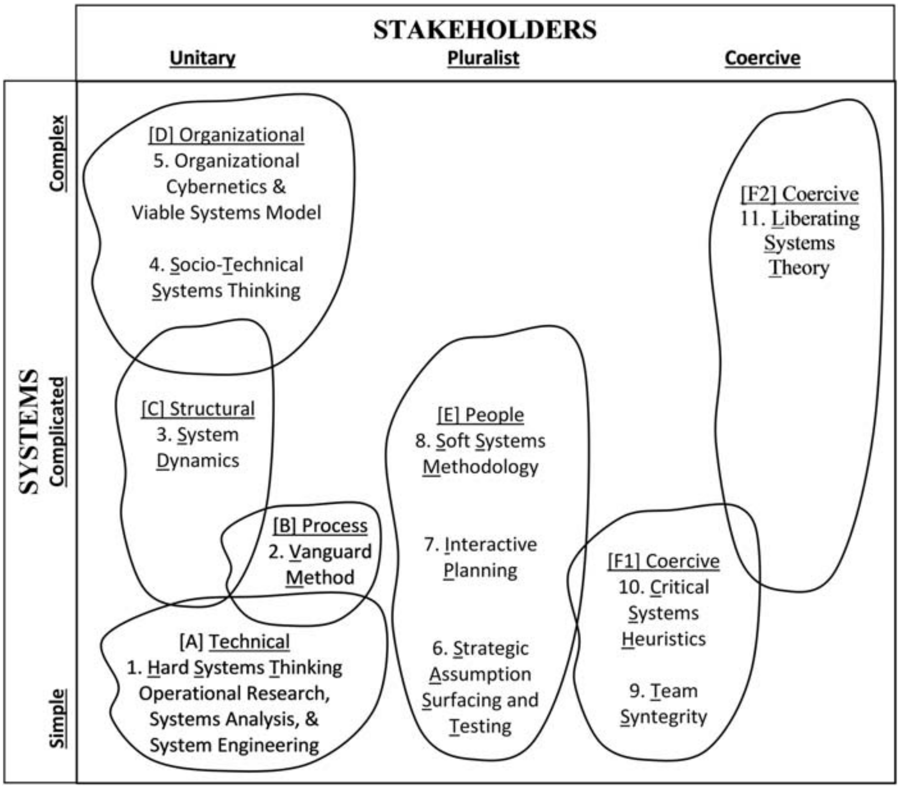


FIGURE 2.4 Positions for six types of complexity (A–F) for systems approaches based on Jackson's System of Systems Methodologies. Note that type F has two areas. Source: *Adapted from Jackson, M. C. (2019).* Critical systems thinking and the management of complexity. *Hoboken, NJ: Wiley, p. 592.*

complex. Simple systems have few subsystems with a small number of highly structured interactions. Complex systems have a large number of subsystems that have many loosely structured interconnections with outcomes that are not predetermined and change over time.

The *x*-axis represents a continuum of increasing divergence of values and interests among the stakeholders concerned with or affected by a problem situation. Positions of the methodologies along a vertical column in the diagram are based on their ability to be used for improving systems where stakeholders have the following three relationships.

- Stakeholders in a *unitary* relationship have similar values, beliefs, and interest. They have common purposes and objectives and are involved in decision-making.
- Stakeholders in a *pluralist* relationship have compatible interests but do not have the same values and beliefs. Interventions need to allow for debate, disagreement, and conflict. Their participation enables accommodations and compromises that can lead to productive paths forward.
- Stakeholders in *coercive* relationships have few interests in common due to irreconcilable values and belief. No agreed objective can result in action because compromise is not possible. Those with the most power make the decisions and use coercion to maintain their power. In some situations, terms like emancipation or improvement can replace coercive.

Jackson groups the methodologies into six types of systems approaches, labeled A–F. Type F has two positions, F1 and F2. Added to the original diagram were numbers 1–11 for the methodologies and six underlined headings with letters A–H for the type and its identity (technical, process, structural, organizational, people, or coercive, from Jackson).

2.5.1.2 System of systems methodologies

Methodology number 1 in the system of systems methodologies (SOSM) diagram is the complexity type A called *technical* for hard systems thinking. It actually includes three methodologies; operational research, systems analysis, and systems engineering which are some of the well-known tools for systems thinking. The term *hard* indicates the objectives are firm, well-known, and agreed with by stakeholders and interveners. The systems studied are considered simple enough to build a quantitative model that can be used to evaluate possible solutions. The worldviews of the stakeholders are close enough that they can agree on the objective and find the most efficient solution. Hard systems thinking includes methods such as linear programming, dynamic programming, and queuing theory. The produce quality simulator (Aggarwal et al., 2004a) is an example of systems analysis with user interaction added.

Methodology number 3 is also well known as system dynamics. It is a complexity type C called *structural*. Hallmarks of systems dynamics include information feedback, causal loop diagrams, experimental models, computer simulations, unintended consequences, limits to grown, and learning organizations. The Peach Game (Aggarwal, Prussia, Florkowski, & Lynd, 2004b) and the FruitGame (Busato & Berruto, 2006) are examples of systems dynamics applied to FFVV chains.

Methodology number 8, for SSM in complexity type E for *people*, is the last one discussed here. SSM describes a learning system where consultants or practitioners guide actors in an organization to understand a problem situation and then deliberately visualize situations from different worldviews (Weltanschauungen). Agreed to desirable and feasible changes are then implemented by the same actors. Repeated small changes are encouraged over one large change.

Methods such as rich pictures, root definitions, and conceptual models have resulted from using SSM. The round table workshops described in Section 2.3.4.3 included SSM conceptual models to help leaders from links in FFVV chains identify key activities that needed changed or added to their operations (also see Chapter 5). Table 2.1 uses verbs (a SSM tool) to describe the actions shown for the three ways of learning the unknown.

The value of a methodology is not based on its position on the SOSM. "It is important to insist, again, that the positioning of any systems methodology on the grid does not make it any 'better' or 'worse' than other methodologies placed elsewhere. It simply points out differences" (Jackson, 2019).

2.5.2 Critical systems practice

Critical systems practice (CSP) is a multimethodology approach while the previous methodologies shown in the SOSM diagram in Fig. 2.4 are single methodologies. A premise of this section is that FFVV chains would benefit from studies or interventions using the CSP multimethodology. Free courses on CSP are available from the Open University in the United Kingdom (OpenLearn, n.d.).

CSP consists of four desired outcomes:

Creativity-identifying critical issues to be studied
Choice-methodologies and methods to be employed
Implementation-changes that will be incorporated from different perspectives in the process
Reflection-ways to view the outputs and initiating future studies.

Jackson (2019) states that CSP is positioned over the entire diagram in Fig. 2.4. He provides examples of CSP in action. Over five decades of commendable effort has not resulted in satisfactory improvements in consumer nutrition, loss reduction, or family farmer income. As far as known, only three of the eleven methodologies in Fig. 2.4 have been applied to FFVV chains. The applications were very limited in scope, duration, and resources. All eleven methodologies were developed through applications in business and organization environments (Jackson, 2019). It is reasonable to expect that experienced practitioners would be able to help business links in FFVV chains to realize worthwhile improvements. In addition, the advancement of multimethodologies could be achieved by learning how to intervene in complex value chains such as were made in statistical methods applied to agricultural research.

2.5.3 Adding interactive leadership experiences to the SOSM

This section proposes adding to the SOSM diagram in Fig. 2.4 a new systems methodology, initially called *interactive leadership experiences* (ILE), in a new paradigm called *Learn*. If developed, then ILE could help practitioners, leaders, and others learn critical systems thinking and practice. Then, when invited to intervene in complex organizations, appropriate methodologies from SOSM would be selected based on systems thinking guided by CSP. The proposed methodology of ILE will need to be informed by several areas of social science and the learning opportunities afforded by simulations and gaming.

ILE incorporates andragogy "the art or science of teaching adults" (Merriam-Webster, 2021). It provides a foundation for adults to learn about complex systems. The technique incorporates personality typology that helps a person better understand their own personality and why others think and act differently. This information helps managers appreciate the plurality of world viewpoints of different methodologies on the SOSM diagram. A prime example of this testing is Myers/Briggs testing (The Myers & Briggs Foundation, n.d.). The use of the personal construct theory, especially the technique of using repertory grids, helps explain how people perceive their relations with others during simulations to learn about FFVV chains and interventions for making improvements (Neimeyer & Torres, 2015).

Another technique that fits into ILE is experiential learning that supports the benefits of experience. The old adage that "Experience is the best teacher" is given new life by Kolb (2015). Kolb and Kolb (2013, 2017) illustrate the experiential learning cycle incorporating the learning styles of concrete experience, reflective observation, abstract conceptualization, and active experimentation. Participants in each learning style provide leadership at each stage. Each additional turn of the cycle further refines the process.

2.5.3.1 *Enhancing ISE through simulation and gaming*

ISE is enhanced through simulation and gaming as described in Section 2.4.1.3. Jackson (2019) describes some personal experiences of using simulations during many years of teaching postgraduate students and executives all over the world. They gained insights from viewing case studies from different systems perspectives. Jackson designed role-playing exercises where groups acted as consultants using CSP to analyze a case that was presented to members of the faculty acting as senior managers.

2.5.3.2 *Development of an* **interactive leadership experiences** *methodology*

Fig. 2.4 has 11 methodologies in the system of systems methodology diagram. A new methodology could be developed for ILE if a need is determined (Jackson, 2019).

Some characteristics suggested for an ILE are listed here.

- Consultants and teachers learn CSP, and the methodologies in the SOSM diagram.
- Consultants and teachers employ: andragogy, personality typology, personal construct theory, and experiential learning styles.
- Educators teach systems thinking using simulations and interactive and experiential learning.
- Consultants and leaders learn from previous intervention approaches by simulating alternative outcomes.
- Organizations emphasize leadership in addition to management.
- Consultants gain leadership experience through physical and virtual simulations.
- Consultants and researchers conduct interventions based on CSP and SOSM.
- Users reflect on experiences to improve the ILE methodology.

The ILE methodology could use learning methods such as interactive techniques, experiential learning, computer simulations models, board and video games, role-playing, case studies, and other tools to generate interest and depth of understanding and retention. Considerable efforts would be necessary by people with expertise using CSP and other systems' approaches to develop this initial concept into a functional methodology comparable with the original 11 paradigms shown in the SOSM diagram.

The shaded area in Fig. 2.5 is a suggested new complexity type G, which was added to the previous diagram in Fig. 2.4. The label *Learn* for complexity type G applies to both learning what is necessary to develop a new methodology and to the learning that results from using it during interventions to improve complex situations. The suggested new methodology (labeled number 12) is *Interactive Leadership Experiences*. **I**interactive implies both dynamic interactions of system parts and of the people involved with interventions. **L**eadership is the term used rather than management to emphasize the need for creative changes rather than excellence at managing existing systems. **E**xperiences are real or virtual.

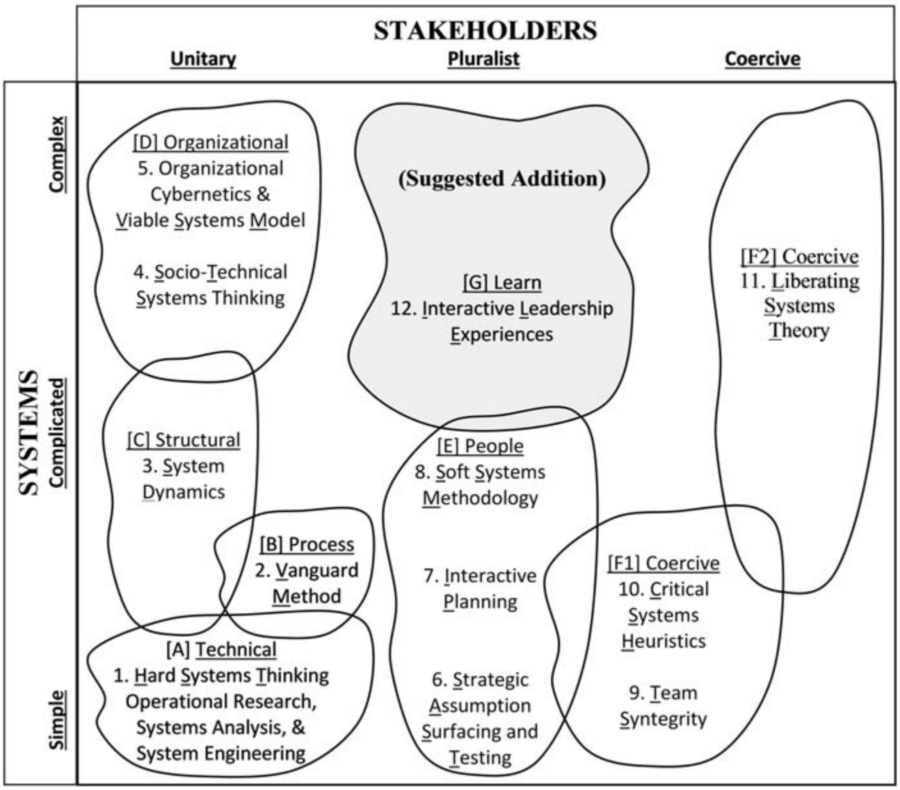


FIGURE 2.5 The shaded area is a suggested addition to Fig. 2.4. It contains a new complexity type labeled "G" that is titled "*Learn*" with a methodology initially called "ILE". (Note that type F has two areas.). *ILE*, Interactive leadership experiences. Source: *Adapted from Jackson, M. C. (2019).* Critical systems thinking and the management of complexity. *Hoboken, NJ: Wiley, pp. 592 & xxvii.*

The position for complexity G is in the Pluralist region because leaders of organizations are required to combine outputs from other methodologies. The position for G in the complex region is based on the need to consider various worldviews of complex management situations that are often unpredictable.

The process of developing a methodology for interactive leadership experience would require a comprehensive knowledge about the other methodologies in the SOSM diagram. The foundation for ILE can be broadened by combining all three ways to learn the unknown shown in Table 2.1. Computer simulations and games are gaining acceptance for executives and other leaders. Simulations enable leaders to experience the consequences for their decisions in ways similar to airplane pilots using flight simulators. Extreme situations can be experienced without physical harm or economic loss. Unique learning results when players deliberately simulate worldviews they do not favor, such as coercive complexities (F1 and F2).

Features of some simulations could enable players to modify an existing system or design new ones. An exciting game could be developed based on real-time engagement of multiple players representing leaders of links for a FFVV chain. Interactions could also include businesses, agencies, and other entities related to a chain. Players could use SSM (SOSM number 8) to identify multiple root definitions and conceptual models for a FFVV chain. Then various activities, structures, processes, and information flows could be suggested that would be necessary for their chain to function as if it were a system.

"Gaming is a kind of modeling in which 'actors' adopt and play out the roles of significant decision makers in a system. They are supposed to behave as would their real-world counterparts in order that matters of choice, judgment, values, and politics can be investigated" (Jackson, 2019). Common video games have reached a level of detail and complexity that it seems feasible to develop simulations games with the purpose of providing leaders of FFVV chains with entertaining experiences for learning innovative approaches to improving complex situations.

2.5.3.3 Recommendations for adding ILE to the SSOM

The evidence provided in this section seems adequate to nominate ILE as a methodology that joins the others on the system of systems methodologies family. Researchers, practitioners, and other interested parties are encouraged to complete additional enquiries and conduct interventions using ILE. When appropriate, an evaluation could be made about the status of ILE as a methodology. Then, a consensus could be reached to accept or reject ILE as a methodology in a new type G complexity type in the grid position of complex pluralist as shown in Fig. 2.5.

2.6 Systems thinking for moving forward

The Vice President of Bell Telephone Laboratory challenged his section leaders in 1951 to redesign telephone technology. The two constraints were that the redesign should be "technologically feasible" and "operationally viable." In less than one year the six subgroups identified most of the innovations in telephones that are in use today (Jackson, 2019).

Efforts at improving FFVV chains have focused on individual links but have not looked enough at the interaction of links within chains. The emphasis has been on links and not chains.

2.6.1 Critical systems practice for FFVV chains

The leaders in all organizations related to fresh fruit and vegetable chains would benefit from incorporating CSP to implement systems thinking into their programs, services, curricula, and other endeavors. The UN Food and Agricultural Organization can be expected to continue to increase the prominence of systems thinking. Other international, national, and local organizations will benefit from CSP interventions. Likewise, researchers, extension workers, businesses, professional associations, and others could experience improvements from adapting CSP to their activities.

In the United States, the National Institute of Food and Agriculture (NIFA) (USDA, n.d.) has mandates that enable it to be a lead agency for implementing CSP for FFVV chains and other food and agricultural applications. The NIFA website specifically mentions: Ag systems, small-farm culture, end hunger, nutrition, from farm to table, improve the quality of foods and reduce postharvest losses, small and family farms, develop and improve experiential learning programs, enhance learning methods, and hands-on experience.

2.6.2 Interactive leadership experiences

A recommended approach for evaluating the proposed new SOSM methodology for ILE is for experienced systems thinking consultants and practitioners to evaluate the need for a new paradigm such as learn. If they agree to move forward, then new names for the paradigm and methodology could be considered if desired. Then constitutive rules could be developed for the new methodology. An international workshop could be a forum for organizational leaders, practitioners, instructors, researchers, and others to present papers and have interactive sessions on how to accelerate the implementation of ILE. Sessions could use systems methodologies to facilitate desired results.

Organizations like the Food Systems Leadership Institute (FSLI, n.d.) could assume leadership roles in developing and applying the Interactive Leadership Experience methodology by conducting interventions for improving FFVV chains. Similar groups around the world could initiate similar efforts.

2.7 Conclusion

Previous approaches have failed to make adequate progress on improving global needs related to fresh produce: Low per capita consumption levels, Losses and wastes are high, Low farmer income. New approaches are essential. Systems thinking reveals that:

- FFVV *chains are not systems*.
- "The Postharvest Chain" *does not exist*. There are multitudes of value chains; not one.
- Each business link is a system. Viewing chains as a system reveals missing interactions.

- Business schools have ways for integrating systems thinking with science and engineering.
- Simulations and games are experiential ways to improve system structures and processes.
- Businesses and agencies should fund interventions based on systems thinking.

We can barely start to imagine the innovations that could be realized from using systems thinking to focus on innovative ways for consumers to enjoy tasty fresh fruits and vegetables that are affordable, delivered with minimum loss, and that provide growers with adequate incomes.

References

Accorsi, R., Bortolini, M., Baniffaldi, G., Pilati, F., & Ferrari, E. (2017). Internet-of-things paradigm in food supply chains control and management. *Procedia Manufacturing*, *11*, 889−895, 27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27−30 June 2017, Modena, Italy.

Accorsi, R., & Manzini, R. (Eds.), (2019). *Sustainable food supply chains: Planning, design, and control through interdisciplinary methodologies*. London: Academic Press. Available from https://doi.org/10.1016/B978-0-12-813411-5.00003-X.

Acedo, A. L. (2019). Postharvest handling and storage technologies for fresh horticultural produce. *Acta Horticulturae*, *1245*(14), 93−100. Available from https://doi.org/10.17660/ActaHortic.2019.1245.14.

Ackoff, R. L. (1999). *Ackoff's Best: His classic writings on management*. New York: John Wiley.

Ackoff, R. L., Addison, H. J., & Carey, A. (2010). *Systems thinking for curious managers*. Devon: Triarchy Press.

Aggarwal, D., Prussia, A. J., Prussia, S. E., Nunez, A., NeSmith, D. S., Florkowski, W. J., & Lynd, D. (2003). Predicting fresh produce quality in supply chains. *Acta Horticulturae*, *604*, 179−188.

Aggarwal, D., Prussia, S. E., Florkowski, W. J., & Lynd, D. (2003). Simulation game for fresh produce retailing. *Focus on Biological Engineering Features Resource*, *10*(5), 12.

Aggarwal, D., Prussia, S. E., Florkowski, W. J., & Lynd, D. (2004a). Produce quality simulator. In D. R. Heldman (Ed.), *Encyclopedia of agricultural, food and biological engineering*. New York: Marcel Dekker Inc. (on-line version).

Aggarwal, D., Prussia, S. E., Florkowski, W. J., & Lynd, D. (2004b). Simulation game for peach retail ordering systems, in IMEJ of CEL. *Interactive Multimedia Electronic Journal of Computer-Enhanced Learning*, *6*(1).

Aggarwal, D., Prussia, S. E., Florkowski, W. J., & Lynd, D. (2011). Produce quality simulator. In D. R. Heldman, & C. I. Moraru (Eds.), *Encyclopedia of agricultural, food and biological engineering* (2nd ed.). New York: Marcel Dekker Inc.

Agricultural Systems. (n.d.). [WWW document]. https://www.journals.elsevier.com/agricultural-systems. Accessed 27.02.21.

Alamar, M., Falagán, N., Aktas, E., & Terry, L. A. (2018). Minimising food waste: A call for multidisciplinary research. *Journal of Science & Food Agriculture*, *98*.

Berja, S., Capone, R., Debs, P., & Bilali, H. E. (2018). Food losses and waste: A global overview with a focus on near East and North Africa Region. *International Journal of Agricultural Management and Development (IJAMAD)*, *08*.

Bourne, M. (1977). Post harvest food losses − The neglected dimension in increasing the world food supply. *Cornell international agriculture mimeograph 53*. New York: Cornell University. Available from https://ecommons.cornell.edu/handle/1813/28900, [5 May 2020].

Busato, P., & Berruto, R. (2006). FruitGame: Simulation model to study the supply chain logistics for fresh produce. In F. Zazueta, J. Kin, S. Nimomiya, & G. Schiefer (Eds.), *Computers in Agriculture and Natural Resources: Proceedings of the 4th world congress conference* (pp. 488−493). ASABE Publication, Number 701P0606.

Centers for Disease Control and Prevention. (2005). *5 A day works!* U.S. Department of Health and Human Services.

Checkland, P. (1999). *Systems thinking, systems practice* (revised (ed.)). Chichester: Wiley, Includes a 30-year retrospective.

Checkland, P., & Poulter, J. (2006). *Learning for action*. Chichester: John Wiley & Sons.

Chiquita Brands International. (2021). *Wikipedia*.

Day-Farnsworth, L., & Miller, M. (2014). *Networking across the supply chain: Transportation innovations in local and regional food systems* (pp. 2). Madison, WI: University of Wisconsin. Web. https://doi.org/10.9752/TS202.06-2014 [14 April 2020].

Dole Food Company. (2021). *About us* (dole.com) [30 April 2021].

Electronic Arts. (2021). *Maxis studios – Official EA sites* [2 April 2021].

Falagán, N., & Terry, L. A. (2018). Recent advances in controlled and modified atmosphere of fresh produce post-harvest technologies to reduce food waste and maintain fresh produce quality. *Johnson Matthey Technology Review*, *62*, 107–117.

FAO. (2011). *Global food losses and food waste – Extent, causes and prevention. Rome. Global food losses and food waste* (fao.org) [30 April 2021].

FAO. (2013). *Food wastage: Key facts and figures*. Rome.

FAO. (Ed.) (2014). *Innovation in family farming, The state of food and agriculture*. Rome.

FAO. (2015). *Sustainable development goals* [WWW document]. http://www.fao.org/sustainable-development-goals/overview/en/. Accessed 26.02.21.

FAO. (2018). *FAO's work on family farming preparing for the decade of family farming (2019–2028) to achieve the SDGs*.

FAO. (2019). *The state of food and agriculture 2019. License: CC BY-NC-SA 3.0 IGO*, Rome.

FAO. (2021). *Family farming knowledge platform* [WWW document]. http://www.fao.org/family-farming/background/en/. Accessed 26.02.21.

FAO and IFAD. (2019). *United nations decade of family farming 2019–2028. Global action plan. licence: CC BY-NC-SA 3.0 IGO*, Rome.

Farming Simulator. (2021). *Official website | farming simulator* (farming-simulator.com) [2 April 2021].

Fresh Del Monte Produce. (2020). *Wikipedia*.

FSC. (n.d.). [WWW document]. http://foodsupplychain.din.unibo.it/aims-and-scope/ [27 February 2021].

FSLI. (n.d.). *ND Food Systems Leadership Institute* [WWW Document]. https://fsli.org/. Accessed 27.02.21.

Galanakis, C. M. (2019). *Saving food: Production, supply chain, food waste and food consumption*. Academic Press. Available from https://doi.org/10.1016/B978-0-12-815357-4.00018-3.

Gogo, E. O., Opiyo, A. M., Ulrichs, C., & Huyskens-Keil, S. (2017). Nutritional and economic postharvest loss analysis of African indigenous leafy vegetables along the supply chain in Kenya. *Postharvest Biology and Technology*, *130*, 39–47.

Heaton, K. (1981). *Personal communication*.

HLPE. (2014). *Food losses and waste in the context of sustainable food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security, Rome 2014*. http://www.fao.org/3/a-i3901e.pdf. Accessed 22.05.20.

Hung, Y. C., McWatters, K. H., & Prussia, S. E. (1998). Sorting performance of a nondestructive laser air-puff firmness detector. *Applied Engineering in Agriculture*, *14*(5), 513–516.

Jackson, M. C. (2019). *Critical systems thinking and the management of complexity*. Hoboken, NJ: Wiley.

JFDR. (n.d.). *Jornal of food distribution research*. The Food Distribution Research Society, INC [WWW document], https://www.fdrsinc.org/journal/. Accessed 27.02.21.

Kolb, A. Y., & Kolb, D. A. (2013). *The Kolb learning style inventory- version 4.0 A comprehensive guide to the theory, psychometrics, research on validity and educational applications. ©Experience based learning systems. Technical specification – LSI version 3* (learningfromexperience.com) Accessed 30.01.21.

Kolb, A. Y., & Kolb, D. A. (2017). *The experiential educator: Principles and practices of experiential learning*. Haunakakai, HI: Experience Based Learning Systems Press.

Kolb, D. A. (2015). *Experiential learning: experience as the source of learning and development* (2nd ed.). Upper Saddle River, NJ: Pearson Education, Inc.

Lane, A. (2018). '*Mastering systems thinking in practice*', The Open University. Walton Hall, Milton Keynes, United Kingdom, MK7 6AA. https://www.open.edu/openlearn/science-maths-technology/mastering-systems-thinking-practice/content-section-overview?active-tab = description-tab. Accessed 02.11.20.

Law, A. M. (2014). *Simulation modeling and analysis* (5th ed.). New York: McGraw-Hill Education.

Lewrick, M. P., Link, P., & Leifer, L. (2018). *The design thinking playbook: Mindful digital transformation of teams, products, services, businesses and ecosystems* (p. 352) Hoboken, NJ: John Wily & Sons.

Lewrick, M. P., Link, P., & Leifer, L. (2020). *The design thinking toolbox: A guide to mastering the most popular and valuable innovation methods* (p. 320) Hoboken, NJ: John Wily & Sons.

Lin, B. H., & Morrison, R. M. (2016). '*A closer look at declining fruit and vegetable consumption using linked data sources*', Amber Waves, July 05, 2016 https://www.ers.usda.gov/amber-waves/2016/july/a-closer-look-at-declining-fruit-and-vegetable-consumption-using-linked-data-sources/.

Mampholo, B. M., Sivakumar, D., & Thompson, A. K. (2016). Maintaining overall quality of fresh traditional leafy vegetables of southern Africa during the postharvest chain. *Food Review International*, *32*, 400−416.

Meadows, D. H. (2008). *Thinking in systems* (p. 13) White River Junction, VT: Chelsea Green Publishing.

Meinke, H. (2019). *The role of modeling and systems thinking in contemporary agriculture*. *Sustainable food supply chains*. Academic Press.

Meng, T., Klepacka, A. M., Florkowski, W. J., & Braman, K. (2016). Determinants of recycling common types of plastic product waste in environmental horticulture industry: The case of Georgia. *Waste Management*, *48*, 81−88.

Merriam-Webster. (2021). *Andragogy | definition of andragogy* [WWW document]. https://www.merriam-webster.com/dictionary/andragogy. Accessed 27.02.21.

MIT Sloan. (n.d.) [WWW document]. MIT Sloan. https://mitsloan.mit.edu/teaching-resources-library/about. Accessed 27.02.21.

Müller-Roterberg, C. (2020). *Design thinking for dummies* (p. 304) Hoboken, NJ: John Wiley & Sons.

Neimeyer, R. A., & Torres, C. (2015). *Constructivism and constructionism: Methodology*. *International encyclopedia of the social & behavioral sciences* (2nd ed., pp. 724−728). Elsevier Science.

NeSmith, D. S., Nunez-Barrios, A., Prussia, S. E., & Aggarwal, D. (2005). Postharvest berry quality of six rabbiteye blueberry cultivars in response to temperature. *Journal of American Pomological Society*, *59*, 13−17.

Nunez-Barrios, A., NeSmith, D. S., Chinnan, M. S., & Prussia, S. E. (2005). Dynamics of rabbiteye blueberry fruit quality in response to harvest method and postharvest handling temperature. *Small Fruits Review*, *4*(2), 73−81.

OpenLearn. (n.d.). *Systems thinking free courses* [WWW document]. OpenLearn. https://www.open.edu/openlearn/science-maths-technology/engineering-technology/systems-thinking-free-courses. Accessed 27.02.21.

Parfitt, J., Barthel, M., & Macnaughten, S. (2010). Food waste within supply chains: Quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B*, *365*, 3065−3081.

Prusky, D. (2011). Reduction of the incidence of postharvest quality losses, and future prospects. *Food Security*, *3*, 463−474.

Prussia, S. E. (2000). Soft systems methodologies for modeling postharvest chains. *Acta Horticulturae*, *536*, 653−660.

Prussia, S. E., Astleford, J. J., Hewlett, B., & Hung, Y. C. (1994). *Non-destructive firmness measuring device. US5372030A*.

Prussia, S. E., & Birmingham, D. (2000). $R^3 + D^3 =$ A learning tool for science and engineering. *Journal of Engineering Education*, *89*(4), 435−438.

Prussia, S. E., Florkowski, W., & Lynd, D. (2004). ¿El productor empuja o el comprador jala? (Producer push or consumer pull?), Invited and the first lecture at, 50 Anos de Trayectoria en Excelencia y Desarrollo Simposium Internacional "Desarrollo de Cadenas de Valor," 24−26 February, Universidad Autonoma de Chihuahua, Mexico.

Prussia, S. E., Florkowski, W., Sharan, G., Naik, G., & Deodhar, S. (2001). Management simulation game for improving food chains. *Acta Horticulturae*, *566*, 231−236.

Prussia, S. E., & Hung, Y. C. (2001). Improved laser-puff food firmness detector. *Acta Horticulturae*, *562*, 151−155.

Rohs, F. R., Prussia, S. E., Beristain, S. C. I., & Cortez, J. (2002). Using a soft systems approach to planning and extension program. *The Journal of Extension Systems*, *18*(2), 1−12.

Senge, P. M. (2006). *The fifth discipline: The art & practice of the learning organization* (Revised edition, p. 445)New York: Doubleday, Currency.

Shewfelt, R. L. (2017). How can we eat more sustainably to save our earth for our children and grandchildren? *In defense of processed food* (pp. 143−160). Cham: Springer Nature, Ch. 9.

Shewfelt, R. L., & Prussia, S. E. (1993). *Postharvest handling: A systems approach*. San Diego, CA: Academic Press.

Simio. (n.d.). *Free simulation software − Simio personal edition* [WWW document]. https://www.simio.com/free-simulation-software/index.php. Accessed 27.02.21.

Simon, H. A. (1996). Understanding the natural and the artificial world. *The sciences of the artificial* (3rd ed., p. 256) MIT Press, 2019 Reissue (ed.).

Smith, J. S., Sturrok, D. T., & Kelton, W. D. (2018). *Simio and simulation: Modeling, analysis, applications* (5th ed.). CreateSpace Independent Publishing Platform.

Sterman, J. (2020). *Management simulation games. Management simulations*. MIT Sloan, [8 February 2021].

Teese, J., Currey, P., & Somogyi, S. (2019). Strategic information flows within an Australian vegetable value chain. *Acta Horticulturae*, *1258*, 189–194. Available from https://doi.org/10.17660/ActaHortic.2019.1258.26.

The Myers & Briggs Foundation. (n.d.). [WWW document]. https://www.myersbriggs.org/. Accessed 27.02.21.

U.S. Department of Health and Human Services and U.S. Department of Agriculture. (2015). *2015–2020 Dietary guidelines for Americans*. 8th ed. Available at http://health.gov/dietaryguidelines/2015/guidelines/ and at https://health.gov/sites/default/files/2019-09/2015-2020_Dietary_Guidelines.pdf.

U.S. Department of Health and Human Services, U.S. Department of Agriculture. (2020). *2020–2025 Dietary guidelines for Americans*. 9th ed.

USDA. (n.d.). *National Institute of Food and Agriculture* [WWW document]. https://nifa.usda.gov/. Accessed 27.02.21.

USDA Economic Research Service. (2020). *Over a third of the U.S. food dollar is spent on eating-out services* [WWW document]. http://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId = 58354. Accessed 24.02.21.

Van Haaften, M. A., Lefter, I., Lukosch, H., van Kooten, O., & Brazier, F. (2020). Do gaming simulations substantiate that we know more than we can tell? *Simulation & Gaming*, *52*, 1–23. Available from https://doi.org/10.1177/1046878120927048, Do Gaming Simulations Substantiate That We Know More Than We Can Tell? - M. A. van Haaften, I. Lefter, H. Lukosch, O. van Kooten, F. Brazier, 2020. Available from sagepub.com.

Wilson, C. L. (2013). Establishment of a world food preservation center: Concept, need and opportunity. *Journal of Postharvest Technology*, *01*(01), 001–007. Available from http://jpht.info/index.php/jpht/article/view/17423/8939, [18 April 2020].

Table 5.2, page 190. In K. Wilson, & G. E. Morren, Jr. (Eds.), *Systems approaches for improvement in agriculture and resource management*. New York: Macmillan Publishing Co.

Zeide, A. (2019). Grocery garbage: Food waste and the rise of supermarkets in the mid-twentieth century United States. *History of Retailing and Consumption*, *5*, 71–86.

Zespri. (2020). *Zespri-5-year-outlook*.

https://www.worldfoodpreservationcenter.com/postharvest-losses.html, 2021 (Accessed 1 November 2021).

Further reading

Forio. (2021). *ND global supply chain: Management simulation – Simulation ready-to-run* [WWW document]. https://forio.com/store/harvard-global-supply-chain/index.html. Accessed 27.02.21.

"Kolb Learning Style Inventory (klsi)" – Korn Ferry Ecommerce. (n.d). [WWW document]. https://store.kornferry.com/en/search?search = klsi. Accessed 27.02.21.

Sanford, J. C. (2014). *Genetic entropy*. Waterloo, NY: FMS Publications.

CHAPTER

3

Postharvest regulation and quality standards on fresh produce

Kerry Walsh

Central Queensland University, Rockhampton, QLD, Australia

Abbreviations

AHC	Australian Horticultural Corporation
AQIS	Australian Quarantine Inspection Service
CAC	Codex Alimentarius Commission
FSANZ	Food Safety Australia and New Zealand
HACCP	hazard analysis and critical control point
JAS	Japan Agricultural Standard
NGO	nongovernmental organization
OECD	Organization for Economic Cooperation and Development
TA	total acidity
TSS	total soluble solids
UNECE	United Nations Economic Commission for Europe
WHO	World Health Organization
WTO	World Trade Organization

3.1 Setting the task

The crop is sown, grown, and tended, following years of investment in land preparation and development (see also Chapter 7: Fresh-cut products—implications for postharvest). Finally, the crop reaches maturity and picking crews can be set to work. The postharvest phase of the crop begins (see also Chapter 2: Systems approach in postharvest handling of fresh produce and Chapter 14: Nondestructive evaluation: detection of external and internal attributes frequently associated with quality and damage). By this time, the producer should have decided which value chains to participate in, and thus the intended market for the crop. The chain's ability to present and manage all aspects of "quality," in all its

DOI: https://doi.org/10.1016/B978-0-12-822845-6.00003-8

meanings, will determine how much of the product's potential value is achieved (see also Chapter 1: Postharvest systems—some introductory thoughts).

The term "quality" for fresh fruit and vegetables (FAVs; also termed "fresh produce") has as many definitions as there are participants in value chains (see also Chapter 6: Challenges in handling fresh fruits and vegetables and Chapter 11: Tracking products from field to consumer). To the product supply manager and to the retailer, a major component of "quality" is product shelf life. To the government regulator, quality is primarily conceived in terms of public risk, with each government department focused to a different concern. For example, that branch concerned with quarantine risk will cast "quality" in terms of entomological and microbiological issues (see also Chapter 20), while that concerned with human health risk (food safety) will cast "quality" in terms of the presence of chemical residues and microbial contaminants (see also Chapter 19: Nutritional quality of fruits and vegetables). To the retail client, "quality" is often viewed in terms of issues related to the remaining shelf life of the product, and esthetic issues that affect consumer purchase decisions (fruit color, size, shape, blemish severity).

To the consumer, fruit "quality" is described in terms of both shelf life and the eating experience. The latter is a function of visual appearance and taste-related attributes such as fruit firmness, sugar content, organic acid content, and tissue juiciness (see also Chapter 15: Cooling fresh produce). As with all stages in value chains, though, the consumer is not a single entity, and many fractions exist. For example, different ethnic or age groups may have different taste preferences (see also Chapter 19: Nutritional quality of fruits and vegetables). Further, some consumers link "quality" to the issue of local production, or to organic production practices. Other consumers place value in larger environmental issues, such as "production without destruction" (e.g., use of crop netting rather than killing of flying foxes or birds), or on issues related to CO_2 emissions (e.g., food miles).

This chapter summarizes regulation that exists to enforce "quality" in fresh produce, postharvest, in terms of both government regulation and private regulations within a given value chain. Such regulations may be imposed within any step in the value chain and may impact broadly to all produce (e.g., heavy metal levels), to a single level within the chain (e.g., in transit temperature), or a segment of the market (e.g., organic product) (see also Chapter 8: Multiomics approaches for the improvements of postharvest systems, Chapter 16: Investigating losses occurring during shipment: forensic aspects of cargo claims, Chapter 18: Consumers as arbiters of system performance, and Chapter 21: Measuring consumer acceptance of vegetables). Such regulation will change the competitive advantages of a given value chain, altering regional, and international flows of fresh produce (Florkowski, 2019). The issue of eating quality is considered further, in terms of the drivers for adoption of standards.

3.2 "Supra"-regulations

A value chain is a commercial construct and, as such, is driven by issues extending beyond the biology of the commodity. The impact of regulation on fresh produce value chains is considered in this section first at the very broad level of the social and regulative milieu in which it is set. As these issues are effectively beyond the influence of any individual business, the influence of this "supra-regulation" on value chain viability is often ignored. Sometimes this milieu is relatively static, changing "slower than the eye can see." At other times, however, an abrupt change in social or regulative conditions occurs, with corresponding abrupt change in trading conditions. In the following text, examples are drawn from the areas of trade, taxation, intellectual property, labor market, and infrastructure.

3.2.1 National taxation policy

Taxation policy influences investment activity and, thus, can influence horticultural value chains. For example (SSCoE, 2016), Managed Investment Schemes in Australian forestry and perennial crop horticulture offered a tax-effective treatment of funds for urban professionals on higher marginal tax rates. Large amounts of capital were accessed by these schemes. However, in 2007, the Australian Taxation Office removed the tax advantages, causing the collapse of most of these schemes and related enterprises.

3.2.1.1 A carbon tax?

Many forms of a "carbon tax" or an emissions trading scheme have been proposed, with implementation in some jurisdictions, notably within Europe (e.g., https://taxfoundation.org/carbon-taxes-in-europe-2019/; Narassimhan & Gallagher, 2018). Horticultural value chains may be impacted by costs associated with carbon (C) emissions tagged to land clearing, soil organic matter loss, fertilizer, fuels, or refrigeration. Conversely, they may benefit from payments associated with C sequestration, for example, use of biochar. This is a fluid topic that will evolve rapidly in the next decade, in terms of the form of the "tax," its level, exemptions, or compensation for certain sectors and applications to imported and exported produce. For example, Norway exempts the greenhouse horticultural sectors from its tax of Euro 52 per ton of C, although there is uncertainty on how long this exemption will hold (Svebestad & Botheim, 2020).

3.2.2 Intellectual property rights

Successful marketing requires a point of differentiation for the product. Members of the World Trade Organization (WTO) are required to have a system to recognize creation of, and provide intellectual property rights to, new varieties of plants, following the International Union for the Protection of New Varieties of Plants (UPOV) convention. Plant variety rights (PVR), also known as plant breeder rights (PBR), and in some jurisdictions normal patents provide a tool to enforce differentiation.

Unfortunately, members of the WTO are not consistent in their approach in this area (2020). For example, China is a signatory to UPOV 1978 convention, while Australia is signatory to the UPOV 1991 convention. UPOV 1991 requires all genera and species to be protected, while UPOV 1978 does not, with China affording plant variety protection to only 191 genera and species, and with no protection for "essentially derived varieties." Further, UPOV 1978 rights do not cover harvested materials. Even China's system does not cover as well, including import and export, and it provides a decreased period of protection. For example, protection is provided for 15 years for most agricultural varieties and 20 years protection for

FIGURE 3.1 "Calypso" mango, a variety under PVR, available under exclusive production and marketing arrangements. Fruits have been sorted nondestructively (using near infrared spectroscopy) on dry matter content at the time of harvest. After 2 days of ripening, low dry matter fruits remain green relative to high dry matter fruit. Dry matter at harvest is related to fruit maturity and thus subsequent rate of ripening and also to fruit eating quality as indexed by Brix of ripened fruit. *PVR*, Plant variety rights.

vines, trees, and ornamentals, in contrast to 20 and 25 years, respectively, in Australia. Navigating the legal system in China is also difficult, and this is a commercial barrier to enforcement of intellectual property rights. Hou (2019) posits that the Chinese position on PVR is rooted in priority of collectivism over "individual benefit."

With PVR protection, commercial return on a new variety may be achieved through a royalty on plant or produce sales, or the genotype can be released under exclusive production and marketing arrangements. The latter strategy allows for ease of implementation of a quality standard and of standard (pre and) postharvest practices. For example, the B74 cultivar of mangoes has intellectual property protection (e.g., US Patent 17777OP3) and is traded under the trademark "Calypso" (Fig. 3.1). Fruit can only be produced by licensed growers, with fruit marketed by one company, Perfection Fresh, in a "closed" arrangement accepted by the Australian Competition and Consumer Commission as providing consumer advantages in funding continued development of the cultivar and thus increased competition in the mango market.

The intellectual property of new technologies for postharvest storage or sorting may also be protected and thus commercially controlled. There is increasing incidence of exclusive marketing arrangements for postharvest technologies (e.g., Maxtend, a modified atmosphere control system for shipping containers is licensed to Mitsubishi, see http://www.maxtend.com.au).

3.2.3 National labor market and immigration

The viability of a fresh produce value chain is highly influenced by the cost of harvest labor, particularly for on-farm tasks that are not easily mechanized. This cost is high in developed countries relative to that in developing nations and regulated by a government-imposed minimum labor cost. For example, under the Australian Horticultural Award harvest labor must be paid USD$19/h while in Brazil this is the daily rate.

Immigration regulations favor different horticultural labor solutions in different countries. For example, in Israel the horticultural sector effectively lost the use of Palestinian labor but has been supported by South-East Asian (particularly Thai) labor, present on 2-year working visas. The southern United States horticultural industry traditionally utilized Mexican labor. The Australian horticultural industry relies to a surprising degree on “backpackers” on short-term working visa schemes, but these staff have a high turnover on farm and a low (horticultural) skill level. The Pacific Seasonal Worker scheme allows for groups of Pacific Islanders to work for 4–6 months each year across several years, providing a more stable and skilled workforce (Firth, 2006).

Changes in government policy relevant to the labor market or immigration can thus have rapid impact on horticultural operations, both pre and postharvest. For example, the number of nonresident migrant horticultural workers (visa types 417 and 162) in Australia decreased following introduction of a 15% tax rate on annual income up to AUD $37,000 (Department of Home Affairs, 2020). More recently, government-imposed travel closures during the COVID crisis of 2020 were associated with a 25% decrease in these visa classes between January and June 2020, leading to shortages of workers in horticultural industries.

At a higher level, an immigration policy that supports population growth and contributes to ethnic diversity in the population will create new domestic markets for horticultural produce that are larger but also more diverse in taste preferences. The FAV market in nations with high immigration rates and a focus on multiculturalism, such as Australia, Canada, and USA, will therefore evolve differently to those with low or negative migration rates, such as Japan and China.

3.2.4 National infrastructure

Value chains need national infrastructure. Cool rooms and packhouses need reliable supply of electricity. Fresh produce transport needs quality roads and railways, and availability of refrigerated transport vehicles. Cross-border trade relies on efficient handling of product and records at sea and airports. The entire system relies upon communication technologies for transfer of information and funds. All these items are influenced by government policy.

China has provided spectacular examples of national infrastructure development, extending to international development through its “Belt and Road” initiative, in the last

FIGURE 3.2 Example infrastructure development in China—the Shanghai Yang shan Deepwater Port, part of Maritime Silk Road initiative. In 2019 the port handled 43 million TEU. *TEU*, 20-ft equivalent units. Source: *http://www.cscecos.com/page.aspx?node=17&id=170 doa 6/2/2021.*

decades (Fig. 3.2). Special development zones have been designated and supported with land reform, transport, power, water, and civil infrastructure. Where horticultural production is a focus, areas suited to production in terms of soil type have been identified, water allocations provided, and postharvest facilities provided (e.g., improved market facilities). Land reform has split the communal farms for individual use and then allowed a consolidation of land parcels for agribusiness activity. Improved transport infrastructure (particularly road and rail) and electronic trading has facilitated the movement of produce to consumers in urban centers and to export facilities. Large production units and associated packing facilities are private, but often supported by state capital.

Two examples follow of national infrastructure projects mentioned in Asia Fruit Magazine reports within a 1-month period in 2020: (http://www.fruitnet.com/asiafruit/topic/production-trade)

1. A blockchain-based technology was launched in Dubai for commodity trading between growers in India and the UAE food industry (September 3, 2021).
2. Tenders awarded by the Singapore Food Agency for the construction of vertical farming systems on the top of carparks intended to produce 1600 t/year of vegetables, working toward the production of 30% of total food needs by 2030 (October 5, 2021).

3.2.5 Global trade environment

It is technically possible to grow horticultural crops in harsh environments through the creation of protected environments. Conversely, in an era of cheap transport, it is possible to air- and sea-freight produce across the world. The economic viability of such activity is not an “absolute.” Rather these activities are a function of broader economic and political settings.

As an undergraduate, I was greatly impressed on a tour of a local (Australian) Department of Primary Industries postharvest physiology laboratory. It was explained that insurance premiums on shipments of citrus to the United Kingdom were effectively unaffordable because of the high incidence of physiological disorders and disease, but that after a range of technical postharvest "fixes," it was not necessary to insure the loads! But the entry of the United Kingdom into the (then) European Common Market fundamentally altered trade between Australia and the United Kingdom, and citrus exports to the United Kingdom withered as Europe raised a trade tariff barrier. The "technical fix" was overwhelmed by changes in terms of trade. The overriding "quality" criterion became country of origin. The 2020 exit of the United Kingdom from the European Union changes this situation and new trading opportunities are likely to result.

The reality is that global horticultural trade is constantly shifting in response to the "realpolitik" of trading agreements and disputes between countries, with phytosanitary standards and research used as ammunition in this tussle. For example, Asia Fruit Magazine reports the following trade agreement items within a 1-month period within 2020 (http://www.fruitnet.com/asiafruit/topic/production-trade):

September 17: Vietnam made a first shipment of passion fruit to Europe under the EU-Vietnam Free Trade Agreement.
September 22: The Philippines banana export fell by 20% from 2019, with agricultural attaches in major markets instructed to "win the export war."
September 23: United States Department of Agriculture (USDA) assisting US citrus growers to gain access to Vietnam, following success with the granting by China for an export quota.
September 24: Phytosanitary requirements for Chilean Hass avocado released by Korea, effectively granting market access for the fruit.
September 25: New standards set by China blamed for a 25% decrease in export of fruit from Vietnam to China.
October 7: Italy gained access for export of apples to Thailand in April 2020.
October 14: Export protocol for Peruvian citrus to Thailand near finalization.
October 15: China and Cambodia agreed on an FTA to start in early 2021.

3.2.6 Summary

Directly or indirectly, "supra-regulations" impact the horticultural sector. Although these issues are basically beyond the control of a given value chain, it is useful to acknowledge their impact. "Watershed" changes in such regulation, for example, in immigration policy or C trading, require businesses to formulate a strategic position in the new trading environment.

The issue of regulation of international trade in fresh produce is continued and expanded in Section 3.3.

3.2.7 A case study: Nepal

A case study: Nepal

Following conflict with the British Raj, the Kingdom of Nepal isolated itself from foreign contact from 1816 until 1951. Hilary ascended Mt Everest in 1954, and the Tribhuvan Highway, between Kathmandu and the Indian border, was started in 1956. Despite large campaigns to extend the electrical grid and road network, infrastructure remains poorly developed, with load shedding for up to 20 h a day, and much of the population remains several hours walk from a road. Traffic flow is erratic, such that a 180 km trip between the main cities of Kathmandu and Pokhara can easily take 8 h. While much horticultural production remains at a subsistence or local level, domestic value chains are developing to supply the urban populations of Kathmandu and Pokhara. Notable developments include the introduction of the supermarket format, with an expansion of the retailer Bhatbhateni from a single store in 2012 to 10 stores in 2020, and the introduction of protected cultivation of tomato and other small crops in periurban areas, supported by expertise of workers returning from Israel.

The Kingdom of Nepal became the 147th member of the WTO in 2004, but there is little export of horticultural produce (SAWTEE, 2016). In 2009–10, vegetable and fruit imports to Nepal were valued at NR 2.1 and 4.7 billion, respectively, while exports were 26 and 486 million, respectively. Bangladesh imposes a 25% duty on Nepalese horticultural imports, limiting prospects for that market. A bilateral duty-free trade agreement exists with India, but stronger enforcement of quarantine by India than Nepal and the relative weakness of Nepalese value chains create a trade imbalance of approximately 9:1. Much of the Nepalese trade to India is through small value chains operating along the porous border. Indeed, over 50% of the cross-border trade with India is estimated to be informal.

While India has historically dominated trade with Nepal, however, interaction with China is rapidly increasing, given improved rail infrastructure from China to Tibet and improved roads within Tibet to the Nepalese border. For example, Chinese apples dominate in Nepalese markets (Fig. 3.3). Given availability of transport as backloads from Nepal to China, there may be opportunity for export of Nepalese produce. China allows for the export of Nepalese citrus to Tibet, but Nepalese producers and government agencies have yet to achieve the level of organization required to meet phytosanitary requirements in terms of field and in packhouse disease and pest checking and produce labeling.

Improvement in postharvest training and an approach to postharvest process as a system by both government and private sector is occurring. Such improvements should allow for gains to be realized from trade agreements, through targeted improvements in national infrastructure and the business environment.

FIGURE 3.3 Apples from China, transported through Tibet and being unloaded in Pokhara, Nepal.

3.3 International trade regulation

3.3.1 The World Trade Organization

The WTO acts in the field of regulation related to trade between nations. The overall intent is to support "free" trade to improve market efficiency. For a nation to participate in the WTO (Agriculture Agreement) framework, support programs that stimulate production directly and import tariffs on imported product must be reduced on the basis that such policies advantage domestic production over imports or result in "dumping" of product on world markets (World Trade Organization, 2013). The strengthening of the New Zealand horticultural sector following deregulation represents an apparent success story for the thesis that free trade can improve market efficiency (Walker, Bell, & Elliott, 1993).

WTO members were required to estimate the annual value of agricultural production support ("total aggregate measurement of support") for the base years of 1986–88. Developed countries agreed to a 20% reduction of the support level over 6 years from 1995, while developing countries agreed to a 13% reduction over 10 years, and least developed countries were not required to make any reduction.

Programs that are not considered to have a direct effect on production (e.g., a nationally funded R&D program, an infrastructure program, or a food security program) are exempt from this process. Certain other payments made directly to farmers that do not directly stimulate production, such as drought support, industry restructuring programs, payments to limit production, and environmental and regional assistance programs, are also exempted. Qualified government assistance programs to encourage agricultural and rural development in developing countries are also exempt, as is small scale support (5% or less of the total value of the product in the case of developed countries and 10% or less for developing countries).

The inherent expectation is that developed countries should have no import restriction on, or production support to, horticultural produce. The major barrier to trade, then, becomes quarantine or food safety issues. Of course, there are always gray areas, with a good scope for legal maneuvering between trading nations! Sound science on the underlying quarantine issues is required to achieve a rational outcome. However, incomplete science or bad science may be used to justify trade restrictions. Resolution of such issues typically involves diplomatic trade-offs, involving a compromise on one trade issue to achieve success on another trade issue. The resolution process is effectively beyond the capacity of a marketing or industry group and relies upon government support and, thus, on political lobbying by industry groups for allocation of resources.

To resolve trade disputes, the WTO provides a forum (court) for "independent arbitration." For phytosanitary-related disputes, such decisions come down to a risk analysis on the possibility of transfer of a pest or pathogen. A mechanism is initiated when a trading body proposes to market fruit across a national border. The proposal will be vetted by the quarantine service and production associations of the importing nation and may be opposed on scientific grounds (e.g., the risk of introducing fire-blight disease). The technical merits of this objection may be argued against by, typically, a government supported research agency from the country of origin. If the matter is not resolved between the parties, the case may be taken to the WTO for a ruling. Such rulings may be appealed, so the process typically takes many years to resolve.

For example, the United States and New Zealand had long sought to export apples to Japan and Australia, respectively, but in both cases had been blocked on the basis that the apple disease fire-blight exists in the United States and New Zealand, but not in Japan and Australia. Controversy exists on the technical side as to whether fire-blight can be transmitted via the fruit alone, with research organizations in the proposed exporting countries (USDA and Plant and Food Research, NZ) providing data to demonstrate that the disease is not fruit borne. Responding to a 2003 WTO ruling, Japan allowed for import of mature symptomless fruit from fire-blight affected areas but required field inspections of United States orchards by Japanese inspectors three times a year. Trade was effectively prevented by compliance complexity and cost. This requirement was removed by a WTO ruling in 2005. Using this precedent, and following further challenges through the WTO, New Zealand achieved access to the Australian apple market in 2011.

A "pure" free trade environment would limit trade only by the technical merits of a phytosanitary case. World trade, however, is not so "pure," and a successful postharvest system also requires legal and diplomacy expertise. Two examples follow of the diplomacy involved in trade agreements. Example 1: In the 1990s, the export of Philippine-grown mangoes to Australia was blocked on the basis of the potential to import mango seed weevil into Australia. The Philippines subsequently blocked the importation of live cattle from Australia, a likely retaliatory measure. Australian aid funds were sourced to assist in the development of processes to disinfest mango shipments of seed weevil. Fresh mango fruit may now be imported into Australia from the Philippines (DAWR, 2020b). Example 2: During the second half of 2020, China imposed a number of trade restrictions on a range of Australian produce in an apparent diplomatic leverage on other issues (Suri, 2020). Protests have been lodged with the WTO, but this process will take many years to progress and the result is nonbinding. It will be interesting to follow the progress of this interaction, and similar cases occurring with other countries, in terms of the sustainability of the current global trade resolution mechanism.

3.3.2 International bilateral trade agreements

Governments may negotiate trade agreements outside of the general WTO framework. This typically involves a compromise between the parties, with reduction in regulatory and tariff barriers in various commodity classes. For example, in the 2004 United States—Australia free trade agreement (Australian Government—Department of Foreign Affairs and Trade, 2013), Australia agreed to provide immediate duty-free tariff treatment on all incoming United States fruit imports, removing a 5% tariff, and to resolve outstanding phytosanitary issues, for example, for apples, Florida citrus, and stone fruits. The United States agreed to grant duty-free access for over half of the listed fruit, including oranges, tree nuts, mandarins, and strawberries, and to phase out import tariffs (from rates as high as 30%) on the remaining fruit products, including pecans, dried apricots, peaches, pears, and canned fruit over the next 4—18 years, while maintaining phytosanitary restrictions on many fruits, such as avocados and tropical fruit. Presumably, the seeming imbalance in this agreement with respect to trade in fruit was balanced by the terms of other areas.

3.4 Regulation of the horticultural sector

3.4.1 Goal of regulation

The world has a web of intergovernmental and nongovernmental organizations (NGO), national and subnational (state) government agencies and individual value chains involved in the setting of regulations and standards on fresh produce. The intergovernmental standards (e.g., Codex, see Section 3.4.3) are voluntary in nature and must be translated into national legislation or regulations to be enforceable. The aim of national regulation of the fresh produce sector is for a gain to the wider society, either by improving economic function of an area (e.g., fair trading regulations) or through direct protection of consumers or the general product (e.g., limits on chemical residue in produce). Private "within-chain" regulation aims to achieve compliance with any national standard and to further achieve a gain in product "quality" to advantage that value chain.

There is an evolving balance between the level of regulation maintained at the national (government) level and that left for "private" (within value chain) implementation. In addition to evolving over time, this balance differs between nation states. For example, in a not-so-distant past, agricultural industries in many Western countries were regulated in terms of marketing arrangements, often with the effect of limiting production. These practices were aimed at providing a benefit to the producer, based on an ethic of "agarian socialism." These practices belong to an era of large rural populations in democratic systems in which the rural vote was important. Marketing boards with quasi-government agency status were given authority to require all growers to market through a single desk. Such exclusivity improved the marketing clout of that body, albeit at the loss of individual freedom. These arrangements typically served to maintain product quality, and thus a pricing level.

As marketing boards curtail individual activity, they are considered to stifle entrepreneurial activity and, thus, to run counter to free trade principles. Such arrangements are, therefore, targeted in international trade negotiations under the WTO. Following the removal of regulatory protection, these state marketing boards may dissolve as functional units or evolve as private marketing entities. For example, the South African "state ordained" horticultural marketing body was dismantled following the passing of the Agricultural Marketing Act 1996, with over 60 export licenses granted for deciduous fruit alone in the first season following deregulation (Scrimgeour & Sheppard, 1998). The original marketing board morphed into a private producer and exporter, Capespan, dominating South African horticultural export, with a 2019 separation of logistics assets to The Logistics Group (Zeder, 2019).

Another "evolutionary path" is illustrated by the New Zealand based Zespri (kiwifruit) group, with a centralized marketing function retained due to support from growers (Zespri, 2013). In the 1950s and 1960s, kiwifruit grower groups in New Zealand were fragmented in their approach to export of fruit. The Kiwifruit Marketing Licensing Authority was created in the 1970s to regulate the activities of exporters, and grade standards and a coordinated marketing strategy was established across the industry. However, a rapid increase in production and a rising value of the NZ$ led to a collapse in fruit prices, leading to "cannibalistic" competition in export, and the exodus of many growers from the industry. The NZ government established the New Zealand Kiwifruit Marketing Board in 1988 as a single desk exporter under grower control. The single export entity concept was endorsed by growers across New Zealand and legislated within the Kiwifruit Industry Restructuring Act (1999) (http://www.legislation.govt.nz/act/public/1999/0095/latest/DLM38169.html doa October 18, 2020). The public company ZESPRI International Limited was then formed to act for the export of New Zealand grown kiwifruit. The key to the continuation of a centralized export marketing function was formal agreement of growers.

Other involuntary "producer-centric" regulations have been eliminated in Western nation states. For example, the Australian producer group Queensland "Committee of Direction" once maintained a program of research, marketing and political advocacy, supported by a compulsory levy on all horticultural product sold. However, the right to collect this levy was lost. The group reincarnated in August 2004 as "Growcom" but now depends on voluntary support from growers (Growcom, 2020).

Examples of government level regulation include:

1. Fair trading. Most countries regulate all commerce in terms of fair trading provisions. In the horticultural area, this includes enforcement of product identity and content labeling (e.g., accuracy of weight or count labels). In the United States, traders of fresh produce must obtain a license under the Perishable Agricultural Commodities Act (1930). This Act allows for the enforcement of contracts between buyers and sellers (Agricultural Marketing Service—USDA, 2020a). Similarly, the Australian Horticulture Code of Conduct (enacted May 14, 2007) requires written agreements between buyers and sellers, ensuring that the parties define and document the level of any required quality attributes (DAWR, 2020a).
2. Product labeling for biosecurity. There is an increasing requirement for traceability, from the broad level of labeling country of origin to the specific level of traceability of every lot from orchard to retail outlet. (See Chapter 12: Managing product flow through postharvest systems.)

3. Product treatment for biosecurity issues. In responding to quarantine phytosanitary regulations, typically with respect to entomological or microbiological issues, fruit consignments may be required to be subject to certified treatments such as vapor heat or gamma radiation. Such treatments can impact shelf life (i.e., cause loss of "quality").
4. Product safety. Regulations typically target heavy metal and organic chemical residues and microbiological contamination.
5. Product origin. In Europe, the use of geographic names in labeling is regulated (European Commission—Agriculture and Rural Development, 2013).

3.4.2 A language for regulation

A value chain effectively consists of a series of tribes trading with each other, with each of these tribes varying in "dialect or language." Adding to this polygot are the government and NGO groups that interact with a fresh produce value chain. In addition to being literally true in international trade, the metaphor here is in the "language" used by each group to describe their product. The success of a regulation exercise rests on the ability of participants to understand the intended requirements, that is, to speak a "common language."

Grade standards can improve marketing efficiency by providing a common language for the understanding of the product to both sellers and buyers (Florkowski, 1999). This comment is valid for communication both "up" and "down" the value chain. For example, the producer must be able to interpret and effectively measure the standards set by a retailer, while the retailer must set meaningful standards and adjust these specifications according to production limits.

Production description languages are an attempt to use a common set of descriptors across the value chain. Such documentation exercises may be simple and visual (e.g., a poster produced by a marketing organization detailing quality characteristics), to complete manuals. The languages may be produced for use within a single value chain (Fig. 3.4), for use at a national level (e.g., Story & Martyine, 1996), or for international use (e.g., OECD, 2020).

3.4.3 Writing a fresh produce specification

Consider the difference between a standard, a specification and certification. In broad terms a standard should be a general principle while a specification should be a set of values on associated attributes of a product, to achieve conformance with a standard. In practice the two terms are used somewhat more loosely, with the term standard generally referring to a specification established by an institution of authority. In this definition, all standards are specifications but not all specifications are standards. Certification involves a mechanism by which the enforcement of a standard is achieved, for example, through testing of produce by a certifying body. A standard setting body may act in certification, or these functions may be separated.

An example specification from a retailer is illustrated in Fig. 3.5. This specification provides a measure against which produce arriving at the retailer distribution center can be assessed. Such a specification should include all requirements of relevant national

FIGURE 3.4 Color cards used in assessment on internal flesh color of mangoes in a closed marketing chain.

standards and any additional features that the value chain desires to achieve product differentiation from its competitors.

Writing an effective specification is not an easy task. Indeed, there is a specification on writing specifications (BRI, 2001). McManus (2018) makes the following points on the design of specifications used in fresh produce value chains:

- There can be multiple versions of a specification, for example, from supplier to packing team, or from buyer to QC teams.
- There should be a process for version control and for consistent changes to all versions if updates are made.
- A good specification is a short specification. Long specifications look impressive but cannot be fully implemented, cause loss of focus, and can create confusion and inefficiency, increasing costs.
- Specifications should be written to match what customers value. This can be estimated using consumer panels or surveys, through store visits and by monitoring complaints and social media. "Ugly" lines can be used to test customer tolerance of defects. Specifications can be benchmarked to those used by other businesses, although with caution as the customer sets may be different.
- Suppliers should be involved in the setting of specifications for feedback on which specifications are hard to meet and to build trust. However, this requires an honest interchange, so the choice of person involved is critical.

Effective: 1 November 2006

FMA **FreshSpecs** PRODUCE SPECIFICATIONS

PRODUCE:	MANGO		
TYPE	Ripened	VARIETY	Kensington Pride
CLASS	One	NOTES	

GENERAL APPEARANCE CRITERIA	
Colour	Pale yellow with or without pink to pink red-blush. None with > 40% of visible surface with light green colour; no chimeral variants (discoloured lines) with >1 line of green, not >2mm wide or 5cm long; not sunken or raised.
Visual Appearance	Yellow flesh moderate, not excessive fibre. With need for stickers with PLU and produce/variety name, or bar code when available, per requirements.
Sensory	Firm, yields slightly to finger pressure; smooth skin; sweet, with some acid; pleasant aroma; no unpleasant odours/flavours (abnormal ripening).
Shape	Round to oval heart shaped.
Size	In pre-ordered size per requirements; uniform per tray.
Maturity	>14 % dry matter. Fully coloured ripened fruit.
MAJOR DEFECTS	
Insects	With evidence of live insects.
Diseases	With fungal or bacterial rots (decaying areas).
Physical/Pest Damage	With cuts, holes, cracks (that break the skin).
Temperature Injury	With scattered, small dark-brown spotting on dull, discoloured skin. (chilling injury)
Physiological Disorders	With internal breakdown, eg. watery, translucent area in flesh or around seed (jelly seed), or with spongy stem end (grey brown flesh/cavity at stem end).
MINOR DEFECTS	
Physical/Pest Damage	With >5 attached scale insects. With sooty mould (brown-black spotting) or bacterial spot (black spotting), not open or weeping, affecting in total >1 sq cm. With pink spot >15 spots (each 5mm diameter) (former scale attachment areas). With shallow (<2mm), healed scarring, eg. hail or with cleavage scar affecting in aggregate >2 sq cm or with bruising affecting > 2 sq cm.; no deep scars or soft/moist deep-seated bruises.
Temperature Injury	With bleaching (sunburn) affecting >20% of visual surface; no grey-brown blotches or black depressed areas (sunscald).
Physiological Disorder	With pronounced/dark lenticels (>1-2mm wide) affecting >20% of skin; not star shaped or cracked.
Skin Marks/Blemishes	With sap burn or sap stain/spotting affecting >1sq cm. With light blemish, eg. dense, thick russet lines affecting >6 sq cm; scattered thin lines are allowable.
CONSIGNMENT CRITERIA	
Tolerance Per Consignment	Total minor defects (within allowance limit) to be < 2 defects per item Total minor defects (outside allowance limit) must not exceed 10% of consignment. Total major defects must not exceed 2 % of consignment. Combined Total not to exceed 10%.
Packaging & Labelling	Packaging manufactured from new food grade materials or sanitised returnable crates. All labelling must meet the current legislative requirements. Labelling to identify grower's name/brand (plus growers name/code if via a packhouse), address, contents, class, size and/or minimum net weight. Produce to identify Country of Origin (eg. Produce of Australia) on outer container.
Shelf Life	Produce must provide not less than 14 days clear shelf life from date of receival.
Receival Conditions	Compliance with Quarantine Treatments (if required) for Interstate Consignment. Stacked onto a stabilised pallet. Refrigerated van with air bag suspension, unless otherwise approved. Pulp Temperature 13 - 18 °C for Receival.
Chemical & Containment Residues	All chemicals used pre/postharvest must be registered and approved for use in accordance with the requirements of the APVMA regulatory system. Residues, Contaminants and Heavy Metals to comply to the FSANZ Food Standards Code ML's and MRL's.
Food Safety Requirements	Produce is to be grown and packed under a HACCP based food safety program that is subject to an annual third-party audit. A copy of current certification to be forwarded to receiver.

Specifications reviewable: e.g. to account for specific regional effects or adverse seasonal impacts on quality or early or late seasonal variances as agreed and communicated formally in writing.

FIGURE 3.5 Retailer specification example. https://freshmarkets.com.au/wp-content/uploads/Mango-Ripened-Kensington-Pride.pdf.

- Specifications should be reviewed and updated at least every season. All aspects of a specification should be justified, with the reason why a particular level was chosen recorded and dated, along with record of any change in sales or consumer feedback. Such records will inform future reviews and assist continuity with staff changes.
- Photographs should be used in specifications to reduce ambiguity.
- Quality specifications left in place for a long period without reevaluation can cause waste. Temporary specifications can be used when seasonal conditions affect quality, but good communication is required to inform suppliers of the period involved. Consideration of how customers should be informed is also needed. Internal policy and process to make such changes should be clear as a quick response to requests to alter specification is essential. If the same request is made repeatedly, it should be built into the specification.
- Waste can result from overgrading caused by overcautious suppliers or overly eager quality control personnel. Solutions include training/discussion, improving working conditions (e.g., lighting), and/or technology (e.g., automated grading, provided these are calibrated regularly). The issuing of warnings for minor defects rather than rejection of loads will help suppliers pack to specification more confidently.
- Minimum and maximum size criteria can greatly impact on crop utilization. Relaxation of these specifications will improve efficiency and reduce costs. Size requirements should be tightened only on evidence that consumers value this character.
- A shelf life assessment protocol should be included in specifications. For example: "A minimum of one pack per production run to be held in conditions that replicate the value chain from dispatch to consumption."

Valero and Ruiz-Altisent (2000) describe a quality control system on fruit quality intended for implementation at the retailer distribution center that involves statistical sampling protocols and quantitative measures of quality attributes, including fruit firmness, temperature, skin color, juice total soluble solids (TSS) content, and juice total titratable acidity (Fig. 3.6). This system represents an "ideal"—the reality at a retailer receival warehouse is more likely to be a small table at which a few fruits are sporadically cut and visually assessed.

Specifications should give instruction on the number of units in a lot (pieces of fruit in a consignment) to be tested. The required number should increase as attribute standard deviation of the population increases, as discussed in Walsh, McGlone, and Han (2020) (see also Chapter. 15: Cooling fresh produce). The relationship between required sample number, n, population standard deviation, SD, required error (e), and probability for a population with a normal distribution is

$$n = \left(t \cdot \frac{SD}{e}\right)^2 \tag{3.1}$$

where t is the t statistic (1.96 for a population >30 and a probability of 95%). For example, if a fruit consignment was to be sampled for Brix (sweetness) for assessment of the mean to a 95% probability with an accepted error of 0.5°Brix, given an SD of 2°Brix obtained from a preliminary sampling, 61 fruits should be sampled.

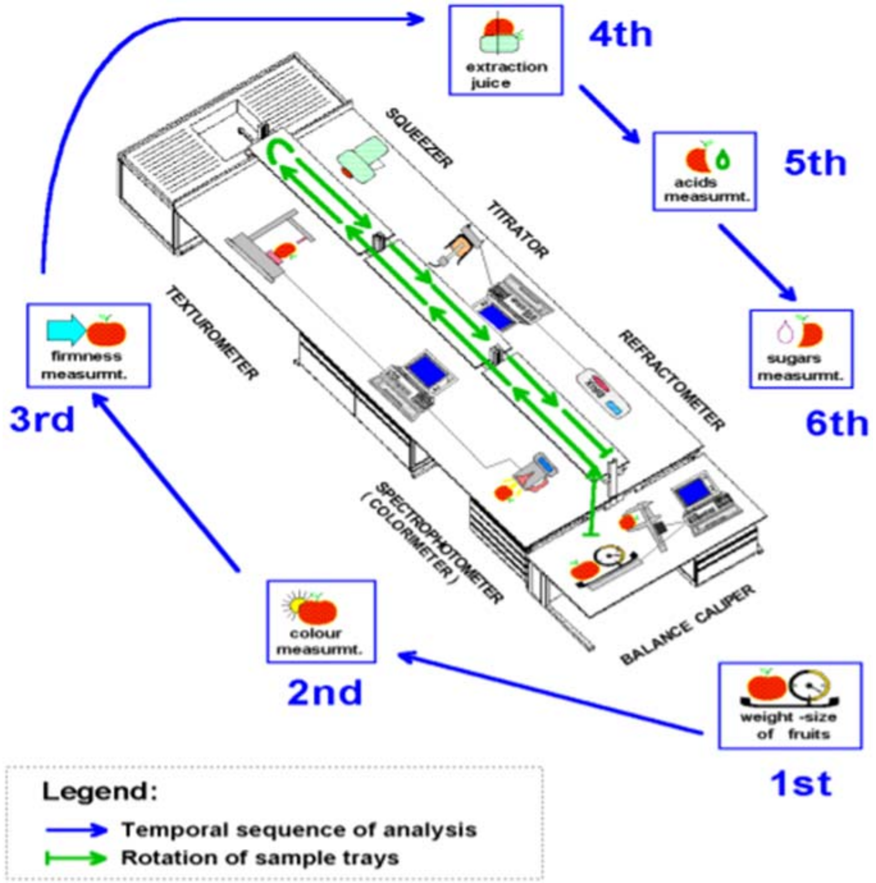


FIGURE 3.6 Quality control station layout recommended for implementation at a retailer distribution center (Valero & Ruiz-Altisent, 2000).

3.5 Fresh produce standards

3.5.1 The players in setting of standards on fresh produce

This section reviews the organizations involved in the setting of standards for fresh produce. As noted earlier, the standards set by intergovernmental bodies are voluntary. National governments can adopt, adapt, and enforce standards. The primary source of intergovernmental standards on fresh produce is the Codex. Codex standards are informed by work of the Organization for Economic Cooperation and Development (OECD), United Nations Economic Commission for Europe (UNECE), and national institutions. The role of these bodies is reviewed later.

3.5.2 Codex

The Codex Alimentarius Commission (CAC) was created in 1963 by FAO, World Health Organization (WHO), and other bodies to develop food standards, guidelines, and codes of practice, with the aim of protecting the health of consumers, ensuring fair trade practices in the food trade, and promoting coordination of work on food standards (Codex, 2020a). In these activities, the CAC acts as an aide to the WTO, allowing for the minimization of "the negative effects of technical regulations on international trade." The CAC aims to act as the internationally recognized body for food standards, to be used by all members as a basis for domestic regulation and international trade. Guidance is also provided to member countries on labeling and import/export inspection, on certification systems, and on food safety management systems (Pineiro & Diaz, 2007).

The CAC does not conduct any direct technical work on standards, but rather it relies on expert Committees convened by FAO and WHO, and upon the technical work of member nations. For example, the Joint FAO/WHO Meetings on Pesticide Residues and the Joint FAO/WHO Expert Meeting on Microbiological Risk Assessments are independent of the CAC (Codex Alimentarius Commission, 2020b).

The growth in global food trade has resulted in a substantial growth in membership of the CAC, with developing countries now accounting for a majority of total membership. To achieve agreement across all members, however, CAC product specifications can be a case of the lowest common denominator. The CAC has been successful, however, in the setting of specifications to cover maximum heavy metal, chemical residue, and microbiological contamination criteria, and issues such as labeling of country of origin, fruit size, and esthetic issues. Specifications on a few commodities include eating quality attributes (e.g., for table mangoes, Fig. 3.7).

3.5.3 The Organization for Economic Cooperation and Development

The OECD is a group of 34 countries (http://www.oecd.org/about/members-and-partners/; accessed October 18, 2020) committed to "democracy and the market economy" that acts to "facilitate international trade through the harmonization, implementation, and interpretation of marketing standards." The OECD claims to be the "main reference for the certification and standardization of certain agricultural commodities." The OECD is active in developing standards in collaboration with the UNECE and Codex, and in promoting uniform quality assurance and inspection systems under its "Scheme for the Application of International Standards for Fruit and Vegetables" (including a methods manual on testing fruit and vegetable eating quality) (OECD, 2020). The OECD and UNECE standards on FAVs are identical, with the OECD website on these standards (OECD, 2020) linked to that of UNECE (2020a).

3.5.4 The United Nations Economic Commission for Europe

The UNECE was established in 1947 and includes the countries of North America, Europe, and Russia. UNECE reports to the United Nations Economic and Social Council. Within UNECE, the "Specialized Section on the Standardization of Fresh Fruit and Vegetables" is part of the Working Party on Agricultural Quality Standards. This body sets standards on

CODEX STAN 184 Page 1 of 4 Amended 2005.

STANDARD FOR MANGOES (CODEX STAN 184-1993)

1. **DEFINITION OF PRODUCE**

This Standard applies to commercial varieties of mangoes grown from *Mangifera indica* L., of the *Anacardiaceae* family, to be supplied fresh to the consumer, after preparation and packaging. Mangoes for industrial processing are excluded.

2. **PROVISIONS CONCERNING QUALITY**

2.1 **MINIMUM REQUIREMENTS**

In all classes, subject to the special provisions for each class and the tolerances allowed, the mangoes must be:
- whole;
- sound, produce affected by rotting or deterioration such as to make it unfit for consumption is excluded;
- clean, practically free of any visible foreign matter;
- practically free of damage caused by pests;
- free of abnormal external moisture, excluding condensation following removal from cold storage;
- free of any foreign smell and/or taste;
- firm;
- fresh in appearance;
- free of damage caused by low temperatures;
- free of black necrotic stains or trails;
- free of marked bruising;
- sufficiently developed and display satisfactory ripeness.

When a peduncle is present, it shall be no longer than 1.0 cm.

2.1.1 The development and condition of the mangoes must be such as to enable them:

to ensure a continuation of the maturation process until they reach the appropriate degree of maturity corresponding to the varietal characteristics;

to withstand transport and handling; and

to arrive in satisfactory condition at the place of destination.

In relation to the evolution of maturing, the colour may vary according to variety.

2.2 **CLASSIFICATION**

Mangoes are classified in three classes defined below:

2.2.1 **"Extra" Class**

Mangoes in this class must be of superior quality. They must be characteristic of the variety. They must be free of defects, with the exception of very slight superficial defects, provided these do not affect the general appearance of the produce, the quality, the keeping quality and presentation in the package.

2.2.2 **Class I**

Mangoes in this class must be of good quality. They must be characteristic of the variety. The following slight defects, however, may be allowed, provided these do not affect the general appearance of the produce, the quality, the keeping quality and presentation in the package:
- slight defects in shape;
- slight skin defects due to rubbing or sunburn, suberized stains due to resin exudation (elongated trails included) and healed bruises not exceeding 3, 4, 5 cm² for size groups A, B, C respectively.

2.2.3 **Class II**

This class includes mangoes which do not qualify for inclusion in the higher classes, but satisfy the minimum requirements specified in Section 2.1 above. The following defects, however, may be allowed, provided the mangoes retain their essential characteristics as regards the quality, the keeping quality and presentation:
- defects in shape;
- skin defects due to rubbing or sunburn, suberized stains due to resin exudation (elongated trails included) and healed bruises not exceeding 5, 6, 7 cm² for size groups A, B, C respectively.

In Classes I and II, scattered suberized rusty lenticels, as well as yellowing of green varieties due to exposure to direct sunlight, not exceeding 40% of the surface and not showing any signs of necrosis are allowed.

FIGURE 3.7 Excerpt from Codex specification for mango.

fresh fruits and vegetables intended for application at the point of export and so informs the OECD, Codex, and GlobalGAP standards (UNECE, 2020a).

The function of this body is illustrated by a report of one of its meetings, the 57th session of the Specialized Section on the Standardization of Fresh Fruit and Vegetables (UNECE, 2020b). This meeting was held as a webinar on February 11, 2020, attended by representatives of 26 countries, to consider modifications of UNECE standards on citrus, table grapes, persimmon, and stone fruits. For example, the "minimum maturity requirement" for peaches and nectarines was defined by the criteria of: "the refractometric index of the pulp measured at the middle point of the fruit flesh at the equatorial section must be greater than or equal to 8 °Brix and the firmness must be lower than 6.5 kg measured with a plunger of 8 mm diameter (0.5 cm^2) at two points of the equatorial section of the fruit, with skin intact, except for fruits with Brix values greater than 10.5°, in which case firmness must be lower than 8 kg measured with a 8 mm diameter plunger."

3.5.5 National regulation

National standards focus to issues of product safety and biosecurity for domestic trading. For countries with strong export programs, national standards may reflect specifications as agreed under respective trade agreements. The standards will be, at a minimum, those of the Codex Alimentarius and thus informed by the OECD-UNECE standards.

Each nation will differ in organizational structure employed to enforce quarantine and food safety standards, with the Australian structure presented by way of example in this section. A US example is provided for an inspection service and an example specification from The Philippines is presented. Additionally, an example is given of the additional regulatory criterion of locality, as offered within Europe.

3.5.5.1 Layers of responsibility—Australia

FAV quality is regulated in Australia in terms of quarantine and food safety issues by several federal government agencies, notably the Australian Pesticides and Veterinary Medicines Authority (APVMA), Food Safety Australia and New Zealand (FSANZ), and Australian Quarantine Inspection Service (AQIS). These bodies apply Codex standards relevant to food safety and biosafety, but not on eating quality, per se. The agencies are part-funded by cost recovery, for example, through application fees to register products, an annual fee to maintain product registrations and levies on the annual wholesale sales value of registered products.

The APVMA is an Australian government statutory authority established in 1993 to centralize the registration of all agricultural and veterinary chemical products into the Australian marketplace (https://apvma.gov.au/node/1063 accessed October 19, 2020). For example, a sanitizer or a descaling agent used in a packline wash plant is subject to verification and approval by APVMA. The burden of the approval falls to the chemical manufacturer but the user is responsible for judicious use. As the cost of preparing a case for registration of a chemical is high, this process is a major issue for horticultural crops of relatively low total farmgate value. An international standard on chemical registration would be very useful.

Food Safety Australian and New Zealand (FSANZ, 2020; https://www.foodstandards.gov.au/code/Pages/default.aspx) is a regulatory body that develops standards that define maximum allowable chemical residue and microbial loads on fruits and vegetables, and permissible irradiation treatments. FSANZ does not monitor these levels, leaving this to state agencies or commercial practices. It can also be involved in dispute resolution. This body is also responsible for the registration of chemicals for use on a given crop, for labeling requirements.

The AQIS is charged with the responsibility of preventing entry of unwanted fruit and vegetable pests and diseases into the country (Australian Quarantine Inspection Service, 2013a). The service also issues statements of compliance for specified treatments (e.g., vapor heat treatment) of produce destined for export markets. Within country, quarantine issues are dealt with by State Agriculture Departments. For example, papaya fruit fly is a serious pest of tropical fruit that entered Australia through the Cairns airport, presumably with a passenger carrying infected fruit and despite AQIS inspection. The state agriculture agency enforced bans on fruit transport through road blocks in concentric rings around Cairns until the pest was eliminated. Similarly, when citrus canker appeared on a mandarin farm in Emerald, Central Queensland, despite AQIS inspection of all imported equipment and budwood, the state agriculture agency enforced bans on fruit and equipment movement and oversaw a destruction of all citrus trees in a 200 km radius (CoA, 2016).

The FAV trade is also subject to the interests of other state and federal agencies. For example, Therapeutic Goods Administration approval is required on any claim for a health benefit of a product. State Department of Environments can also have interest. For example, frogs are frequently transported from tropical to temperate areas in banana shipments. It is believed that the fungus *Mucor amphibiorum* was introduced to Tasmanian platypus from "banana" frogs (Tasmania - Department of Primary Industries and Water, 2020).

As mentioned earlier, developed economy governments have largely exited from enforcement of eating quality standards. However, this is not universal. For example, the Western Australia government (through its Citrus Fruits Grading Code, legislated in 2008) regulates maturity standards on citrus in terms of minimum Brix, Brix acid ratios, and juice content (https://www.legislation.wa.gov.au/legislation/statutes.nsf/law_s41353.html; accessed October 18, 2020).

3.5.5.2 *An inspection service—The United States*

The Agricultural Marketing Service (AMS) of the USDA began in 1915 with the aim of providing market information and common terminology for quality and the development of grade standards (Agricultural Marketing Service—USDA, 2020b). Given their experience and technical capacity, the AMS has contributed significantly to the development of international produce standards, for example, Codex and UNECE.

The United States Inspection Service acts to apply these fruit and vegetable standards. It was established in 10 of the largest wholesale markets in the United States in 1917 and now arranges for domestic inspection of fruit and vegetables across the country, both for sellers and for buyers. Inspections are made with reference to 158 grade standards for 85 fresh fruits, vegetables, and nuts. Inspections are generally voluntary, made at the discretion of either the seller or buyer, and paid by user fees. However, inspections are mandatory for fruit purchased by government agencies, for example, military or schools. Clients can request a quality and condition inspection, a condition only inspection, or a container weight/count only inspection. A quality and condition inspection of a product "in quantities of 51 or more packages . . .unloaded from the same land or air conveyance, over half a carlot equivalent product" is priced at US $114 (Agricultural Marketing Service—USDA, 2020b).

3.5.5.3 *Geographic origin as an attribute—The European Union*

In Europe, the European Food Safety Authority is the primary source of regulations on fruits and vegetables, for example, maximum residue limits and for health claims. Pascale (1992) has reviewed the wider issue of the impact of European Economic Communit (EEC) regulations on quality on trade in FAVs.

The European Community has regulated the labeling of food by geographic or traditional origin (European Commission, 2013). Three categories are recognized: Protected Designation of Origin (PDO), Protected Geographic Indication (PGI), and Traditional Specialty Guaranteed (TSG). PDO describes foodstuffs produced, processed and prepared in a given geographical area using recognized know-how. For PGI, a geographical link to one of the three stages of preparation must be demonstrated. To achieve designation, a case must be supported by the relevant national government and approved by the European Commission, Agriculture/Food quality section. Well over 100 PDO/TSG assignments have been granted on fruit and vegetables (European Commission, 2020).

3.5.5.4 *A specification example—The Philippines*

The Philippines maintains national standards on a range of fruit and vegetables. For example, The Philippine National Standard on Mandarin (Philippine National Standards, 2020) details specifications on fruit diameter, defects, packaging, color, juice TSS, juice total acidity (TA), juice Brix to TA ratio, and minimum percentage juice content as a maturity requirement. These standards are informed by USDA-AMS and UNECE and directly refer to the CAC standard for allowable levels of heavy metals and pesticides.

3.6 "Private" (within value chain) regulation

3.6.1 Product differentiation

A given value chain must adapt to suit the trading environment set by both government-based regulation and by competing value chains. This competition provides "evolutionary pressure." Indeed, large retailers will often engage at least two "produce supply managers" for each commodity. The resulting competition involves differentiation of product in terms of price, quality or some other aspect of the "offer." To achieve this, a successful value chain will impose "regulations" on its members, seeking to distinguish itself in some way. For example, participants agree to be bound by rules that may include the window and volume of production, the production and postharvest methods, and the marketing path. Sometimes the chain adopts a core piece of intellectual property, such as a cultivar under PBR, or a distinguishing technology. For example, the

SmartFresh quality system, developed in the United States, has been effectively used by some Australian export chains to maintain consistent fruit quality. In this system, fruits are treated with a chemical (1-methylcyclopropene) to delay the ripening process and improve shelf life.

Examples of within value chain regulations include:

1. Product size, color, and appearance. Retailers usually set product specifications in terms of these attributes.
2. Product eating quality. There are increasing attempts within value chains to regulate on eating quality, through specifications on measurable attributes such as TSS. For example, use of the Washington Apple brand requires Red Delicious apples harvested before October to have a minimum TSS of 11%, http://www.bestapples.com/facts/facts_grades2.aspx, while the California maturity standard enforces a citrus harvest criterion based on TSS and acidity. https://www.co.fresno.ca.us/home/showdocument?id = 92; accessed October 22, 2020.
3. Product origin. In Japan, consumers identify specific product qualities by region and retailers may label product with locality and even the identity of the farmer (Fig. 3.8). Dole Organic incorporates a three-digit number on the fruit label visible in store that allows a link to a website displaying information on the growing site.
4. Organic production. Specific value chains may require organic production, vetted by various certification schemes.
5. Other environmental issues. Some consumers/value chains/governments give weight to production issues such as water use and wildlife "friendliness" (e.g., netting to exclude flying foxes), and postharvest issues such as type of packaging and "food miles."

Detail on some example private certification schemes follow. With food safety issues increasing in developed countries, regulations addressing this area are dealt with in a separate section.

3.6.2 Example private certification schemes

3.6.2.1 Who certifies the certifiers?

The International Standards Organization (ISO; https://www.iso.org/home.html accessed October 22, 2020) sets international standards, including requirements for certifying bodies providing audit and certification of food safety management systems (ISO17055; https://www.iso.org/standard/46568.html). While ISO sets standards, it does not offer a certification service. Third party groups are therefore involved in certifying that a food related audit scheme meets the ISO standard.

Example of private certification schemes follow.

3.6.2.2 GlobalGAP

GlobalGAP (http://www.globalgap.org) originated with European retailers as a means of ensuring product was safe, of high quality, traceable from its point of origin, and produced in a humane and environmentally sound way. The specifications set in this scheme

FIGURE 3.8 Produce advertisement in Japan featuring grower and the use of sorting technology (near-infrared spectroscopy for sweetness assessment).

are tighter (extending to eating quality determinants) and broader (extending to social and environmental issues) than that set by the CAC.

Local versions of GlobalGAP can be certified by GlobalGAP, with the standard adapted to local conditions, for example, ChinaGAP, J-GAP, and ThaiGAP. The commonality of GAP programs in different countries is allowing it to develop as an international standard. GlobalGAP also maintains a list of equivalent certifications. For example, as of August 29, 2019, all fresh produce imported to Thailand must have GAP or equivalent certification.

To achieve GAP certification on product, farmers must invest in systems to comply with the standard and pay for independent verification of compliance. The processes and documentation required by GlobalGAP thus factors against the involvement of small producers.

3.6.2.3 *Organic certification*

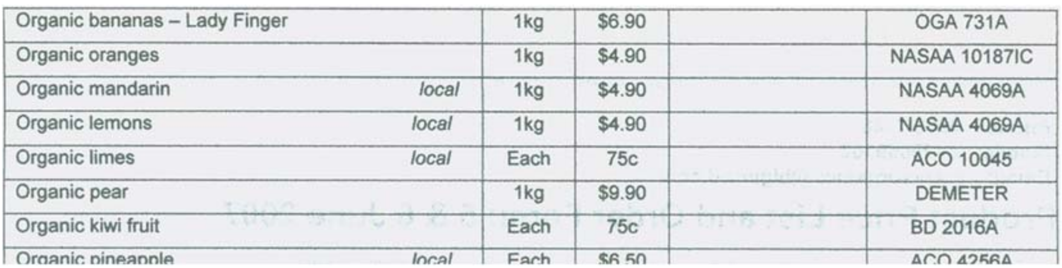
As organic production has increased in volume and extent of trade, there has been an evolution from an informal activity to private certification and to a national certification scheme.

Some countries, for example, United States, European Union, Canada, and Japan, have consolidated organic certification at a national level, and the term "organic" may be used only by certified producers. In the USA, the organic standards are implemented by the USDA (USDA Certified Organic), and the common standard allows interstate trade under an "organic" label. A fine of $11,000 per instance is levied on product carrying the label "organic" that is not certified.

Australia has an enforced single standard for exported organic product but in the domestic market the use of the term "organic" is not legally restricted. Seven private certification bodies exist who base their standards around the National Standard used for export certification. These certifiers must be accredited by Australian Biosecurity (an agency of the Federal Department of Agriculture). The existence of multiple standards (Fig. 3.9) can be confusing to the marketplace and there is a trend toward standard consolidation (Lockie, Lyons, Lawrence, & Halpin, 2006; also see the useful review at http://en.wikipedia.org/wiki/Organic_certification).

In China over 430 institutions offer organic certification, but with enforcement spread over a number of government departments there has been inconsistent regulation, and counterfeit organic labels also exist (Collen, 2007). The China Green Food Development Center (http://www.greenfood.agri.cn/ywlssp/aboutcgfdc/ accessed October 23, 2020) aims to improve enforcement, and oversees two Green Food Standards relevant to horticultural production: A, which allows some use of synthetic agricultural chemicals, and AA, which allows less use of such chemicals. It is reported that the AA standard is less popular with producers. Consistent pressure from value chains is required to achieve consistent enforcement of standards in such an environment.

The various national standards tend to cluster to three blocks, namely, USDA Organic Seal (http://www.ams.usda.gov/NOP), the EU standard (regulation 2092/91), and the Japanese Agricultural Standard (JAS) (Lockie et al., 2006). The standards differ, complicating trade. For example, JAS prohibits the use of alkali humic acid, lignin sulfonate, and



Organic bananas – Lady Finger		1kg	$6.90		OGA 731A
Organic oranges		1kg	$4.90		NASAA 10187IC
Organic mandarin	local	1kg	$4.90		NASAA 4069A
Organic lemons	local	1kg	$4.90		NASAA 4069A
Organic limes	local	Each	75c		ACO 10045
Organic pear		1kg	$9.90		DEMETER
Organic kiwi fruit		Each	75c		BD 2016A
Organic pineapple	local	Each	$6.50		ACO 4256A

FIGURE 3.9 Example of multiple organic standards quoted on retail advertising.

potassium bicarbonate, items allowed under the USDA standard. However, bilateral arrangements are developing. For example, a US–Japan mutual recognition of organic standards was achieved in 2014.

The International Federation of Organic Agricultural Movements (IFOAM) is a German-based international NGO which is striving to achieve a private standard that is recognized by all major trading blocs. The IFOAM Family of Standards was introduced in 2011 in an attempt to simplify harmonization. This action was intended to establish the use of a single global reference (the Common Objectives and Requirements of Organic Standards), rather than focusing on bilateral agreements (http://www.ifoam.org/en/ifoam-norms).

Biodynamic agriculture involves a more "fastidious" form of organic farming. The term *Biodynamic* is a trademark held by the Demeter association of biodynamic farmers and the biodynamic certification "Demeter," created in 1924, was the first certification and labeling system for organic production. The movement involves a network of national associations. As such, this production system has long enjoyed clear branding.

3.6.2.4 *In house labels—Tesco C footprint example*

The past half century has seen the rise of the global retailers. These retailers dominate their value chains and, therefore, can drive (regulate) change. In driving change the retailers often seek to reflect perceived public interests, with the timing of action linked to a judgment of when a specific value client group appears sufficiently large and cohesive. For example, when public attention swung to the issue of greenhouse gases and global warming, Tesco, the UK-based transnational retailer, announced intent to label air-freighted produce with an airplane symbol in 2007, and committed to introduce a carbon labeling system (of emissions due to production, transportation, storage, and packaging) on all products in 2008 (Tesco, 2013). However, the data and assumptions required for such an exercise are not trivial, and in 2013 Tesco announced it would discontinue the program. Tesco currently attempts to report to shareholders on its carbon footprint from a 2015/16 baseline. The accounting practices involved in such reporting are yet to settle, however, with Tesco (2020) reporting that the recalculation could occur "when structural changes occur," for example, acquisitions, divestitures, or methodology change.

3.6.2.5 *Recent "private" certification schemes*

Asia Fruit Magazine (http://www.fruitnet.com/asiafruit/topic/production-trade) reports relevant to private certification schemes within a 1-month period within 2020 include:

September 9: The CO_2 Correct scheme was launched. The product aims to take the strain out of the Life Cycle Analysis calculations on carbon footprint, with the fruit or vegetable to be sold as carbon compensated under the CO_2 Correct label or a private label.
October 1: Fairtrade International proposed an actionable plan to achieve living wages for workers on Fairtrade-certified banana plantations.
October 16: Retailer Kyffs announced a Human Rights Impact Assessment conducted across its value chain.

3.7 Food safety

3.7.1 The issue

A primary duty of any fresh produce value chain is the reduction of risk associated with food safety to consumers. Such risks can be prevalent but chronic, for example, chemical residues or heavy metals at low levels, are rare but acute, for example, needle in fruit scares or human pathogen contamination. National standards specify relevant requirements (e.g., maximum chemical residue levels and microbial loads and the absence of foreign objects) but not the procedure to achieve these specifications.

Proactive action by private value chains to remove food safety risk reduces the need for further government-imposed regulation. Value chain members are typically required to participate in a food safety management program scheme, which historically varied somewhat between retailers. Differences in such programs can lead to compliance difficulties for suppliers attempting to supply multiple retailers under multiple programs, so there is reason to seek harmonization.

Escherichia coli, *Listeria*, *and Salmonella* are the most prevalent human pathogens in fresh produce—related food poisonings, with a number of incidents raising the profile of microbial hazards for fresh produce over the last decades (for USA: https://www.cdc.gov/foodsafety/outbreaks/multistate-outbreaks/outbreaks-list.html accessed October 22, 2020; for Australia: https://www.productsafety.gov.au/products/food-groceries/fruit-vegetables). This has led to increased scrutiny of the food safety of fresh produce, in general, and leafy vegetables, in particular, by regulatory agencies and by fresh produce value chains.

A food safety management plan involves documentation and verifiable records. Example inclusions are requirement to ensure that employees are qualified to perform assigned duties as demonstrated in their education, training and experience, monitoring and record keeping of temperature in a washing process to kill pathogen or sanitizer level, and recall plans.

The US Food Safety and Modernization Act was passed in 2011 and its provisions became mandatory in 2016 (Florkowski, 2019) with a goal to prevent microbial contamination incidents. This act applies to firms in the United States, including firms dealing with export of produce. Each facility must establish and implement a food safety system that includes analysis of hazards and risk-based preventative controls and a written food safety plan.

In Australia, the use of a food safety system in fresh produce value chains is not mandated by law, but all substantial value chains implement such systems. For example, Freshcare (http://www.freshcare.com.au, accessed 23/10/2020) offers a food safety system that is compliant with the Global Food Safety Initiative and compliant to ISO17065. Its requirements evolve with time, with changes in recent years, including security of packing facilities, separation of lunch facilities in packhouses, and frequency of microbiological testing of water supply.

3.7.2 Case studies: food safety incidents

3.7.2.1 Needles in fruit (Australia)

Deliberate actions to compromise food safety cannot be prevented in a food safety plan; however, the consequences can be mitigated.

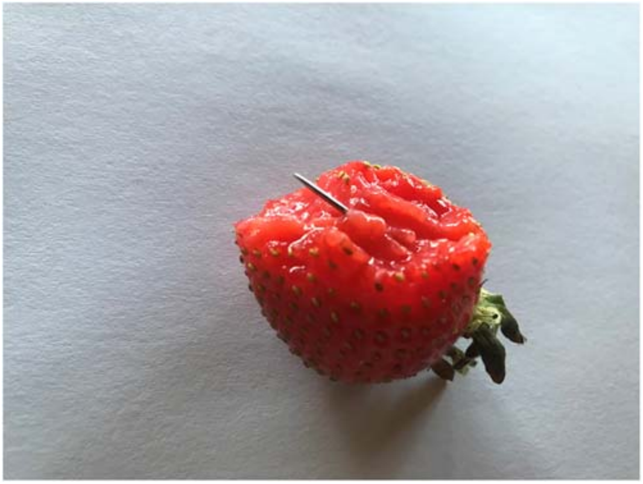


FIGURE 3.10 Needle in strawberry.

In 2018, a disgruntled employee placed needles into strawberries destined for market (https://www.foodstandards.gov.au/publications/Pages/Strawberry-tampering-incident.aspx accessed October 23, 2020) (Fig. 3.10). After discovery in product by consumers, product pulled from this value chain was removed from sale in a "trade recall" rather than a "consumer" level recall, which is much harder to achieve and is more expensive. However, subsequent copycat action and a media "frenzy" caused a level of public panic and cessation of all strawberry sales across Australia and New Zealand. Growers were forced to dump product. A subsequent review called for use of blockchain technology to improve traceability of product and speed of recall, protocols for improved communication across health, police and regulators, involvement of police in public briefings from the outset with stress on the criminal nature of the offense, and the strengthening of penalties.

3.7.2.2 Listeria in melons (Australia)

National and international value chains and large production lots mean that a food contamination incident can involve a large and dispersed population. Elements of this population are particularly at risk, for example, immunocompromised individuals.

In 2018, seven deaths and one miscarriage were caused by the consumption of rockmelon contaminated with *Listeria*. Subsequent publicity resulted in the cessation of all melon sales across Australia and New Zealand. An investigation followed (NSW DPI, 2018). The fruits were traced to one farm. Hygiene and sanitation practices on the farm were acceptable according to current regulations and practice. Raw organic fertilizer was not used on the crop, wash water was not recirculated, sanitizer was constantly monitored and applied through an autodosing system, and all water coming into the facility was treated and considered potable. However, a number of circumstances combined to cause the event. Heavy rainfall prior to harvest, followed by dust storms, increased the amount of *Listeria* on fruit prior to harvest. Dirty fans used to dry fruit following washing and some spongy materials on packing tables that were not easily cleaned were deemed to have contributed to the outbreak.

In addition to changes in media engagement and rate of recall as for the strawberry case, a new guide for industry practice was produced with increased attention to microbiological issues (https://www.melonsaustralia.org.au/wp-content/uploads/2020/09/Melon-food-safety-best-practice-guide.pdf accessed October 22, 2020).

3.7.2.3 Chemical residues (China)

Human ingestion of bis(2-ethylhexyl) adipate (DEHA) can result in fertility problems. The compound can be used in plastic manufacture but can migrate into wrapped food, particularly product with high fat levels. The General Administration of Quality Supervision, Inspection and Quarantine (https://www.aqsiq.net) banned the use of DEHA in plastic wrap in 2005.

A testing program identified plastic wrap with DEHA levels at up to 23% in retail outlets across several cities. In comparison, EC regulation 10/2011 stipulates a limit of 18 mg/kg (0.18%). The product was traced to a company in Tongxiang, China, which admitted to use of DEHA instead of the permitted dioctyl adipate to achieve a 33% decrease in the cost of raw materials for manufacture of PVC plastic wrap (http://www.fruitnet.com/asiafruit/pdf/159030 accessed October 22, 2020).

3.7.3 Food safety management programs

Globally significant food safety management programs include the British Retail Consortium Global Food Standard, International Food Standard, 2000 Safe Quality Food Scheme, and the hazard analysis and critical control point (HACCP) Scheme. The HACCP program, for example, is used in the United States, Europe, East Asia, and Australasia (e.g., HACCP Australia, 2020). In these programs, an analysis of what and where hazards can occur is made, and systems and procedures are implemented to minimize the risk of failure. Subsystems such as pest control, recall protocols, hygiene, and sanitation are also implemented. For example, an analysis of a packinghouse operation might consider the risk of use of contaminated water in the fruit-washing process, or the possibility of contamination of fruit from the breakage of a glass component in the packline. On-site operators and management are trained, and a maintenance/audit program involving HACCP personnel is implemented.

3.8 On the regulation of eating quality

3.8.1 Defining eating quality

Eating quality is often not considered within discussions of fresh produce quality. Fellars (1985) concedes that the words “flavor” and “flavor quality” often appear in the literature without associated sensory ratings for citrus quality or palatability. The text “Quality Factors of Fruits and Vegetables” Jen (1989) offers little on quantitative levels of components related to eating experience and does not report any minimum standards. The text “Fruit and Vegetable Quality” Shewfelt and Bruckner (2000) details a range of concepts, from the breeding to economics, but again does not address the issue of measurement internal eating quality or the setting of minimum standards. In contrast, the text "Fruit and Vegetable Flavours" Bruckner and Grant Wyllie (2008) does document flavor standards.

Setting a quality standard to deliver eating quality requires the use of quantitative, easily measurable, attributes that can be correlated to eating quality. The primary measurable attributes of a fruit that can be related to taste are texture, concentration of storage materials (carbohydrates or lipids), concentration of organic acids (in some fruit), and level of volatiles.

- Texture is commonly indexed as firmness and measured as the peak force required to plunge a rod of set diameter 1 cm into a sample.
- A few products store energy in the form of lipids (e.g., avocado, macadamia nut) but most store carbohydrates. At eating stage, the carbohydrates may be present in insoluble form, as starch (e.g., potato), or in soluble form as sugars (e.g., melon). In some fruits, starch is accumulated during maturation and converts to sugar during ripening (e.g., apples, bananas, and mangoes). Dry matter content (DM) is a useful index of total storage reserve content. In fruit that convert starch to sugars during ripening, DM at fruit maturity is an index of fruit sugar content at ripeness and, thus, to potential eating quality.
- Sugar levels of a fruit are usually assessed by juice extracted from the fruit and expressed in units of percentage of TSS also termed Brix. A "layman's guide" to the value of fruit TSS testing using a refractometer is given by Harrill (https://stillpointx.files.wordpress.com/2015/11/using_a_refractometer_to-test_the_quality_of_fruits_and_vegetables_by_rex_harrill.pdf accessed October 22, 2020). A refractometer assesses the refractive index of a solution and so is an indirect measure of the sugar levels. The method does not distinguish between the forms of soluble sugar present, for example, fructose, glucose, or sucrose. Fructose elicits a greater sweetness sensation than sucrose.
- In certain fruit, acidity (sourness sensation) is an important component of taste. This attribute is a function of the concentration of organic acids (e.g., citric or malic acids). Like soluble sugars, it is typically assessed by juice extracted from the fruit. The typical measurement technique involves titration of the juice sample with a base.
- Volatiles and semivolatile organic compounds also impact the flavor and aroma of foods. However, analysis of volatiles can be a "daunting task, and obtaining useful information from such measurements can be even more challenging" (Marsili, 1997). Electronic noses have been in development for some time (see Chapter 15: Cooling fresh produce, Section 15.6.2) but have yet to see commercial adoption in fresh produce assessment.

Scientific reports on recommended minimum attribute levels are presented in Table 3.1. Such testing may extend to cover factors such as market differentiation, that is, different grade standards for different market segments (e.g., Crisosto, 1994; Crisosto, Crisosto, Echeverria, & Puy, 2007). To generalize, a TSS level of at least 10% is required for the fruit to taste sweet, and the human palate can differentiate between fruits varying by 1%−2% TSS. However, these values can vary by commodity. Further, the perception of sweetness

TABLE 3.1 Examples of specifications on eating quality attributes, as recommended in the scientific literature.

Fruit	Climacteric	Attribute	Level	References
Avocado	+	DM (at harvest) Oil	21 8	Agrilink (2001) Seymour and Tucker (1993)
Banana	+	TSS	6.7–12.7 (unripe) 23.0–31.0 (ripe)	Choon and Choo (1972)
		Fullness index	Variable per cultivar	Samson (1989)
Citrus	−	TSS:acid	8:1–10:1	Baldwin (1993)
		Limonin (ppm)	≤ 6	Davies (1986)
(Grapefruit)		TSS:acid	6:1	Kader (2002)
(Mandarin)		TSS:acid	8:1	Kader (2002)
(Orange)		TSS:acid	8:1	Kader (2002)
			10:1–16:1	Samson (1989)
			Navels: 7.5:1–9.0:1	Davies (1986)
		Juice content (% FW)	50	Samson (1989)
Grape—table	−	TSS	Ribier, Red malaga, Emperor 16; other 17	Weaver (1976)
		TSS:acid	Thompson seedless, Malaga, Ribier 25:1	Weaver (1976)
			Muscat, Emperor, Cornichon, O'hanez 30:1	Weaver (1976)
Kiwifruit	+	TSS (at harvest)	6.2	Given (1993)
		TSS (ripe)	14	Kader (2002)
			15	Mitchell, Mayer, & Basi, 1991
		TSS (for long-term storage)	7–9	Sale (1985)
		Firmness	0.71	Cheah and Irving (1997)
Lychee	−	TSS:acid	35:1	Greer (1990)
			30:1–40:1	Underhill and Wong (1990)
		TA	4.4	Batten (1989)
Mango	+	TSS	15	Yamashita (2000)
			16	Satyan and Chaplin (1986)
			12	Samson (1989)

(*Continued*)

TABLE 3.1 (Continued)

Fruit	Climacteric	Attribute	Level	References
		DM (at harvest)	14	Bally, Johnson, & Kulkami, 2000
		Specific gravity (g/cm^3)	1.01–1.02	Samson (1989)
		Firmness	1.75–2	Samson (1989)
Melon	+	TSS	10	Mutton, Cullis, & Blakeney, 1981
		Firmness	1–2	Mutton, Cullis, & Blakeney, 1981
Papaya	+	TSS	11.5	Sankat and Maharaj (2001)
Pineapple	−	TSS	14	Smith (1988b)
			12	Bartholomew (2003)
		TA	≤ 1.0%	Kader (2002)
		TSS:acid	20:1–40:1	Bartholomew (2003)
		TSS: citric acid	19:1	Bartholomew (2003)
		Translucency	Optimum 50%–60% cross-sectional area	Bowden (1969)
		Specific gravity (g/cm^3)	0.960–1.004	Smith (1984)
Pome fruit	+			
(Apple)		TSS	Jonathan 11; Delicious and Red Delicious 10	Australian Horticultural Corporation, 1999
			12–14 (ripe)	Harker, Redgwell, Hallet, & Murray, 1997
			Starking and delicious 10.8–12.2	Truter and Hurndall (1988)
			High-quality dessert 14–16, cooking 11–13, Delicious and Spartan: 9–11	Goodenough and Atkins (1981)
		TSS (storage)	Delicious 10; Bonza 13; Golden Delicious 12; Gala 12.5; Granny Smith 12; Fuji 13; Pink Lady 15; Sundowner 14.5; Lady Williams 14.5	Australian Horticultural Corporation, 1999
		pH	High-quality dessert 3.2–3.5, cooking 2.8–3.2, Delicious and Spartan 3.5–3.7	Goodenough and Atkins (1981)
		Firmness	5.5 at sale, 6.5 storage	Australian Horticultural Corporation, 1999

(*Continued*)

TABLE 3.1 (Continued)

Fruit	Climacteric	Attribute	Level	References
(Pear)		TSS	12 (at optimal firmness, suitable TSS: acid ratio)	Harker, Redgwell, Hallet, & Murray, 1997
			13	Kader (2002)
		Firmness	Highly liked at 0.6–1.5; optimum at sale 1.3–1.5	Harker, Redgwell, Hallet, & Murray, 1997
		TSS:acid	2.85:1–3.31:1	Kappel, Fisher-Flemming, & Hogue, 1995
Stone fruit	+			
(Apricot)		TSS	10	Kader (2002)
		TA	0.8	Kader (2002)
(Cherry)	–	TSS	14–16 depending on cv.	Kader (2002)
(Nectarine)		TSS	10	Brady (1993)
			11	McGlasson (2001)
		TA	0.6	Kader (2002)
		Firmness	0.9–1.4	Crisosto (1994)
(Peach)		TSS	10	Brady (1993)
			11	McGlasson (2001)
		TA	0.6	Kader (2002)
		Firmness	0.9–1.4	Crisosto (1994)
(Plum)		TSS	11	McGlasson (2001)
			12	Kader (2002)
		Internal breakdown/TSS	Amber jewel 17% TSS for less internal breakdown	Ward and Melvin-Carter (2001)
		TA	0.8	Kader (2002)
		Firmness	0.9–1.4	Crisosto (1994)
Strawberry	–	TSS	7	Kader (2002)
		TA (citric)	0.8	Kader (2002)
Tomato	+	Moisture content (%fresh weight)	>94	Hobson and Davies (1971)
		Firmness	1.0–1.5	Kader and Morris (1976)

Attributes of dry matter (DM), juice content, total soluble solids (TSS), total acidity (TA), moisture content, and firmness are reported. DM, juice content, and TSS are minimum specifications; TA and firmness are maximum specifications. Units on DM, juice content, TSS, TA and firmness as %fresh weight, %fresh weight; %w/v of extracted juice, cmoH^{+}/kg in extracted juice, and kg/f with an 8 mm diameter plunger, respectively, except were otherwise stated.

can be influenced by firmness and acidity. This interaction has led to the development of indices that combine the measurable attributes. For example, the index "BrimA" (calculated as Brix minus a constant times the acidity level) was proposed by Jordan, Seelye, and McGlone (2001) and has been adopted into several commercial standards, for example, the "California Standard" for citrus.

3.8.2 Who enforces eating quality standards?

Generally national standards are set to address issues of product safety and biosecurity, leaving issues related to eating quality to individual value chains. However, developing nations that have a strong horticultural export industry may maintain national specifications that include eating quality attributes (e.g., a standard on citrus in The Philippines, Section 3.5.5). In Australia, government-enforced standards on eating quality attributes were largely phased out by the end of the 20th century. Before this, for example, Smith (1988a) reported random inspections of fruit in the central markets by government inspectors to enforce a minimum flesh TSS standard (of 12% for summer harvested fruit and 10% for winter harvested fruit) in pineapple fruit. Similarly, Greer (1990) detailed a legal requirement for a minimum TSS to acid ratio of 35:1 in lychee fruit. Fruit could be destroyed if these grades were not met.

Value chains, driven by the large retailers, have developed their own formalized quality control systems that extend to the setting of standards on eating quality criteria.

3.8.3 Setting and enforcing eating quality standards

Taste panel testing results (Table 3.1) inform the attribute levels set in specifications on fresh produce eating quality, as do the levels set in the specification of other bodies. In consequence, the specifications of two international bodies, the CAC and UNECE, and a national body, the Australian United Fresh Fruit and Vegetable Association, (AUF) show general agreement, although the CAC specifications are not as comprehensive as those of the other bodies (Table 3.2).

Within private distribution channels, the retailer generally establishes and enforces the most comprehensive eating quality specifications. Individual value chains may aim to maintain specifications on eating quality, and to influence the retailer to adopt that specification, to the disadvantage of their competitors. Industry Associations may also work with retailers to set specifications that advantage a particular commodity by preventing poor eating experiences and a related decline in sales of that commodity.

An example product specification from a retailer for mangoes covers size, external color, blemish incidence in terms of size and number, and in context of cause (chimera, insect, sap burn), firmness and DM (Fig. 3.5). Of these features, two relate directly to internal eating quality (firmness and DM).

The general level of agreement between specifications set on eating quality attributes by three retailers competing in one market (Table 3.3) indicates that these retailers are not seeking differentiation on the basis of product eating quality.

TABLE 3.2 Official grade standards on eating quality.

Fruit	Attribute	UNECE/OECD	Codex	AUF Story and Martyine (1996)	USA (California)
Avocado	DM at harvest	Hass 21 other 19	–	< 21; 21–23; >23	≥ 18.4–21.9 depending on cv.
Banana	–	–	–	–	–
Citrus					
(Grapefruit)	Juice content	–	35	–	–
(Lemon)	Juice content	25	–	30	≥ 28–30 depending on cv.
(Lime)	Juice content	–	42	–	–
(Mandarin)	TSS	–	–	8	–
	TSS:acid	–	–	8:1	6.5:1
	Juice content	33	–	28	–
(Orange)	TSS	–	–	7–9; 10–11; >11	–
	TSS:acid	Israeli market: pigmented 5.5:1 other 6:1; European market 6.5:1	–	Navel 8:1; other 8.1; 8:1–10.1; >10:1	8:1
	Juice content	Israeli market: Navel ≥ 30 other ≥ 35; European market: ≥ 38	Navel ≥ 33 other ≥ 35	Navel ≥ 30; other ≥ 33	–
Custard apple	–	–	–	–	–
Grape—table	TSS	–	–	–	14.0–17.5 depending on cv.
(Seedless)	TSS	14	–	≤ 14; 15–16; 17; ≥ 18	
(Seedless)	TSS:acid	–	–		≥ 20:1
(Seeded)	TSS	13 (12 some cv.)	–	≤ 14; 15–16; 18; >18	
Kiwifruit	TSS (at harvest)	6.2	–	6	6.5
	Firmness	–	–	1.0; 1.5; 2.0; 2.5	–

(*Continued*)

TABLE 3.2 (Continued)

Fruit	Attribute	UNECE/OECD	Codex	AUF Story and Martyine (1996)	USA (California)
Lychee	–	–	–	–	–
Mango	DM	–	–	14	–
Melon	TSS	10 Charentais; 8 other	–	Honeydew ≤ 10; 10–12; >12	Cantaloupe > 8.0, >9.0
				Rockmelon ≤ 9; 9–12; >12	honeydew 10
Papaya	–	–	–	–	–
Pineapple	TSS	12	12	< 10; <12; >12	–
Pome fruit					
(Apple)	TSS	–	–	Fruit for storage ≤ 10; 11; 12; ≥ 13	Jonathan 12
		–	–	Immediate sale < 10; 10; 11; ≥ 12	Red delicious 11.0
	Firmness	–	–	Fruit for storage ≤ 5.5; 6.0; ≥ 6.5	Jonathan 8.6
				Immediate sale ≤ 5.5; 6.0; ≥ 6.5	Red delicious 8.2
(Pear)	TSS	–	–	–	13
	Firmness	–	–	–	10.4
Stone fruit					
(Cherry)	TSS	–	–	–	≥ 14–16 dep cv.
Strawberry	–	–	–	–	–
Tomato	–	–	–	–	–

Attributes and units as for Table 3.1. Where a single value is presented, only two grades exist (unacceptable/acceptable). Where further values are presented, a number of grades are possible.

AUF, Australian United Fresh Fruit and Vegetable Association; *DM*, dry matter content; *OECD*, Organization for Economic Cooperation and Development; *TSS*, total soluble solids; *UNECE*, United Nations Economic Commission for Europe.

From UNECE http://www.unece.org/trade/agr/standard/fresh/fresh_e.htm. Codex http://www.codexalimentarius.net. AUF Story, A. and Martyine, A. (1996) AUF National Product Description Language. The Australian United Fresh fruit and Vegetable Association, Flemington Market, Australia. ISBN 0 959388 22 2.

TABLE 3.3 Specifications on eating quality attributes of fresh fruit, except apple, as set by three retailers.

Fruit	Attribute	Retailer 1	Retailer 2	Retailer 3
Avocado	DM	Hass 22–26; Shepard 23	21–35	–
	Firmness	–	–	–
Banana	Dry matter	–	–	–
	TSS	–	–	–
Blueberry	TSS	–	10	–
Citrus				
(Grape fruit)	TSS	9	9	–
	TSS:acid	–	4.8:1	–
	Juice content	35	33	–
(Lemon)	Juice content	30	10	–
(Lime)	Juice content	20	10	–
(Mandarin)	TSS	Ellendale 8; Honey Murcott, Imperial 10	9	10
	TSS:acid	Ellendale 7:1, Honey Murcott, Imperial 10:1	8:1; Clementine 7:1	–
	Juice content	33	33	–
(Orange)	TSS	Navel 11; Valencia 7	9	10
	TSS:acid	Navel 8:1; Valencia 7.5:1	8:1; Valencia 7:1	–
	Juice content	33	33; Navelina, Sevile 25	–
Custard apple		–	–	–
Grape—table	TSS	16; Thompson 18; Sweet White seedless 15; Muscatel White 20	16; Calmenia, Red Gum, Ribier 15; Cardmal, Italia, Marro seedless 17	15
	TSS:acid	Seedless: Sweet White 20:1; Crimson, Thompson 19:1; Stanley, Flame 18:1	18:1; Thompson 19:1	–

Attributes and units as for Table 3.1.

3.8.4 Examples of eating quality standards

In the following section, specifications related to eating quality standards are considered for two widely traded commodities, apple, and stone fruits, in terms of the scientific literature, intergovernmental and NGO standards, and retailer specifications.

3.8.4.1 *Pome fruit—apple*

It is generally accepted that fruit TA, TSS, and firmness of flesh are important eating quality factors for apples (e.g., Chen & De Baerdemaeker, 1993; Harker, 2001; Harker, Gunson, & Jaeger, 2003; Yahia, 1994). Malic acid is responsible for the sour and acid taste in apple (Yahia, 1994). Harker (2001) reported on a close relationship between TA and acid taste in apples, although the relationship between TA and consumer acceptability was cultivar specific.

Sweetness in apples is related to sucrose, glucose, and fructose content, with 50% of the sugar present being fructose (Yahia, 1994). Eating quality specifications have historically been set in terms of TSS of extracted juice of ripened fruit. For example, Goodenough and Atkin (1981) recommend that high-quality dessert apples should have a high TSS (14%–16%) relative to "Delicious" and "Spartan" cultivars (9%–11%). Harker (2001), however, contended that, while TSS is a good sweetness indicator for juices and other fruits, it is not for apples. This contention is based on sensory research in which the relationship between perceived sweetness and TSS was poorer than the relationships between perceived texture and puncture force, or perceived acid taste and TA, in apples. This result is suggested to be due to the level of flavor volatiles that alter the perception of sweetness. Returning to the importance of carbohydrate levels to flavor development, Palmer, Harker, Tustin, and Johnston (2010) recommend fruit dry matter concentration as a new quality metric for apples. Nonetheless, apple TSS is widely specified in both official (Table 3.2) and value chain (Table 3.4) standards, with more differentiation by cultivar than seen for any other commodity. The minimum suggested TSS for apples ranges between 12% and 14% (Tables 3.1 and 3.4).

Apple crispness and juiciness are key attributes in determining consumer preferences. Harker, Gunson, Brookfield, and White (2002) report that penetrometer measurements are good predictors of such textural perceptions. Further, Harker et al. (2002) report that apples with a firmness level <5.0 kgf (11 mm diameter probe) are more susceptible to the development of the mealiness (texture) disorder, while fruits with a firmness value greater than 7 kgf are effectively free of the disorder.

The Australian Horticultural Corporation (Table 3.2) recommends different flesh firmness and TSS levels depending on cultivar and whether the fruit is at point of sale or intended for long-term controlled atmosphere storage. For example, flesh firmness (measured using a 11 mm diameter plunger) of no less than 6.5 kgf was recommended for apples for long-term storage, and less than 5.5 kgf for fruit at the point of sale. A Californian standard on "Jonathan" and "Red Delicious" apples sets a minimum TSS of 12% and 11%, respectively, and a maximum firmness of 8.6 and 8.2 kgf, respectively. In practice, value chains vary TSS and firmness specifications by variety and stage of ripeness (e.g., https://riveridgeproduce.com/for-our-retailers/, accessed October 24, 2020).

No specifications are set on apple eating quality–related attributes in the UNECE or Codex guidelines. In contrast, Australian retail stores specify TSS levels for over 20

TABLE 3.4 Specifications on eating quality attributes for apple fruit as set by three retailers.

Retailer	TSS			Firmness		
	1	**2 In season (CA)**	**3**	**1**	**2 In season (CA)**	**3 Feb–Aug (Sept–Jan)**
Apple						
Abas	–	13	–	–	5.8–6.0	–
Akane	11.5	13	–	5.6	5.8–6.0	–
Bonza	12.6	12	12	5.6	5.3–5.5	5.5 (5)
Braeburn	14	15	11.5	6.5	5.8–6.0	6 (5)
Cameo	12	12	–	–	6.8	–
Cox Orange	–	14	–	–	5.8–6.0	–
Crofton	–	14	–	–	5.8–5.8	–
Firmgold	–	12.8	–	–	5.8–6.0	–
Fuji	13	14	13	5.6	5.6–5.8	6 (5)
Golden	12.5	–	12	5.5	–	6 (5)
Golden delicious	–	12.8	–	–	5.8–6.0	–
Granny Smith	–	11	12.5	–	6.3–6.5	6.5 (5.5)
Gravensten	–	12	–	–	5.8–6.0	–
Johnagold	13.6	14	13	6	5.8–6.0	6 (5)
Johnathan	12.6	11.5	13	5.6	5.6–5.8	6 (5)
Lady William	14	12.5	14.5	6.5	6.2–6.4	6.5 (6)
Matsu	–	11	–	–	6.8–7.0	–
Pink Lady	14	13.5	14	6.3	5.8–6.0	6 (5)
Red Delicious	12	12	10	6	5.8–6.0	6.5 (6)
Royal Gala	12.6	12	12	6.5	5.8–6.0	6 (5)

(*Continued*)

TABLE 3.4 (Continued)

Retailer	TSS 1	TSS 2 In season (CA)	TSS 3	Firmness 1	Firmness 2 In season (CA)	Firmness 3 Feb–Aug (Sept–Jan)
Stark Blushing Gold	–	12	–	–	5.8–6.0	–
Sundowner	13	12.8	14.5	6.5	5.9–6.1	6 (5.5)
Toffee Apple	–	11	–	–	–	–
Pear						
Buerre Bosc	13	11 (12)	–	6.3–8.0	6.0–9.0 (4.0–8.0)	–
Packham	11	–	–	6.0–8.0	–	–
Packham Ripe and Ready	13	12	–	4.0–4.5	4.0–6.0 (3.0–5.0)	–
Red Sensation	11.5	–	–	6.0–8.0	–	–
Sensation	–	11	–	–	5.0–9.0 (4.5–8.0)	–
Sirrera	–	12	–	–	8.0–10.0 (5.0–10.0)	–
Sophia Pride	–	11 (12)	–	–	6.0–9.0 (4.0–8.0)	–
William	11	–	–	6.3–9.0	–	–
Ya	9	–	–	6.0–8.0	–	–
Other	–	11 (12)	–	–	6.0–9.0 (4.0–8.0)	–

Attributes and units as for Table 3.1. Retailer 2 specified standards for fruit in season and for fruit going into controlled atmosphere storage (values in parentheses).

cultivars of apples (Table 3.4). These specifications varied slightly between retail chains. For example, the minimum TSS required for "Akane" apples is 11.5% and 13% for two retailers.

3.8.4.2 Stone fruits—peaches, nectarines, and plums

The eating quality of peaches, nectarines, and plums is usually described in terms of flesh texture and firmness, TSS, and acidity. Sucrose is the dominant sugar in peaches, nectarines, and plum fruits, accounting for at least 80% of total sugars (Lill, O'Donoughue, & King, 1989). The predominant organic acid in peaches and nectarines is malic acid (Lill et al., 1989).

Lill et al. (1989) suggested that flesh firmness in conjunction with background color was a reliable indicator of the picking maturity for peaches and nectarines, with a firmness of 5−7 kgf (11 mm plunger) recommended. Further, Crisosto (1994) reported that for peaches, nectarines, and plums, flesh firmness was a useful indicator of postharvest ripening. Peaches with a firmness rating of 2.7−3.6 kgf were "ready to buy," and "ready to eat" at a flesh firmness of 0.9−1.4 kgf.

As a specification on eating quality, McGlasson (2001) recommended a minimum of 11% TSS for peaches, nectarines, and plum fruits produced in Australia, whilst Kader (2002) suggested a minimum TSS of 10% for apricots and peaches, 14%−16% (depending on cultivar) for cherry, and 12% for plum fruits. As noted earlier, Crisosto et al. (2007) have further differentiated consumer groups in terms of preferred TSS levels.

The commercial release of low acid lines of fruit, complimenting the traditional high acid varieties, represents a comment on consumer sweetness preference as much as a preference for low acidity. For fruit of a given TSS level, a lower acidity level increases the perceived sweetness.

Internal breakdown is a physiological disorder of a stone fruit that negatively impacts eating quality. The disorder results from the abnormal ripening and early senescence of the fruit, with symptoms usually occurring during cold storage or during ripening after cold storage. Ward and Melvin-Carter (2001) reported that symptoms in plums appear as internal browning and gel breakdown. Fruits with TSS $\geq 17\%$ were noted to have a significantly reduced risk of developing internal breakdown symptoms, although incidence could be decreased if fruits were appropriately cooled on the day of harvest.

UNECE stone fruit specifications (Table 3.2) are subjective, for example, "they must be sufficiently developed and display satisfactory ripeness." Codex and AUF maturity grades are based on firmness descriptors ("hard," "firm," etc.), with infrequent mention of internal quantitative measures or recommendations (Table 3.2).

Of three retailers surveyed, one retailer provided comprehensive TSS and firmness standards on stone fruits compared to the other retailers, differentiating between cultivars differing in flesh color (Table 3.3). For example, the minimum TSS recommended for yellow flesh (10% TSS) nectarines was lower than that for white flesh (12% TSS) varieties, while the firmness standard of 5.2 kgf was common across all varieties. A second retailer gave only an "all-variety" minimum TSS of 10% and a firmness of 4 kgf, while a third retailer did not specify for TSS in stone fruits (Table 3.3). Of two European retailers surveyed (data not shown), one maintained a minimum TSS of 9% and firmness of 1.4−3.5 kgf for nectarines, while the second provided TSS grades for plums based on color (black plum: 12% TSS and 1.8−3.6 kgf; red plum: 10% TSS and 1.4−2.3 kgf; yellow plum 14% TSS and 1.0−1.8 kgf).

3.8.5 The future for eating quality standards

From the examples provided, it is evident that specifications on eating quality are inconsistent. Florkowski (1999) noted that "intrinsic quality attributes" are not reflected in grading systems and are excluded from fresh produce standards. Florkowski (1999) continues "this gap leaves a place for government as a monitoring, regulatory or even enforcing agency." However, this is only likely for specific commodities and in nations with a strong export industry, that is, where there is a "national" brand to protect (as in The Philippines example). Without such a drive, governments are likely to regulate on issues of food safety and not eating quality. Eating quality specifications are, however, critical to value chains to maintain consumer satisfaction.

The established techniques for the assessment of these attributes are destructive of fruits, severely limiting sampling effort. In the last decade, a technology for noninvasive assessment of TSS and DM of fruit and vegetables has become commercially established, operating both on-packline and in a handheld format (e.g., Walsh, Blasco, Zude-Sasse, & Sun, 2020; Walsh, McGlone, & Han, 2020). Other technologies hold promise for noninvasive assessment of fruit firmness and volatiles.

IX. A Case study—technology and mango eating quality

The question of what limits technology adoption must be considered using a systems approach. Such an approach aids the identification of critical steps in a system and provides a tool for the integration of specific knowledge into a system (Prussia & Shewfelt, 1992).

Our research group has been involved in implementing the use of near-infrared spectroscopy (NRS) in noninvasive assessment of fruit quality under Western agricultural conditions (lower cost, higher packline speeds) (e.g., Golic & Walsh, 2005; Subedi, Walsh, & Owens, 2007; Walsh, Long, & Middleton, 2006; Fig. 3.11). Our experience with the adoption of this technology informs the following discussion.

The sweetness grading (NIRS) technology has been in extensive use in other industries, notably the cereal, sugar, and dairy industries since the 1970s. Thus, although the technology was not mature in the horticultural application, intending horticultural participants had access to technical advisors from both industry and government sectors.

An Australian product supply manager gained exclusive rights to a particular mango cultivars and sought to maintain market profile through ensuring that consumers had good eating experience. Based on taste panel work, it was established that a minimum DM at harvest of 15% was required.

NIRS technology was initially used on fruit grading equipment. However, grading on DM after harvest meant a lower value line of "under specification" produce was created. The technology was also disruptive of packinghouse operations, creating a doubling of lines, for example, two dry matter levels sorted to five size standards creates 10 lines, requiring more pack-out points on the packline, and more pallet lines in the cold room.

NIRS technology was adopted in a handheld format, with use in field to inform the decision to harvest. Harvest of fruit below specification could be left on tree longer, allowing carbohydrates to accumulate

(*cont'd*)

further. Thus this use of the technology allowed for management of attribute level, rather than merely grading. Enforcement of the specification within the value chain contributed to consumer satisfaction and the establishment of the cultivar in the market.

The Mango Industry Association subsequently advocated for the use of the technology generally and commissioned taste panel work to establish minimum dry matter levels for other cultivars. Industry Association officers in the different growing areas were equipped with the portable technology and were available for farm visits, on request. The Association also commissioned random testing of consignments arriving into the major central markets using the technology and published results in a "name and shame" exercise in the industry newsletter. Additionally, the Association also supplied information to major retailers, influencing reviews of their standards to include a dry matter rather than a TSS specification.

Thus the availability of (noninvasive) technology influenced the setting of specifications.

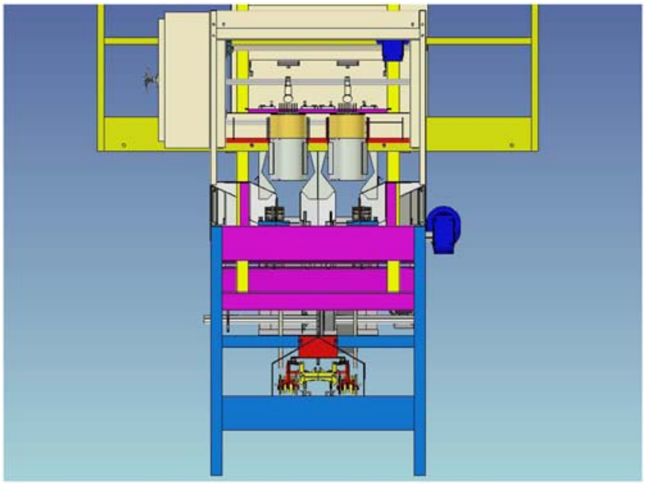


FIGURE 3.11 Diagram of sorting line employing NIR-based grading of sweetness (TSS or dry matter). *NIR*, near infrared; *TSS*, total soluble solids.

3.9 Future regulation

Convergence of heavy metal, chemical residue, and microbiological (phytosanitary) standards has been driven by national and intergovernmental agencies such as UNECE and the OECD, with the Codex Alimentarius emerging as a global minimum standard. Common processes to deal with quarantine issues have developed under the WTO. Consolidation of organic standards is occurring. This trend to harmonization of standards is expected to continue. For example, the IFOAM organic specifications could be mainstreamed into Codex.

Regulation is introduced to address a problem, and so as new social drivers emerge, regulations will evolve. Trends in media reports suggest that there will be future regulatory activity in terms of food safety, nutrition claims, and marketing claims.

Initially the Codex Alimentarius was focused to food hygiene, then focus shifted to chemical residues on fresh produce. Success of related regulation has minimized this issue in Western markets, and focus now shifts to microbiology. For example, the CAC reports that its consumer protection elements are gaining in importance, while the "compositional" elements of individual commodity standards do not appear to attract as much interest as before (CAC, 2020c). It is noted that future direction depends on community attitudes and demands.

The issues of an aging population and of an increasingly sedentary lifestyle and poor diet predispose populations to be less tolerant of microbiological challenges. This provides drivers for increased regulation with respect to food safety. Increased traceability, including use of blockchain technology, is likely to become embedded in standards. However, the stringency of regulations to protect health must be weighed against compliance cost and evasion. Florkowski (2019) warns that over-stringent food safety regulations will result in a parallel distribution system that trades produce outside regulated channels (e.g., farmers markets in developed countries). Negative impact on small growers due to compliance burden and a production trend to use of sterile "plant factories" were also foreshadowed.

The use of nutritionally and functionally enhanced fruit and vegetables is likely to increase, driving need for further regulation of market claims. Health benefit claims require approval by the Food and Drug Administration in the United States and by the Therapeutic Goods Administration in Australia.

Issues related to labeling of the carbon cost of production may become regulated. With increasing population and increased industrialization, urbanization, and competition for water, some markets might require labeling for water efficiency. This could take the form of a water efficiency star rating (ML/t).

The rise of on-line ordering of groceries is a trend greatly accentuated during the COVID 19 pandemic of 2020 that comes with a new set of issues as the consumer buys on the strength of a web site picture. The future may hold a requirement to link back to information on the history of the consignment, to satisfy consumer need for food safety traceability and interest in production issues (carbon or water cost, residue information etc.). Already Dole offered links to pictures and information on the farm supplying the product (http://www.doleorganic.com, accessed October 24, 2020), and various businesses are jostling to provide you information via your 3G phone (e.g., Locavore provides information on closest farmers markets and produce; http://www.getlocavore.com/ accessed October 24, 2020).

In conclusion, regulatory environment of the next decade will evolve from that outlined in this chapter. The complex web of forces at play will result in a change of regulations—hopefully in ways that better match products to their respective market niches.

Acknowledgment

My thanks to Wojciech Florkowski for encouragement and feedback in the preparation of this chapter. The efforts of Robert Long, now a graduated PhD student, in preparation of the tables is also acknowledged.

References

Agricultural Marketing Service—USDA (2020a). AMS Fruit and Vegetable Programs. https://www.ams.usda.gov/rules-regulations/paca. Accessed 18.10.20.

Agricultural Marketing Service—USDA (2020b) https://www.ams.usda.gov/services/sci/fresh-products. Accessed 18.10.20.

Agrilink. (2001). *Avocado information kit*. Nambour, QLD: Department of Primary Industries.

Australian Government—Department of Foreign Affairs and Trade (2013) Australia-United States free trade agreement chapter three—Agriculture. https://www.dfat.gov.au/about-us/publications/trade-investment/australia-united-states-free-trade-agreement/Pages/chapter-three-agriculture. Accessed 15.11.21.

Australian Quarantine Inspection Service (2013a) About AQIS. http://www.daff.gov.au/biosecurity doa: 22 July 2013.

Australian Horticultural Corporation. (1999). *Guide to quality management—Apples*. Sydney: Australian Horticultural Corporation.

Baldwin, E. A. (1993). Citrus fruit. In G. B. Seymour, & G. A. Tucker (Eds.), *Biochemistry of fruit ripening* (pp. 107–149). London: Chapman and Hall.

Bally, I., Johnson, P., & Kulkami, V. (2000). Mango production in Australia. *Acta Horticulturae*, *509*, 59–67.

Bartholomew, D. P. (2003). *The pineapple, botany, production and uses*. New York: CABI Publishing.

Batten, D. J. (1989). Maturity criteria for litchis (lychees). *Food Quality and Preference*, *1*, 149–155.

Bowden, R. P. (1969). Further studies on ripeness in pineapples. *Food Technology in Australia*, *21*, 160–163.

Brady, C. J. (1993). Stone fruit. In G. B. Seymour, & G. A. Tucker (Eds.), *Biochemistry of fruit ripening*. London: Chapman and Hall.

BRI (2001) British Standards Institute: BS 7373–1:2001 Product specifications. Guide to preparation. https://www.thenbs.com/PublicationIndex/documents/details?Pub = BSI&DocID = 253264. Accessed 22.10.20.

Bruckner, B., & Grant Wyllie, S. (Eds.), (2008). *Fruit and vegetable flavours. Recent advances and future prospects*. Boca Raton, FL: CRC Press.

Cheah, L. H., & Irving, D. E. (1997). Kiwifruit. In S. K. Mitra (Ed.), *Postharvest physiology and storage of tropical and subtropical fruit*. New York: Cab International.

Chen, H., & De Baerdemaeker, J. (1993). Effect of apple shape on acoustic measurements of firmness. *Journal of Agricultural Engineering Research*, *56*, 253–266.

Choon, S. C., & Choo, C. G. (1972). Comparative evaluations of some quality aspects of banana *Musa acuminata* (Colla) I. Flavour, sources and sweetness. *Malaysian Journal of Agricultural Research*, *1*, 54–59.

CoA (2016) The administration by the Department of Agriculture, Fisheries and Forestry of the citrus canker outbreak. Commonwealth of Australia Senate inquiry. ISBN 0 642 71657 9 https://www.aph.gov.au/Parliamentary_Business/Committees/Senate/Rural_and_Regional_Affairs_and_Transport/Completed_inquiries/2004-07/citrus_canker/report/index. Accessed 15.10.20.

Codex Alimentarius Commission (2020a) Welcome. http://www.fao.org/fao-who-codexalimentarius/en/. Accessed 18.10.20.

Codex Alimentarius Commission (2020b) Strategic Framework: Strategic objectives and priorities. http://www.fao.org/3/Y2361e/y2361e03.htm. Accessed 18.10.20.

Codex Alimentarius Commission (2020c) http://www.fao.org/3/w9114e/w9114e00.htm. Accessed 18.10.20.

Collen, C. (2007) Mounting food safety scares spur organic demand in China. Asiafruit Magazine July/August, p. 120.

Crisosto, C. H. (1994). Stone fruit maturity indices: A description review. *Postharvest News and Information*, *5*, 65–68.

Crisosto, C. H., Crisosto, G. M., Echeverria, G., & Puy, J. (2007). Segregation of plum and pluot cultivars according to their organoleptic characteristics. *Postharvest Biology and Technology*, *44*, 271–276.

Davies, F. S. (1986). The navel orange. *Horticultural Reviews*, *8*, 129–180.

DAWR (2020a) Horticultural code of conduct. https://www.agriculture.gov.au/ag-farm-food/hort-policy/code-of-conduct. Accessed 18.10.20.

DAWR (2020b) Mangoes from the Philippines. https://www.agriculture.gov.au/biosecurity/risk-analysis/plant/mangoes-phillippines. Accessed 18.10.20.

Department of Home Affairs (2020) Working holiday maker visa program https://data.gov.au/data/dataset/visa-working-holiday-maker/resource/e2e66b90-211b-4e6b-8f55-54b9ac45faf7?view_id = 2462307b-a092-4ce2-a30c-3ccaadce99f4. Accessed 17.10.20.

European Commission (2020) Aims of EU quality schemes. https://ec.europa.eu/info/food-farming-fisheries/food-safety-and-quality/certification/quality-labels/quality-schemes-explained_en. Accessed 18.10.20.

Fellars, P. J. (1985). Citrus: Sensory quality as related to rootstock, cultivar, maturity and season. In H. E. Pattee (Ed.), *Evaluation of quality of fruits and vegetables*. Westport: AVI Publishing.

Firth, S. (2006). In S. Firth (Ed.), *Globalisation and governance in the Pacific Islands*. Canberra, ACT: ANU Press.

Florkowski, W. J. (1999). Economics of quality. In R. L. Shewfelt, & B. Bruckner (Eds.), *Fruit and vegetable quality: An integrated approach*. Lancaster, PA: Technomic Publishing Co., Inc.

Florkowski, W. J. (2019). Consumers and consumption of fruits and vegetables: Who wants more of a good thing? In M. Swainson (Ed.), *Swainson's handbook of technical and quality management for the food management sector*. Duxford: Woodhead Publishing, Elsevier, Ch. 16. Available from https://doi.org/10.1016/B978-1-78242-275-4.00016-2.

Food Standards Australia New Zealand (2020) About FSANZ. https://www.foodstandards.gov.au/about/Pages/default.aspx. Accessed 18.10.20.

Given, N. K. (1993). Kiwifruit. In G. B. Seymour, & G. A. Tucker (Eds.), *Biochemistry of fruit ripening*. London: Chapman and Hall.

Golic, M., & Walsh, K. B. (2005). Robustness of calibration models based on near infrared spectroscopy to the in-line grading of stonefruit for total soluble solids. *Analytica Chimica Acta*, *555*, 286−291.

Goodenough, P. W., & Atkin, P. K. (1981). *Quality in stored and processed vegetables and fruits*. New York: Academic Press.

Greer, N. (1990). *Growing lychee in South Queensland*. Brisbane: Queensland Department of Primary Industries.

Growcom (2020). About us. https://www.growcom.com.au/about/. Accessed 18.10.20.

HACCP Australia (2020) HACCP based food safety programs and endorsements. https://www.haccp.com.au/. Accessed 18.10.20.

Harker, F. R. (2001) Consumer responses to apples. In *Washington fruit trees postharvest conference*. March 13−14, 2001, Wenatchee, WA, USA.

Harker, F. R., Gunson, F. A., Brookfield, P. L., & White, A. (2002). An apple a day: The influence of memory on consumer judgement and quality. *Food Quality and Preference*, *13*, 173−179.

Harker, F. R., Gunson, F. A., & Jaeger, S. R. (2003). The case for fruit quality: An interpretative review of consumer attitudes and preferences for apples. *Postharvest Biology and Technology*, *28*, 333−347.

Harker, F. R., Redgwell, R. J., Hallet, I. C, & Murray, S. H. (1997). Texture of fresh fruit. *Horticultural Reviews*, *20*, 121−223.

Hobson, G. E., & Davies, J. N. (1971). The tomato. In A. C. Hulme (Ed.), *The biochemistry of fruits and their products* (Vol. 2, pp. 347−482). London: Academic Press.

Hou, Y. (2019). Protecting new plant varieties in china and its major problems. In K. C. Liu, & U. Racherla (Eds.), *Innovation, economic development, and intellectual property in India and China*. Singapore: Springer, ARCIALA Series on Intellectual Assets and Law in Asia. Available from https://doi.org/10.1007/978-981-13-8102-7_14.

IP Australia (2020) Understanding IP: IP protection in China. https://www.ipaustralia.gov.au/understanding-ip/taking-your-ip-global/ip-protection-china/plant-variety-rights-in-china. Accessed 22.10.20.

Jen, J. J. (Ed.), (1989). *Quality factors of fruit and vegetables*. Washington, DC: American Chemical Society.

Jordan, R. B., Seelye, R. J., & McGlone, V. A. (2001). Sensory-based alternative to Brix/acid ratio. *Food Technology*, *55*, 36−44.

Kader, A. A. (2002). Standardisation and inspection of fresh fruits and vegetables. In A. A. Kader (Ed.), *Postharvest technology of horticultural crops* (pp. 287−299). Oakland: University of California.

Kader, A.A., Morris, L.L., Tomato firmness as a quality attribute. In *Proceedings of the second tomato quality workshop*. University of California, Davis, 1976.

Kappel, F., Fisher-Flemming, R., & Hogue, E. J. (1995). Ideal pear sensory attributes and fruit characteristics. *HortScience*, *30*, 988−993.

Lill, R. E., O'Donoughue, E. M., & King, G. A. (1989). Postharvest physiology of peaches and nectarines. *Horticultural Reviews*, *11*, 413−452.

Lockie, S., Lyons, K., Lawrence, G., & Halpin, D. (2006). *Going organic. Mobilizing networks for environmentally responsible food production*. Cambridge, MA: CABI.

Marsili, R. (1997). *Techniques for analyzing food aroma*. New York: Marcel Dekker.

McGlasson, B. (2001). Editorial. *Australian fresh stone fruit quarterly*, *3*, 2.

McManus, W. (2018) Delivering customer value in fresh fruit and veg—A guide to setting and maintaining quality specifications. http://www.wrap.org.uk/qualityspecsguidance.

Mitchell, F. G., Mayer, G., & Basi, W. (1991). Effect of harvest maturity on storage performance of 'Hayward' Kiwifruit. In I. J. Warrington, et al. (Eds.), *Proceedings of the II International Symposium on Kiwifruit* (Vol. 297, pp. 617−625). ISHS

Mutton, L. L., Cullis, B. R., & Blakeney, A. B. (1981). The objective definition of eating quality in rockmelons (*Cucumis melo*). *Journal of the Science of Food and Agriculture*, *32*, 385−390.

Narassimhan, E., & Gallagher, K. S. (2018). Carbon pricing in practice: A review of existing emissions trading systems. *Climate Policy*, 1−25. Available from https://doi.org/10.1080/14693062.2018.1467827.

NSW DPI (2018) Listeria outbreak investigation—Summary report for the melon industry, October 18. NSW Department of Primary Industries (NSW DPI) https://www.foodauthority.nsw.gov.au/sites/default/files/_Documents/foodsafetyandyou/listeria_outbreak_investigation.pdf. Accessed 19.10.20.

OECD (2020) OECD Fruit and vegetables scheme. https://www.oecd.org/agriculture/fruit-vegetables/. Accessed 18.10.20.

Palmer, J. W., Harker, F. R., Tustin, D. S., & Johnston, J. (2010). Fruit dry matter concentration: A new quality metric for apples. *Journal of the Science of Food and Agriculture*, *90*, 2586−2594.

Pascale, A. M. (1992). Quality in the fruit and vegetable sector: EEC regulations and influence of quality on trade and processing. *Options Mediterraneennes. Seie A, Seminaires Mediterraneens*, *19*, 89−97.

Philippine National Standards (2020) Philippine National Standard on Mandarin (ICS 065.020.20) http://www.bafs.da.gov.ph/images/Approved_Philippine_Standards/PNS-BAFS57-2007-FreshFruits-Mandarin-GradingandClassification.pdf. Accessed 18.10.20.

Pineiro, M., & Diaz, L. B. (2007). Improving the safety and quality of fresh fruit and vegetables (FFV): A practical approach. In A. N. Fardous, W. Schnitzler, & M. Qaryouti (Eds.), *ISHS acta horticulturae 741: I international symposium on fresh food quality standards: Better food by quality and assurance*. ISBN 978-90-66053-28-1. Available from http://www.actahort.org/books/741/741_1.htm.

Prussia, S. E., & Shewfelt, R. L. (1992). A systems approach to postharvest handling. *Postharvest handling. A systems approach*. Academic Press, Ch. 3.

Sale, P. R. (1985). In D. A. Williams (Ed.), *Kiwifruit culture*. Wellington: New Zealand Government Printer.

Samson, J. A. (1989). *Tropical fruits*. Singapore: Longman Scientific and Technical.

Sankat, C. K., & Maharaj, R. (2001). Papaya. In S. K. Mitra (Ed.), *Postharvest physiology and storage of tropical and subtropical fruits* (pp. 167−189). New York: CAB International.

Satyan, S. H. & Chaplin, A. (1986). An assessment of fruit quality of various mango cultivars. In *Proceedings of the first Australian mango research workshop*, Carins, Queensland, 1986, pp. 324−333.

Scrimgeour, F. & Sheppard, R. (1998). An economic analysis of the deregulation of selected Israeli, South African and South American Producer Boards, *A report prepared for MAF policy by MAF policy information paper no. 20* ISSN 1171 4654 ISBN 0−478-07497-2.

Seymour, G. B., & Tucker, G. A. (1993). Avocado. In G. J. Seymour, et al. (Eds.), *Biochemistry of fruit ripening* (pp. 53−81). London: Chapman and Hall.

Shewfelt, R. L., & Bruckner, B. (Eds.), (2000). *FruIT AND VEGETABLE QUALity*. Lancaster, PA: Technomic Publishing, ISBN 1−56676-785-7.

Smith, L. G. (1984). Pineapple specific gravity as an index of eating quality. *Tropical Agriculture (Trinidad)*, *61*, 196−199.

Smith, L. G. (1988a). Indices of physiological maturity and eating quality in smooth cayenne pineapples. Indices of eating quality. *Queensland Journal of Agricultural and Animal Sciences*, *45*, 219−228.

Smith, L. G. (1988b). Indices of physiological maturity and eating quality in smooth cayenne pineapples. 1. Indices of physiological maturity. *Queensland Journal of Agricultural and Animal Sciences*, *45*, 213−218.

SSCoE (2016) Senate Standing Committee on Economics. Agribusiness managed investment schemes. Bitter harvest. https://www.aph.gov.au/parliamentary_business/committees/senate/economics/mis/Report. Accessed 18.10.20.

Story, A., & Martyine, A. (1996). *AUF national product description language*. The Australian United Fresh fruit and Vegetable Association, ISBN 0 959388 22 2.

Subedi, P., Walsh, K. B., & Owens, G. (2007). Prediction of mango eating quality at harvest using short wave near infrared spectroscopy. *Postharvest Biology and Technology*, *43*, 326−334.

Suri, N. (2020) Australia-China relations: The great unravelling. ORF issue brief no. 366, June. Observer Research Foundation. ISBN 978-93-90159-20-8. https://www.orfonline.org/wp-content/uploads/2020/06/ORF_IssueBrief_366_China-Australia.pdf.

Svebestad, E. & Botheim, H. (2020). Implications of a carbon tax in the Norwegian greenhouse sector: A case study of Wiig Gartneri (Masters thesis). Norwegian University of Life Sciences, Ås, Norway. https://hdl.handle.net/11250/2682082.

SAWTEE (2016) A study of vegetable and fruit export from Eastern Region of Nepal. South Asia watch on trade, economics and environment. http://www.sawtee.org/publications/Research-Brief-6.pdf. Accessed 18.10.20.

Tasmania—Department of Primary Industries and Water (2020) History of platypus fungal disease https://dpipwe.tas.gov.au/wildlife-management/fauna-of-tasmania/mammals/echidnas-and-platypus/platypus/platypus-fungal-disease#:~:text=on%20platypus%20populations.-,History%20of%20platypus%20fungal%20disease,amphibiorum%20was%20positively%20identified5. Accessed 18.10.20.

Tesco (2013) Greener living—what we are doing. https://www.tescoplc.com/sustainability/documents/policies/our-carbon-footprint-recalculation-policy/. Accessed 15/11/21.

Tesco (2020) Our carbon footprint recalculation policy. https://www.tescoplc.com/sustainability/publications/policies/downloads/recalculation-policy/. Accessed 18.10.20.

Truter, A. B., & Hurndall, R. F. (1988). New findings on determining maturity of 'Starking', 'Tropical' and 'Starkrimson' apples. *Deciduous Fruit Grower*, *38*, 26−29.

Underhill, S. J. R., & Wong, L. S. (1990). A maturity standard for lychee (*Litchi Chinensis* Sonn.). In R. E. Paull (Ed.), *Proceedings of the symposium on tropical fruit in international trade* (Vol. 269, pp. 181−187).

United Nations Economic Commission for Europe (2020a) Trade program. http://www.unece.org/tradewelcome/trade-programme.html. Accessed 18.10.20.

United Nations Economic Commission for Europe (2020b) Working party on agricultural standards. http://www.unece.org/trade/agr/welcome.html. Accessed 18.10.20.

Valero, C., & Ruiz-Altisent, M. (2000). Design guidelines for a quality assessment system of fresh fruits in fruit centres and hypermarkets. *Agricultural Engineering International*, *2*, 1−20.

Walsh, K. B., Blasco, J., Zude-Sasse, M., & Sun, X. (2020). Visible-NIR 'point' spectroscopy in postharvest fruit and vegetable assessment: The science behind three decades of commercial use. *Postharvest Biology and Technology*, *168*, 111246.

Walsh, K. B., Long, R., & Middleton, S. (2006). Use of near infra-red spectroscopy in evaluation of source-sink manipulation to increase stonefruit soluble sugar content. *Journal of Horticultural Science and Biotechnology*, *82*, 316−322.

Walsh, K. B., McGlone, V. A., & Han, D. H. (2020). The uses of near infra-red spectroscopy in postharvest decision support: A review. *Postharvest Biology and Technology*, *163*, 111139.

Ward, G., & Melvin-Carter, E. (2001) Strategies to rescue losses from internal breakdown in plums—project SF00024. Horticulture Australia Limited, Sydney.

Weaver, J. R. (1976). *Grape growing*. New York: John Wiley and Sons.

Walker, A. B., Bell, B. & Elliott, R. E. W. E. (1993) Aspects of New Zealand's experience in agricultural reform since 1984. MAF Policy Technical paper 94/5. ISBN 0478073562.

World Trade Organization (2013) Understanding the WTO: Basics—What is the World Trade Organization? http://www.wto.org/english/thewto_e/whatis_e/tif_e/fact1_e.htm doa: 11 July 2013.

Yahia, E. M. (1994). Apple flavour. *Horticultural Reviews*, *16*, 197−234.

Yamashita, K. (2000). Mango production in Japan. *Acta Horticulturae*, *509*, 79−85.

Zeder (2019). Zeder Investments Ltd. Annual report. http://www.zeder.co.za/Zeder-Annual-Report-2019.pdf. Accessed 18.10.20.

Zespri (2013). The history of zespri Sungold kiwifruit. https://www.zespri.com/en-US/blogdetail/history-of-zespri-sungold-kiwifruit. Accessed 15/11/21.

Further reading

Abbott, J. A., Lu, R. F., Upchurch, B. L., & Stroshine, R. L. (1997). Technologies for nondestructive quality evaluation of fruits and vegetables. In J. Janick (Ed.), *Horticultural reviews* (Vol. 20, pp. 1−119). John Wiley & Sons Inc.

Pop, S. Z., Dracea, S., & Vladulescu, C. (2018). Comparative study of certification schemes for food safety management systems in the European Union context. *Amfiteatru Economics*, *20*, 9−29. Available from https://doi.org/10.24818/EA/2018/47/9.

CHAPTER

4

Modeling quality attributes and quality-related product properties

Pol Tijskens and Rob Schouten

Horticulture and Product Physiology, Wageningen University and Research, Wageningen, The Netherlands

4.1 Introduction

Major changes, both in consumer behavior and in technical possibilities of production and understanding, have taken place in agriculture and horticulture in the last couple of decades. Consumers have become increasingly aware of the value of fruit and vegetable quality (Batt, 2006; Benner et al., 2003; Fearne, Barrow, & Schulenberg, 2006; Hewett, 2006) and put more emphasis on the quality of their daily food. While retailers govern the fruit and vegetable supply chain in all developed countries, they have to comply with changing consumer demands and preferences to stay competitive. The increasing number of food quality issues covered in the media (https://en.wikipedia.org/wiki/Category:Food_safety_scandals last visited November 2019) has added to the awareness and concern of the consumer, increasing the challenge to the grower and retailer.

Another change resulted from drastically increased technical and technological capabilities to measure food quality. At the same time the technology of modeling and data analysis has been expanded. Combining these improvements both at the level of product usage and at the level of research and handling makes it increasingly clear that a systematic approach to fruit and vegetable quality, handling, and modeling is vitally important. The traditional way of thinking about quality and of developing empirical models and data analysis must expand to include all available knowledge and information contained in experimental data and in chemical, physical, and physiological expertise accumulated over decades of scholarship.

The ultimate goal of modeling is to predict future behavior of any product, in any circumstance, from any region, and grown in any season. Modeling is the modern version of analyzing and understanding laboratory and practical experiments (Tijskens, 2004). It should allow the transfer of experimental results into practical applications. The world of

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00004-X

food supply chains, however, and especially globalized fruit and vegetable supply chains have grown increasingly complicated. The quality of produce from different origins and growing conditions is sometimes different than expected making the usually applied rules for quality control no longer generally applicable.

Traditional models, mainly statistical or empirical models, are no longer sufficiently reliable to predict quality. We have to include all (as much as possible) available knowledge, both for the preharvest realm (i.e., fruit and vegetable production) as for the postharvest phase (i.e., harvesting, storage, distribution, processing, sales and service). The barrier between both phases desperately needs to be bridged so that ideas and information can be exchanged. Communication, however, between both realms is often problematic (Tijskens & van Kooten, 2006) due to differing viewpoints on the nature of quality and its importance in supply chains. Process-oriented modeling, based on the knowledge of the occurring processes, is a system of modeling that provides a feasible approach to integrate the pre- and postharvest realm (Tijskens, 2004; Tijskens, Hertog, & Nicolaï, 2001).

This chapter attempts to achieve just that by presenting an expanded view on quality, modeling, and modeling of quality. Since the variation in properties of individuals in a batch of commodities accounts for a large part of the problems in understanding and dealing with product behavior, special attention is devoted to the omnipresent biological variation and how to use it for a competitive advantage.

4.2 What is quality?

When applying a systems approach to modeling, built upon the processes active in commodities changing their behavior and quality over time, we also need a framework on quality within the same paradigm of system approach. As long as man is concerned with quality of food, he will attempt to define that notion (see Chapters 3, 8, 9, 11, and 19). It is sometimes assumed that it is easier to define quality in terms of levels of attributes or properties for large groups of consumers. The problem with this approach is that each individual perceives quality differently. As a consequence, every possible definition is of limited use in practice. To deal with the variation between individuals in developing quality models, Sloof, Tijskens, and Wilkinson (1996) developed working concepts on quality that proved to be successful also outside the modeling framework.

The framework (Fig. 4.1) was adapted for evaluating the modeling requirements for globalization in fruit and vegetable supply chains (Tijskens, van Kooten, & Schouten, 2006) and for quality assurance (Tijskens, Schepers, & van Kooten, 2005). The main assumption behind the framework is that the processes by which humans evaluate the quality of any commodity are likely to be highly similar in every human being, regardless of culture, upbringing, and social circumstances. The differences between individuals, regions, states, societies, and cultures are induced by the difference in applied limits and “initial conditions” (Brückner, 2006). Although obtaining suitable data on human behavior in assessing quality and deciding on whether or not to purchase a particular commodity is still out of reach, psychologists are increasingly convinced of these premises (personal communication R. de Wijk). Nevertheless, the fact that obtaining suitable data is virtually impossible should not prevent the consideration of that framework. Lately, some efforts

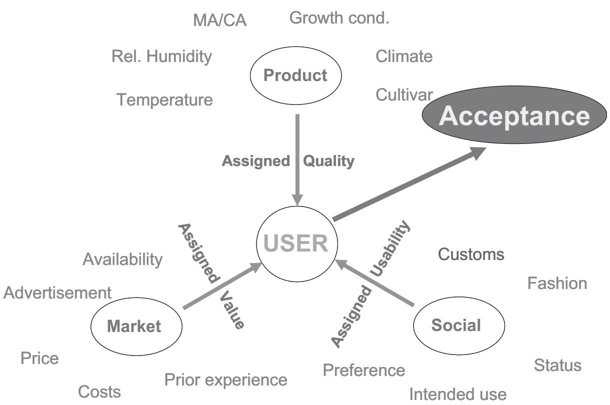


FIGURE 4.1 Schematic representation of quality and acceptance.

have been done to assess the effects of the combined variation in both product properties and consumer liking (Bavay et al., 2013 and the references cited there). A possible approach to deal with variation in both product properties and consumer liking is to estimate the cross section between the distribution of the properties in a batch of products and the distribution in the consumer liking. This approach will be discussed in more detail in Section 4.4.2.6.

Quality is assigned to a commodity by the user (buyer/consumer) in the center of the scheme (Fig. 4.1) based on perceived properties of that particular specimen. By perception, those properties (e.g., sugar content) are converted into attributes (e.g., sweetness). The value of that particular specimen is assigned by the user based on the properties/attributes in respect of the market situation (assigned value). Based on the social circumstances of the evaluator (user, buyer) and the intended use for the commodity, usability is assigned (assigned usability). All three assigned notions are then used to decide on the acceptance of a product.

On the first assigned item, quality (Fig. 4.1), some information is available. Intrinsic or assigned quality depends almost exclusively on the quality attributes of the product and, hence, on properties of that product that are related to the attributes under consideration. On the last two assigned items (value and usability), however, not much is known (Botonaki, Polymeros, Tsakiridou, & Mattas, 2006). Modeling acceptance is, therefore, much more difficult and cumbersome if the market situation and the social circumstance vary, because economical and psychological issues also come into play. Although there is an increased interest in this area (Morris & Young, 2000; Moskowitz, 2005), not much is known on the economical and psychological items in a systems approach framework.

Kramer and Twigg (1983) defined quality as *The composite of those characteristics that differentiate individual units of a product and have significance in determining the degree of acceptability of that unit by the buyer*. Their definition clearly connects acceptability to product properties and attributes (here called characteristics). Keeping the quality of products, which is the time a product remains acceptable during handling and storage, is closely related to acceptability (Rico, Martín-Diana, Barat, & Barry-Ryan, 2007; Tijskens & Polderdijk, 1996; Tijskens, Sloof, Wilkinson, & van Doorn, 1996). At the same time, the definition of Kramer and Twigg stresses the importance of the difference between units of product, which is actually the biological variance present in a batch of individuals.

Efforts are still underway to refine and augment definitions of quality. Recently, the quality of fresh horticultural commodities was defined as *a dynamic composite of their physicochemical properties and evolving consumer perception, which embraces organoleptic, nutritional, and bioactive components* (Kyriacou & Rouphael, 2018). Indirectly, this definition also stresses the importance of biological variation in both product and consumer perception.

Consumer acceptance based on product attributes has been the subject of studies and reports on its own merits (Berna, Lammertyn, Buysens, Di Natale, & Nicolaï, 2005; Crisosto, Crisosto, & Metheney, 2003; Crisosto, Crisosto, & Neri, 2006; Djekic, Radivojevic, & Milivojevic, 2019; Tomlins, Manful, Gayin, Kudjawu, & Tamakloe, 2007). However, the research on consumer acceptance and its effects on postharvest technology applications will stay cumbersome without an attempt to base this on fundamental models (Schouten, Huijben, Tijskens, & van Kooten, 2007a, 2007b).

4.2.1 Attributes versus properties

A consumer assigns attributes to a product based on the relevant properties present in a product (Fig. 4.1). For practical applications, the differences between product properties (physical, chemical) and quality attributes (psychological) are not that important. In fact, sometimes the differences between properties and attributes are not all that clear.

However, for the sake of developing theories and viewpoints and for research in the area of quality and human behavior, it is of utmost importance to understand the difference. This is particularly true when a variable is measured using objective measuring techniques, when very often the variable is assumed to be a property. A good example is color. Does a tomato in pitch darkness have a color? We cannot judge that, since we need light to observe it. What a tomato always has, however, whether or not we observe them, are color compounds like chlorophyll or lycopene. So, the properties related to the attribute color are light-absorbing compounds.

It is important to note that frequently so-called objective measuring techniques are designed in such a way that the impact of the human sensitivity to the factor is already incorporated in the measuring technique. Again, color is a good example: the well-known L*a*b* color space does reflect the sensitivity of the human eye by the mere choice of the wavelengths used.

Firmness can also be regarded as an attribute, based on properties of strength generating compounds. Many of the objective firmness measuring techniques do reflect the way humans observe product strength while chewing, bending, breaking, or touching the product. When dealing with this type of data, it is important to realize the nature of the variable measured, to deduce the proper framework of reasoning.

Most of the time, attributes are based on more than a single property, while properties may affect several attributes. The relations between properties and attributes are very complex and still not well understood. Table 4.1 shows some examples of relations between most common sensory attributes and physical or chemical properties of fruits and vegetables. A more elaborated example from texture research can be found in Table 4.2 as reported by Tijskens and Luyten (2004) based on the work of de Wijk, Rasing, and Wilkinson (2003).

TABLE 4.1 Relations between most common sensory attributes and physical or chemical properties of fruits and vegetables.

Attribute	Property
Color	Amount/concentration coloring compounds
	Wavelength light
Texture	Amount/concentration strength generating compounds
	Tissue structure
	Cell size
Sweetness	Amount/concentration sugars
	Amount/concentration acids
Flavor	Amount/concentration aroma compounds
	Texture (ripeness)
	Adsorbent properties tissue

TABLE 4.2 An illustration of the complexity in the attribute–property relations using the example of mayonnaise and custards.

Physical property	Affects	Sensory property
Viscosity		Thickness, stickiness, compactness, melting, creaminess
Density		Compactness
Particle size		Compactness, creaminess
Adhesion		Thickness, stickiness
Concentration of flavoring compounds		Creaminess
Sensorial property	Relates to	Physical property
Thickness		Viscosity, adhesion
Stickiness		Viscosity, adhesion
Compactness		Viscosity, density, particle size
Melting		Viscosity
Creaminess		Viscosity, particle size, concentration of flavoring compounds

From de Wijk, R., Rasing, F. & Wilkinson, C. (2003). Texture of semi-solids 2: Sensory flavor-texture interactions for custard desserts. Journal of Texture Studies*, 34(2), 131–146.*

4.2.2 Assigned quality versus acceptance

From the definition by Kramer and Twigg (1983) (see the previous section) and the representation of quality relations (Fig. 4.1), it is clear that assigned (or intrinsic) quality differs from product acceptance. The concepts are highly related to one another in a more or less unidirectional way: assigned quality can exist without acceptance; however, acceptance never occurs without quality. In this first case, other issues like availability or costs (Fig. 4.1—market) or personal preference (Fig. 4.1—social) come into play in the context of acceptance. The principles of acceptance of potted plants based on assigned quality are described in Tijskens (2000) and Tijskens et al. (1996). A similar approach has been applied to obtain the information of consumer buying behavior for tomatoes (Schouten et al., 2007a, 2007b), based on color and firmness as limiting attributes.

In most cases, laymen mean acceptance when referring to quality. Even in scientific publications, more often than not, quality is used in the meaning of acceptance. Yet, the concepts are not the same. For economic purposes, commercial companies are much more interested in product acceptance than in product quality. In that sense, acceptance is more important than assigned quality. On the other hand, without quality the acceptance of the commodity is at risk.

In summary, both product acceptance and product quality are extremely important, sometimes hard to discern, and pose a challenge to model. A direct consequence of the applied quality philosophy, however, is that as long as one is primarily concerned with assigned or intrinsic quality and does not include economic or sociopsychological aspects, the modeling approach can be entirely based on the behavior of relevant product properties. If economic and social issues are also considered, modeling becomes very difficult, not so much by practical or mathematical reasons, but by the shear differences in expertise and level of understanding in the three areas of product, market, and consumer research.

4.2.3 Acceptance and genetic effects

In the quality and acceptance scheme presented in Fig. 4.1, it is implicitly assumed that the consumer makes all evaluations and decisions in a conscious and reflective way. There is, however, evidence that the preferences for food product are strongly determined by subconscious drives. The gene pattern of animals, including human beings, urges the individuals to strive for high-density food (Ostan, Poljšak, Simčič, & Tijskens, 2009, 2010; Tijskens, Ostan, Poljšak, & Simčič, 2010), which would signify that besides the mechanism shown in Fig. 4.1, another mechanism has to be included in the food acceptance system that is more related to the subconscious behavior of human beings. How exactly this subconscious mechanism functions is currently unknown.

4.3 Systems approach in modeling

Many scientists consider modeling to be very difficult, highly mathematical and far out of reach. But modeling is as old as science. Every conclusion based on scientific research is, in fact, a model, not a mathematical one, not a statistical one, but a conceptual one, often applied inconsistently and variably, but nevertheless a model.

Modeling in agriculture (as presented in this chapter) started in the late 1960s with, among others, the work of Thornley (1976) and the school of C.T. De Wit at what is now Wageningen University and Research Centre (de Wit 1968; Wierenga & De Wit, 1972; de Wit & van Keulen, 1972; van Keulen, de Wit, & Lof, 1976). For several decades, these traditional empirical/statistical models induced a tremendous impetus in agricultural research and optimization, especially in the area of production, both in open field and in greenhouses.

The technology, however, of modeling has improved considerably over the last decades. Parameter estimation on measured data can now easily be based on nonlinear regression analysis (statistical package like SAS, Statistica, Genstat, R-Project), and mechanisms can be automatically converted into differential equations and (possibly) solved for analytical solutions (e.g., Maple, MapleSoft, Waterloo Maple Inc, Waterloo, Canada or Mathematica, Wolfram Research, Inc., Champaign, IL, United States). Data can nowadays even be statistically analyzed based on numerical integration of the differential equations when no analytical solution can be deduced, even including the estimation of the biological variation (Hertog, Verlinden, Lammertyn, & Nicolaï, 2007).

All these technical developments enable the use of conceptual models as directly derived from available expertise, and all laws of nature and scientific rules of disciplines in developing improved and more reliable, and more understandable models.

4.3.1 Process-oriented modeling versus statistical models

The main and often sole source of information for traditional mathematical models is the data gathered during experiments. The expertise and rules of statistics and data analysis are applied through the models and very often these types of models are developed, extended, and refined over several years or even decades and have often an amazing applicability (Sucros: Simane, van Keulen, Stol, & Struik, 1994, still in use and maintained: https://models.pps.wur.nl/simple-and-universal-crop-growth-simulator-sucros last visited November 2019; Tomsim: Heuvelink, 1999).

However, those models mostly ignore the expertise and scientific knowledge that also exists. Concepts of processes occurring in nature, which are part of expert knowledge of a particular area of research, are much more valuable in general application power as well as in understanding power than the mere mathematical/statistical models. For example, William of Ockham (the 14th century scholastic philosopher and theologian) was right with Ockham's razor ("Entities should not be multiplied without necessity," or in other words: make models as simple as possible). Statisticians have, however, wrongly translated his wisdom into tests on the number of parameters of a model (e.g., goodness of fit). As Passioura (1996) reported, a relation exists among the estimation error (or measures for goodness of fit), the structure of a model, the number of parameters in the model, and the complexity of the model.

Only for very simple models, a minimum number of parameters provide a (statistically) better, more useful model (Fig. 4.2). For more complex models, decreasing as much as possible the number of parameters seems futile. The structure of the model (which processes need to be included) becomes much more important. Ockham's razor can be applied perfectly in deciding which processes that occur in the product are important and which must be disregarded to arrive at models applicable in practice. In other words, the problem has to be decomposed into the constituting processes (Sloof, 2001). Simplification needs to be done on the level of processes to be included or not, and not on the level of mathematics and statistics.

Fundamental rules of disciplines (e.g., chemical kinetics) and the laws of nature (e.g., basic physics) are well established. Besides the use of statistical and mathematical skills, these rules and all the available expertise should be used in full in building models in complex and variable fields such as agriculture and food. Gathered data can and must

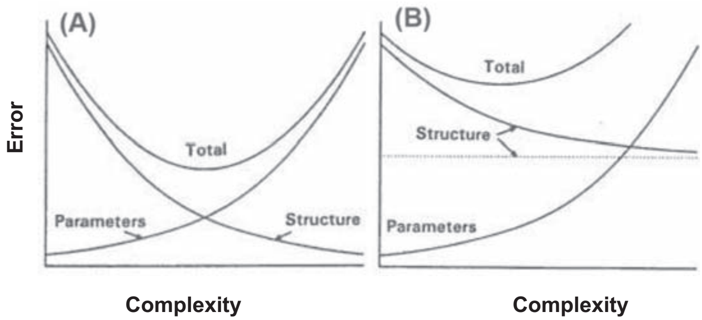


FIGURE 4.2 Notional components of prediction error in models of increasing complexity: (A) when the structure of the system is well understood; (B) when the model structure or the mechanism applied is wrong, with the irreducible structural error represented by the dotted asymptote. Complexity and error increase away from the intercept. Source: *From Passioura, J. B. (1996). Simulation models: Science; snake oil, education, or engineering?.* Agronomy Journal*, 88, 690–694. Courtesy Agronomy Journal.*

then be used only for setting up the problem framework (i.e., determine the processes at play), and finally for calibration and validation of the developed models.

By including all available fundamental knowledge that is at our disposal, we achieve the ultimate goal of modeling: the prediction of future behavior in any circumstance, from any region, grown in any season, while generating more knowledge about the process under study. This approach yields the so-called fundamental, process-oriented models. Research on the modeling effects for globalization (world-wide expansion of fruit and vegetable trade) is, as far we are aware, nonexistent. Effects of different batches, seasons (both within 1 year and from year to year), harvest maturity, and field management conditions are abundant. Proper interpretation in a global view, however, is mostly absent. By considering these differences, we basically deal with biological variation. Lately, reports have covered this subject (Farneti et al., 2014; Hertog, 2002; Hertog, Lammertyn, Desmet, Scheerlinck, & Nicolaï, 2004; Jordan and Loeffen, 2013; Schouten et al., 2009; Schouten, Farneti, Tijskens, Algarra Alarcón, & Woltering, 2014; Schouten, Jongbloed, Tijskens, & van Kooten, 2004; Schouten, Natalini, Tijskens, Woltering, & van Kooten, 2010; Schouten, Woltering, & Tijskens, 2016; Schouten, Zhang, Tijskens, & Van Kooten, 2008; Tijskens, Konopacki, & Simčič, 2003; Tijskens, Konopacki, Schouten, Hribar, & Simčič, 2008; Tijskens, Lin, & Schouten, 2005; Tijskens, Schouten, Konopacki, Hribar, & Simčič, 2010; Tijskens, Unuk, Tojnko, Hribar, & Simčič, 2009; Unuk et al., 2012). These reports indicate that by applying process-oriented modeling, it should be possible to pool data of different experiments into a single analysis and to interpret all these experimental data into a global view. Researchers and statisticians more and more realize the importance of analyzing variation properly (Cook & Robertson, 2016; Cook, Julias, & Nauman, 2014; Robertson & Cook, 2014; Verbeke, Molenberghs, & Rizopoulos, 2010; Zhang, Zhang, Zhou, Gu, & Tian, 2017). Analyzing experimental data while taking care of the always present biological variation has been conducted by indexed nonlinear regression (references to Tijskens and to Schouten) or by mixed effects analysis (references to Hertog and to de Ketelaere). Both systems have each their own benefits and pitfalls but are always superior to working with mean values (Cook & Robertson, 2016; Cook et al., 2014; Robertson & Cook, 2014).

The most basic rule of modern science is the repeatability of experiments. Under the same conditions, the same setup and ingredients should provide identical results. That means, for example, that the rate constant of chemical reactions should be the same regardless of the level of reactants present. Considering that many, presumably most, processes occurring in food products are of a chemical nature, the rate constant of a process has only to be determined once in the controlled circumstances of a laboratory, and henceforward, can be reused in different situations outside the lab. Moreover, a rate constant has to obey the fundamental rule of temperature dependence, according to Arrhenius' or Eyring's law (van Boekel & Tijskens, 2001). If, during model development and calibration, the rate constant of a process does not meet these requirements, either a wrong mechanism was selected or more processes are active than considered in the model. In other words the decomposition of the problem was improper (Sloof, 2001).

Applying the fundamental rules and problem decomposition in a systems approach to build process-oriented models are two of the powerful tools capable of describing phenomena under any circumstances in fruit and vegetable supply chains (Djekic et al., 2019; Hertog et al., 2011; Hertog, Lammertyn, De Ketelaere, Scheerlinck, & Nicolaï, 2007). The next sections discuss examples of this approach applied to quality behavior in any link of a supply chain.

4.3.2 Area of dedication

Traditional empirical/statistical models are frequently specified for a very dedicated application, for one actor in a supply chain (growing, storage, transportation, etc.). When building models based on occurring processes however, it does not matter where the product is in the chain or what conditions are forced upon it. For the occurring processes, for example of degreening, it is not important whether they occur in storage or during transport. The mechanism will be the same, as will be the derived model. Therefore, models developed based on the mechanism of occurring processes have a much wider applicability throughout the entire supply chain. Moreover, data gathered in different parts of the chain can be pooled and analyzed, increasing their applicability, reliability, and falsifiability of the model structure.

4.4 Examples of modeling

Firmness and color are the main attributes of the majority of agricultural commodities simply because they are important to consumers and trade. Moreover, firmness and color can be measured rather easily. Because both attributes have been measured for quite some time, a lot of knowledge has been accumulated about these attributes. That does not mean that other quality attributes (e.g., sugar content, acid content, taste, flavor, and juiciness) are less important for fruit and vegetables, but merely that there is less opportunity to analyze them because of the relatively more difficult measurement procedures. The majority of examples in the next sections are predominantly concerned with color and firmness of fruit and vegetables. In all examples, color and firmness must be defined to deal properly with the changes in these attributes.

Color is generated by coloring compounds such as chlorophyll, pheophytin, lycopene, and anthocyanins by reflection/absorption of incident light and by scattering of incident light by the structure of the tissue as observed by human senses. Changes in observed color can be caused by any of the four major constituents: the senses, the light, the tissue structure, and the content of coloring compounds. For practical product research, incident light and senses are kept or considered constant, while the coloring compounds are items to be described and modeled. When the target area is changed, for example, to consumer research (e.g., what apple color does separate population segments like?), the models developed for product research should not be translated/reused without considering the possible effect of changes in perception. However, in the product research, the main focus is on the chemistry of the coloring compounds involved in the product under study.

Most horticultural products are green (chlorophyll) in some stage of development but develop toward maturity into a whole range of colors and coloring compounds. Chlorophyll content is or should be a good reference when considering maturity and ripening in any stage of development. The specific coloring compounds that are developed upon ripening (red tomatoes, yellow bananas, and brown nuts) can also be used for that purpose, but only in the later (more critical) stages of maturity. The typical red coloration (e.g., the blush in nectarines, apples) caused by anthocyanins is most of the time primarily related to the amount of sunlight received during growth (Reay & Lancaster, 2001) and is barely related to that part of quality that is affected in postharvest handling.

Firmness can originate from different sources. Most common are pectines, cellulosic structuring materials, cell turgor, granules inside cells, shape and size of cells (Tijskens & Luyten, 2004; Van Dijk & Tijskens, 2000). Firmness is detected by applying a force to a structure. Again, the observer and the type and circumstances of the force applied may affect firmness behavior. In the case of objective firmness measurement, it is a standardized procedure with a machine. Nonstandardized human forces and senses are used in the case of subjective assessment, again the major difference between product research and consumer/sensory research.

The different sources of firmness directly affect the development of models. Sometimes, but rarely, only one source of firmness is present in a commodity. In that case, modeling of firmness is rather straightforward by focusing on that one process. More frequently, multiple sources of firmness are present. In those cases, each source of firmness can change at its own rate in actual conditions under study, including no change (zero rate). The latter case is the most common effect of multiple sources of firmness: firmness does not decay toward zero, but to a fixed end value. In any case, one has to be aware of multiple processes acting concurrently on multiple sources of firmness and take these into consideration when building a model on firmness.

4.4.1 Models for storage

4.4.1.1 Color

Changes related to chlorophyll breakdown and pheophytin production are the most common color changes in fruit and vegetables during storage. The most frequent behavior of color, especially expressed in the L*a*b* system, shows a sigmoidal pattern that can be modeled using a logistic function (see Table 4.3 for notation for this and other equations):

$$col = \frac{col_{\max} - col_{\min}}{1 + \left((col_{\max} - col_0)/(col_0 - col_{\min})\right) \cdot e^{k_{col} \cdot (col_{\max} - col_{\min}) \cdot t}} + col_{\min} \tag{4.1}$$

The logistic equation, of which Eq. (4.1) is just a specific case, has been used empirically to describe various kinds of sigmoidal behavior. The equation, however, can be deduced assuming an autocatalytic reaction:

$$\begin{aligned} col_{pre} + Enz &\xrightarrow{k_{col}} col + Enz \\ Enz_{pre} + Enz &\xrightarrow{k_{Enz}} 2 \cdot Enz \end{aligned} \tag{4.2}$$

This reaction can progress under the influence of an enzyme (*Enz*) or a hormone (ethylene). The application of the fundamental rules of chemical kinetics, including the mass conservation laws, and the assumption that the two rate constants (k_{col} and k_{Enz}) are the same, gives the analytical solution as shown in Eq. (4.1). When the two rate constants are different, a more elaborated model describes an asymmetrical sigmoidal behavior often found in preharvest growth phenomena (Tijskens & van Kooten, 2006):

$$col = \frac{col_0}{(Enz_0 + Enz_{pre,0})^{-k_{col}/k_{Enz}}} \cdot \left(Enz_{pre,0} + e^{(k_{Enz} \cdot (Enz_0 + Enz_{pre,0}) \cdot t)} \cdot Enz_0\right)^{-\frac{k_{col}}{k_{Enz}}} \tag{4.3}$$

In Fig. 4.3, an example is shown for both types of behavior. Although the models cannot be considered to be fully kinetic models (the mechanisms are not proven, only assumed), the meaning of their parameters can be clearly described. Some model parameters are concentrations or related to concentrations (*Enz*, *Col*), while others are reaction rate constants (k_{col} and k_{Enz}). From the rules of chemical kinetics, one can deduce that reaction rate constants inherently depend on temperature (T) according to the fundamental rule like Arrhenius Eq. (4.4) or Eyring found in textbooks on chemical or enzymatic kinetics:

$$k = k_{ref} \cdot e^{\frac{Ea}{R} \cdot \left(\frac{1}{T_{ref}} - \frac{1}{T}\right)} \tag{4.4}$$

Heaton and Marangoni (1996) and van Boekel (1999, 2000) provided extended descriptions of the mechanism involved in the change of color in horticultural products, in terms of concentration of different coloring compounds. Schouten, Tijskens, and van Kooten (2002) applied part of that mechanism to describe the color changes in cucumbers (expressed in RGB value from computer imaging), including the sometimes observed deepening of the green color in the early part of storage in the dark.

4.4.1.2 Firmness

Changes in firmness of horticultural products can be caused by a plethora of reactions. For fruit of deciduous trees, the major cause of softening is pectin degradation. For fruit from shrubs and herbs and for vegetables (like currants, strawberries, grapes) the major cause is moisture loss. But firmness and changes in firmness of the horticultural products

TABLE 4.3 Description of notation and subscripts used in equations legend of symbols.

Name	Description
Col	Color (any type)
Decay	Unnamed decay product
E_a	Activation energy
Enz	Enzyme activity
F	Firmness
k	Reaction rate constant
P	Density function
Pr	Probability function
Q	Quality
q_a, q_b	Lower and upper limit quality class
t	Time
T	Temperature
Δt	Time shift/biological shift factor
μ	Mean value
Σ	Standard deviation or biological variation
Φ	Cumulative normal probability function
All dimensions are arbitrary unless indicated	
Subscripts	Description
Col	Color
Enz, e	Enzyme
F	Firmness
fix	Invariable part/asymptotic end value
post	Postharvest conditions
max	Maximum value
min	Minimum value
pre	Precursor or preharvest conditions
ref	At some reference
0	Initial/at harvest
1	Source 1
2	Source 2
3	Source 3

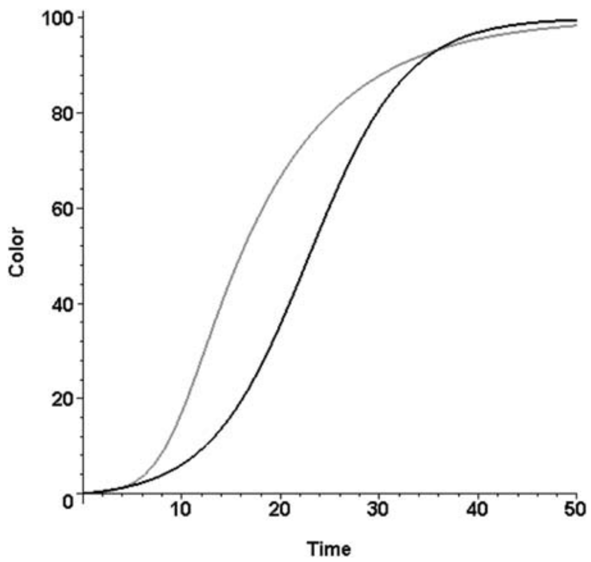


FIGURE 4.3 Behavior of the symmetrical (*black line*) and asymmetrical (*gray line*) sigmoidal function according to Eq. (4.1) and 14.3, using $Col_{max} = 100$ and $Col_{min} = 0$. All parameter values and time units are arbitrarily selected.

cannot be attributed to a single cause. A possible mechanism is depicted in the following simple reaction scheme:

$$\begin{aligned} F_1 &\xrightarrow{k_{f,1}} decay \\ F2 &\xrightarrow{k_{f,2}} decay \\ F3 &\xrightarrow{k_{f,3}} decay \end{aligned} \tag{4.5}$$

where F_1, F_2, and F_3 are possible sources of firmness. The observed firmness is then related to the total of all items involved. Not all of the sources of firmness have to change under the same conditions [temperature, controlled atmosphere (CA)]. For some of them the rate of change is so low that no change can be observed in the period of study. The application of the fundamental rules of chemical kinetics and the solution of the derived differential equations for constant external conditions (e.g., temperature) yields

$$F = F_{1,0} \cdot e^{-k_{f,1} \cdot t} + F_{2,0} \cdot e^{-k_{f,2} \cdot t} + F_{3,0} \cdot e^{-k_{f,3} \cdot t} \tag{4.6}$$

All three reactions in Eq. (4.5) depend on temperature according to the Arrhenius relation (Eq. 4.4), but each with its own set of parameter values. Eq. (4.6) indicates that at different storage temperatures an apparently completely different behavior is observed. Fig. 4.4A shows an example for some imaginary fruit stored at seven temperatures (0°C−30°C in 5°C increments) using parameter values from Table 4.4. At low temperatures, only the first reaction actually takes place, while at higher temperatures, the second reaction also starts to develop due to the higher activation energy (E_a). The third reaction is kept constant ($k_{f,3}$ is zero) to induce a frequently observed fixed end value. Fig. 4.4A indicates a change in asymptotic end value with increasing temperatures, while maintaining an apparent exponential behavior for each series separately. This behavior is frequently found in measured data, but rarely taken into account. All kinds of variations on this central mechanism (Eq. 4.5) can occur.

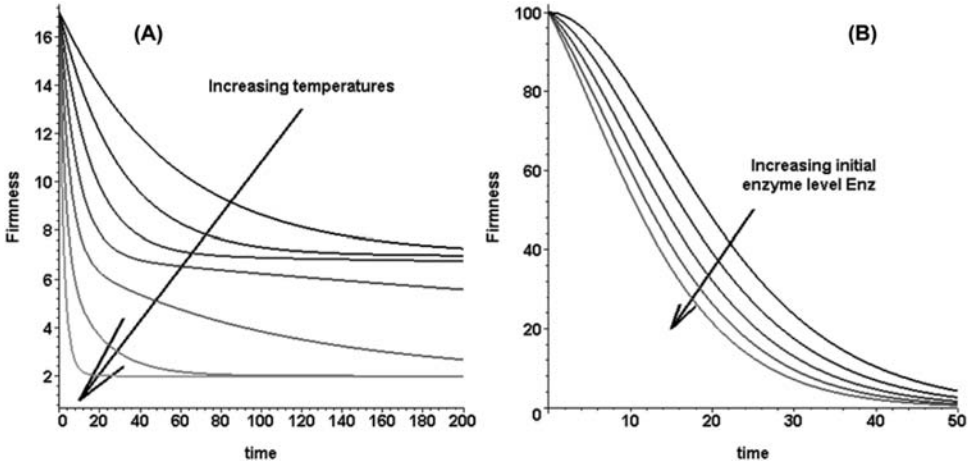


FIGURE 4.4 Firmness behavior according to Eq. (4.6) based on parameter values as shown in Table 4.4. (A) At different levels of temperature. The model includes different sources of firmness that start changing only at higher temperatures, reflected in the different levels of the asymptotes as the time increases. (B) At different levels of initial enzyme activity, indicating the increasing rate of decay with increasing enzyme activity, thereby changing the apparent behavior of softening (from sigmoidal to exponential).

TABLE 4.4 Parameter values for Eq. (4.6) used for simulation in Fig. 4.3A.

Reaction	$F_{x,o}$	$k_{f,x}$	E_{a_x}
1	10	0.2	80
2	5	0.01	250
3	2	0	0

Note: Dimensions and values selected completely arbitrary.

In horticultural products, almost all reactions are catalyzed by some enzyme (*Enz*). When the enzyme activity is (nearly) constant during storage, the results are like those depicted earlier without the effect of enzymatic action. However, batches of different origin or different stages of maturity may have different levels of enzyme activity. Consequently, the apparent rate of change (i.e., the specific rate constant times the enzyme activity) may vary from batch to batch, depending on, for example, growing conditions and maturity at harvest. This complex mechanism can simply be represented as

$$\begin{aligned} F_1 + Enz &\xrightarrow{k_{f,1}} decay + Enz \\ F_2 + Enz &\xrightarrow{k_{f,2}} decay + Enz \\ F_3 + Enz &\xrightarrow{k_{f,3}} decay + Enz \end{aligned} \tag{4.7}$$

The result is an equation similar to Eq. (4.6) but includes the rate constants multiplied by the actual enzyme activity. Each reaction however could also be catalyzed by different enzymes. In that case the situation rapidly gets very complex. The approach to achieve a feasible model, however, is highly similar to the mechanism shown in Eq. (4.7).

When the enzyme activity is not constant during storage but, for example, increases, a completely new situation arises. The mechanism of enzyme change will have a profound effect on the observed behavior. A possible mechanism is shown in the following equation:

$$\begin{aligned} &F + Enz \xrightarrow{k_f} decay + Enz \\ &Enz_{pre} \xrightarrow{k_e} Enz \end{aligned} \tag{4.8}$$

where F is again the firmness (only a single source is considered to keep it simple), k the rate constant, and Enz the available enzyme activity. The subscript "pre" indicates a precursor, f for firmness, and e for enzyme. Fig. 4.4B shows an example for increasing initial levels of Enz activity using parameters values shown in Table 4.5. With higher levels of Enz_0, the enzyme activity at the moment of harvest (time, $t = 0$), the firmness breakdown does resemble the normally found exponential behavior. On the other hand, when the level of initial enzyme activity is very low, the behavior resembles the sigmoidal behavior, frequently modeled using the logistic curve (Eq. 4.1). For example, such behavior was found in ripening nectarines (Tijskens, Eccher Zerbini, Schouten, et al., 2007).

Another possible situation is when one of the reactions in Eq. (4.5) or (4.7) is inhibited by CA and the other is not. CA slows physiological aging reactions in many fruits and vegetables by decreasing the product's respiration. Application of CA conditions would then lead to behavior as depicted in Fig. 4.4, but now not as a function of temperature, but of the intensity of the CA condition (Hertog, Nicholson, & Jeffery, 2004). Tijskens modeled the change in firmness behavior of Golden Delicious apples in different CA regimes already in (1979). The findings were used in a simulation application for Elstar apples (Tijskens, Hertog, Van Schaik, & De Jager, 1999). Additional details regarding the modeling of respiration and its effects on the quality of horticultural products can be found in Hertog, Peppelenbos, Evelo, and Tijskens (1999), Hertog (2001), Schouten, Veltman, et al. (2004) and the references cited therein.

Gwanpua et al. (2013) presented an extended study on the effects and management of the biological variation in apple cultivars in supply chains, as related to the maturity at harvest. Schouten et al. (2018) presented a model on the variation of mango firmness depending on the region of origin and the duration of reefer transport. The amount of ethylene, thought to be responsible for the softening, was estimated. The model not only indicates desirable softening (ready to eat) but also the mangoes unfit for maturation at any condition by lack of ethylene sensitivity.

TABLE 4.5 Simulation parameters (Eq. 4.8 and Fig. 4.3B).

Parameter name	Value
F_0	100
$Enz_{pre,0}$	1
Enz_0	0 to 0.41
k_f	0.1
k_e	0.05

Note: Dimensions and values selected completely arbitrary.

4.4.1.3 *Glucosinolates in broccoli*

Breakdown products of glucosinolates protect against carcinogenesis, mutagenesis, and other forms of toxicity of electrophiles and reactive forms of oxygen. Consequently, glucosinolates are assumed to be healthy and are therefore frequently studied (Bekaert, Edger, Hudson, Pires, & Conant, 2012; Wittstock & Burow, 2007; Sugiyama & Hirai, 2019). Schouten et al. (2008, 2009) developed a model on the behavior of several glucosinolates in broccoli during postharvest storage and related to the preharvest growth condition, storage temperature, and conditions of CA storage.

Upon a disruption of the tissue, the enzyme myrosinase (MYR) comes into contact with gluosinolates (GLS) and starts the decay of the latter compounds:

$$\begin{aligned} &nil \xrightarrow{kM} Myr \\ &Myr + GLS \xrightarrow{kG} Myr \end{aligned} \tag{4.9}$$

Since tissue needs to be disrupted for MYR to be available, the activity of this enzyme at $t = 0$ can safely be assumed to be zero. Applying the rules of basic kinetics, the differential equations for this system can be deduced and solved for constant external conditions (Eq. 4.10):

$$GLS = GLS_0 \cdot e^{-\frac{kG \cdot kM \cdot t^2}{2}} \tag{4.10}$$

The initial level of GLS (at $t = 0$) will depend according to the same mechanism at preharvest conditions. Expressing this variable as a time shift factor (Δt) results in an expression that describes the behavior of glucosinolates during both growth and storage:

$$GLS = GLS_{ref} \cdot e^{-\frac{1}{2} \cdot \left(kGM_{pre} \cdot \Delta t^2 + kGM \cdot t^2\right)} \tag{4.11}$$

With Δt the biological shift factor, kGM is the combined rate constants kG and kM in postharvest conditions, and kGM_{pre} is the combined rate constant in mean growing conditions (12°C). Δt is the time to change glucosinolates from their initial value (GLS_0) to the reference value (GLS_{ref}). The rate constant kGM depends on temperature according to Arrhenius function, and on the applied CA conditions, characterized by the relative respiration (RR, Eq. 4.12), that is, the ratio between the O_2 consumption at the actual conditions relative to the consumption in regular air at the same temperature (Hertog et al., 1999; Tijskens, 1995):

$$RR = \frac{Km_{O_2} \cdot O_2 \cdot \left(1 + \left(0/Kmu_{CO_2}\right)\right)}{Km_{O_2} \cdot 21 \cdot \left(1 + \left(0/Kmu_{CO_2}\right)\right)} \tag{4.12}$$

The levels of glucoraphanin (GR), glucobrassicin (GB), neoglucobrassicin, and 4-methoxyglucobrassicin (4-MetGB) were determined by high-performance liquid chromatography during storage of broccoli heads at 5°C, 10°C, and 18°C and several combinations of CO_2 and O_2. All data were analyzed per compound combined for all levels of temperature and CA conditions simultaneously. Explained parts obtained (R^2_{adj}) ranged from 70% (4-MetGB) to 92% (GR).

In Fig. 4.5, the behavior for GR is shown, based on the estimated values as shown in Table 4.6. The major effect of temperature can clearly be noticed, compared to the smaller

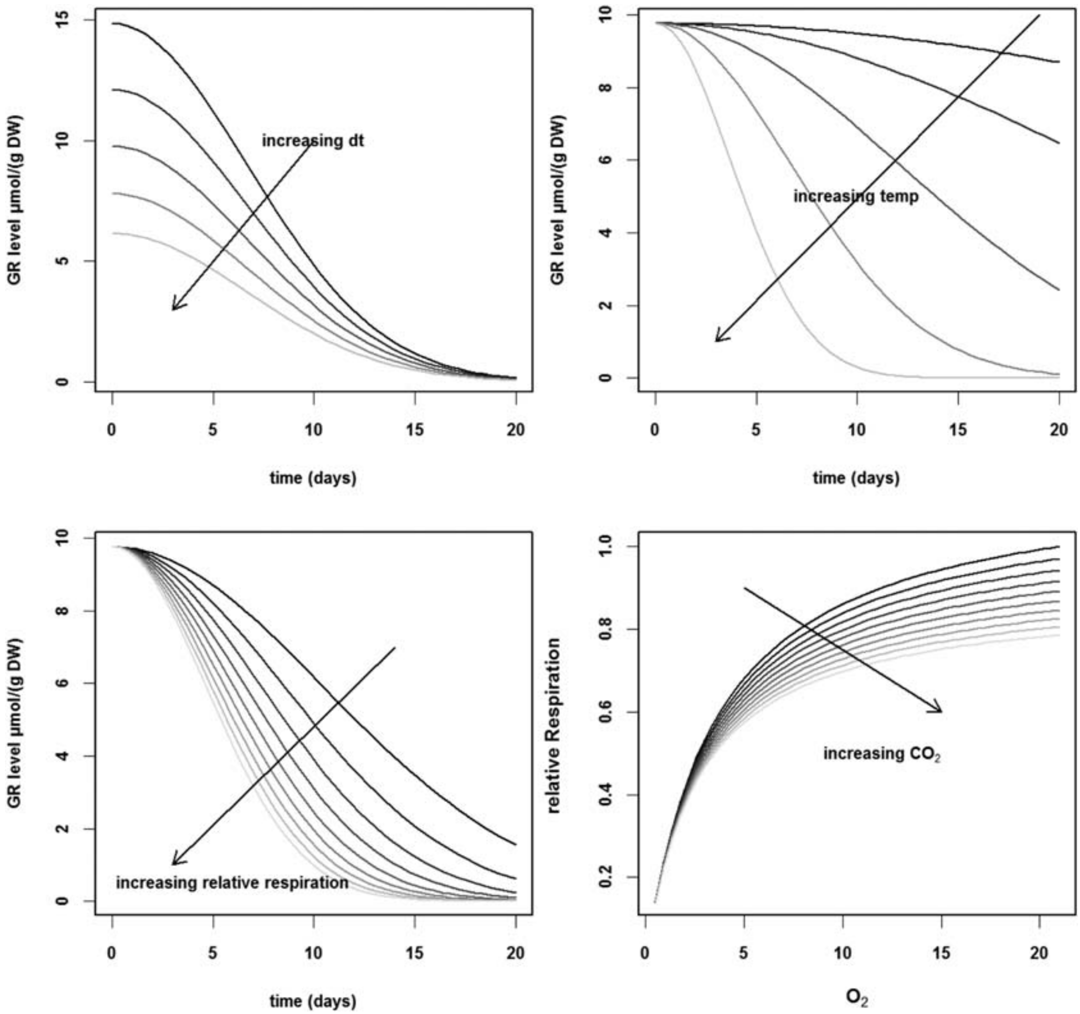


FIGURE 4.5 Behavior of GR. Top left: as a function of time for different values (from 23.5 to 28.5 days) of the biological shift factor (Δt), Top right: for different temperatures (5°C−25°C), bottom left for different values of the relative respiration (from 0.2 to 1), Bottom right: behavior of the relative respiration versus level of oxygen for different levels of CO_2 (0%−10%). *GR*, Glucoraphanin.

effect of CA conditions. The latter only becomes important or effective in the lower O_2 region (bottom right). The maturity state, expressed as biological shift factor (Δt), exhibits, however, the largest effect (only 5 days difference in Fig. 4.5, top left) in defining the initial values of the glucosinolates.

4.4.1.4 Color in the apple orchard

The effects of crop load and fertilization (Tijskens et al., 2009) and location in the canopy (Unuk et al., 2012) on the color development of individual apples at the tree during

TABLE 4.6 Parameter values glucosinolate analysis for glucoraphanin (Schouten et al., 2009).

Parameter	Units	Value
$K_{m_{O_2}}$	kPa	3.62
$K_{m_{CO_2}}$	kPa	31.54
kGM_{ref}	mol/day	0.0289
EGM	kJ/mol	164.9
GLS_{ref}	μmol/g/DW	100
Mean Δt	Day	26.02
Stand dev Δt	Day	1.23

the last couple of months before harvest was assessed nondestructively. Data were analyzed using the logistic color model (Eq. 4.1), expressing the initial color in biological shift factor Δt. The data over several seasons (2001, 2002, 2009) and cultivars (Braeburn, Fuji, Gala, and Golden delicious) obeyed the same model, including per cultivar the same value for the kinetic parameters.

All variations observed could be attributed to the biological shift factor estimated for each individual fruit. The differences in estimated values and standard deviation of the biological shift factor proved to be useful for interpreting the effects of the different treatments and conditions. Explained parts ($R^2{}_{adj}$) reached quite extraordinary levels of about 95% for all combinations of cultivar, season or treatment. In Fig. 4.6, an example is shown for Braeburn apples growing at different locations in the canopy.

4.4.2 Models for batches

Dealing with general patterns and variations in measured properties or attributes is, in its basic premises, the technical goal of modeling. The previous few years have seen the emergence of a new type of models: batch models. This type of model describes the variation resulting from slightly different conditions during growth for all individuals with a common growth history ("batch"). This variation is known as biological variation and may be described as the composite of biological properties that differentiate individuals in a batch (adapted from Tijskens et al., 2003).

In fruit and vegetables, biological variation is often larger in magnitude than other sources of variation, such as random and systematic errors related to data gathering (observational errors, technical variation). Until recently, however, biological variation has been neglected for various reasons. Tijskens et al. (2003) describe how, in practice, variation in properties has been addressed by sorting and grading with emphasis on uniform production. However, uniform production methods do not produce batches with zero biological variation because small spatial or temporal variation in growth conditions cannot be avoided. Hertog, Lammertyn, et al. (2004) mentioned that if all fruit would be harvested at the same stage of maturity, the variation at harvest would be negligible and

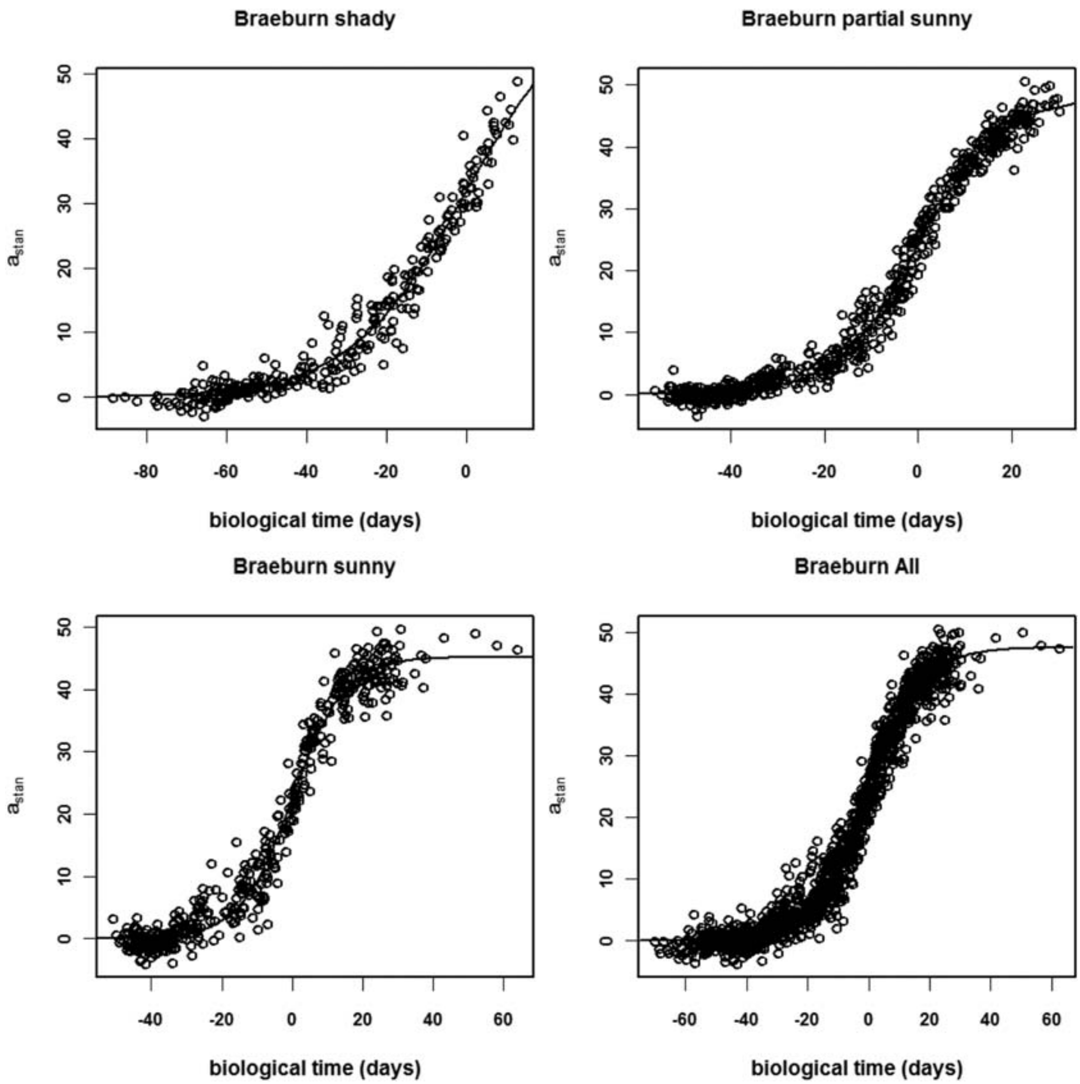


FIGURE 4.6 Example of color development (a*) as a function of biological time for individual Braeburn apples growing in shady, partial sunny, and sunny locations in the canopy, and all combined (*bottom right*) for the season 2009. Parameter values are shown in Table 4.7. Standardization is done ($a_{stan} = a - a_{min}$) to avoid the effect of different ranges of changes between the treatments. Note the different ranges of the *x*-axis as determined by the effect of the biological shift factor, different for each individual.

would remain negligible throughout the postharvest period. But this is never the case. The problem with sorting and grading is twofold. First, sorting and grading on (external) quality attributes will only sort on the current quality attributes. Limiting variation in the quality attribute by mixing batches will mask information how the variation will develop later in the supply chain. Second, given the available commercial technology, sorting and

TABLE 4.7 Results of the analysis of a* per season, combined for all locations in the canopy.

	Parameters				Admin info		
CV	col_{min}	col_{max}	k_{col}	Δt	R^2_{adj}	N_{obs}	N_{gr}
Braeburn	−16.44	31.16	0.0023	−48.92	0.98	1429	120
Fuji	−20.23	28.06	0.0011	−53.43	0.96	1630	118
Gala	−6.71	37.20	0.0029	−31.41	0.95	1194	109

grading is primarily conducted for external attributes. Sorting and grading might reduce the variation in other (internal) attributes (see Chapter 14: Nondestructive Evaluation: Detection of External and Internal Attributes Frequently Associated With Quality and Damage,and Chapter 15: Cooling Fresh Produce), but much less than for the external properties (Tijskens et al., 2003).

This section illustrates different aspects of biological variation and its propagation in time with examples of how these batch models advance the understanding of physiology. Progress is swift and it is likely that this overview will be outdated in a few years, but the practical benefits will become clear in the section on globalization.

Batch models combine quality models that describe the change of properties or attributes of individual products over time (see examples in the previous sections) with the probability (Pr) theory, which describe the variation of measured properties or attributes as a function of time. Biological variation is a mathematical concept, which can be incorporated into the quality models by assuming that the change in quality behavior is deterministic and any biological variation is included as a stochastic deviation of a single individual around the deterministic part (De Ketelaere, Stulens, Lammertyn, Cuong, & De Baerdemaeker, 2006; Jordan & Loeffen, 2013). For the deterministic part a whole range of (individual) quality models are available in literature (see, e.g., the previous sections).

4.4.2.1 *Incorporating biological age*

One approach to obtain information about biological variation is to adapt an individual model to allow for the estimation of the biological age (Δt in the equations) for each individual fruit or vegetable in a batch. This procedure requires that individuals are measured repeatedly over time using nondestructive measuring techniques. An overview how to analyze longitudinal data (measured nondestructively), including stochastic effects has been published (Tijskens, Schouten, Konopacki, & Jongbloed, 2015). Recently a technique to analyze cross-sectional data (measured destructively), including stochastic effects has been published (Tijskens, Konopacki, Schouten, Jongbloed, & Penchaiya, 2017), based on the work of Jordan and Loeffen (2013). The biological age can be defined as the age of the individual relative to an arbitrary reference point (see *Example 1*). The individual model is adapted to allow the estimation of the biological age for each individual fruit as the time necessary for the change in the initial firmness to reach arbitrarily chosen reference firmness (Δt_F) and the estimation of all other model parameters in common for the whole batch.

There seem to be two (almost identical) methods to incorporate the biological age. The first method is used by Hertog, Lammertyn, et al. (2004), Hertog, Lammertyn, Scheerlinck, and Nicolaï (2007), and Schouten et al. (2007a) who showed, by comparing root mean square error plots, that most of the variation between tomatoes of the same batch originated from picking at a different initial color. The concept that biological age can be applied to the initial values of a quality attribute or property to develop individual models is shown later in this chapter. The second method is to add the biological age (which is actually the transformed initial condition F_0 to the time frame, using the model under study) to the time variable as a stochastic variable called biological time. This biological time will have a different value for each individual in a batch. This second method has been presented by Tijskens et al. (2003), Tijskens, Eccher Zerbini, Schouten et al. (2007) and De Ketelaere et al. (2006).

Both methods of incorporating biological variance mentioned earlier can be used to obtain information about the biological variation present in a batch. Using nonlinear mixed effects or indexed regression analysis, it is possible to estimate the joint model parameters, such as $k_{f,\,post}$, $k_{f\ pre}$, and F_{fix} in *Example 1*, and all the values for the biological age of the individuals in the batch. Nonlinear mixed effects regression analysis assumes implicitly that the variable containing the variation is normally distributed, while for indexed regression, no assumption whatsoever is made. That makes the latter more useful in determining that actual distribution of the variable containing the variation. The estimated values, expressed as biological shift factor (Tijskens, Heuvelink, Schouten, Lana, & van Kooten, 2005), appear to be distributed according to a normal or Gaussian distribution; for example, the color biological age in tomatoes (Hertog, Lammertyn, et al., 2004) and the firmness biological age measured by the chlorophyll-related absorption coefficient μ_a of nectarines (Tijskens, Eccher Zerbini, Schouten, et al., 2007; Tijskens, Eccher Zerbini, Vanoli, et al., 2006). The distribution of biological age can be characterized by the mean and the standard deviation. It is clear from Fig. 4.7 that this approach successfully describes the large differences present between batches, both in the value of the mean and the standard deviation of the biological age distribution.

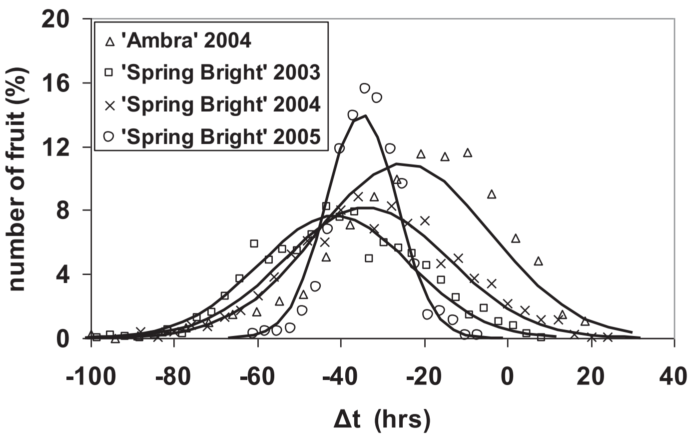


FIGURE 4.7 Distribution of the firmness biological age of nectarines by the absorption coefficient μ_a measured at 670 nm for four batches, differing in season (2003–05) and cultivars (Ambra and Spring Bright) at commercial harvest. Source*: From Tijskens, L. M. M., Eccher Zerbini, P., Schouten, R. E., Vanoli, M., Jacob, S., Grassi, M., . . . Torricelli, A. (2007). Assessing harvest maturity in nectarines.* Postharvest Biology and Technology, 45*(2), 204–213.*

Example 1: Firmness of tomatoes (adapted from Schouten et al., 2007a).

Tomatoes tend to lose firmness according to an exponential function when they have reached commercial size either on the plant or off the plant. Apparently, two sources of variation suffice for tomato firmness: a changing property and an invariable one (see Eq. 4.6. Firmness breakdown occurring over time during postharvest can then be described according to Eq. 4.9):

$$F(t) = (F_0 - F_{fix}) \cdot e^{-k_{f,post} \cdot t} + F_{fix} \tag{4.13}$$

with F_0 the firmness at harvest (in N), with $k_{f,\ post}$ (in day^{-1}) the reaction rate constant for the firmness breakdown after harvest and F_{fix} the invariable part (in N). The firmness at harvest, F_0, was assumed to be the result of firmness changes during preharvest. Subsequently, the postharvest firmness change model can then be expressed as a function of the storage time after harvest and the biological age firmness at harvest for constant temperature conditions as shown in the following equation:

$$F(t) = (F_{ref} - F_{fix}) \cdot e^{-k_{f,post} \cdot t - k_{f,pre} \cdot \Delta t_F} + F_{fix} \tag{4.14}$$

with $k_{f,\ pre}$ (in day^{-1}) the reaction rate constant for the firmness change before harvest, F_{ref} an arbitrary reference firmness, and Δt the biological age expressed as the time (in days) necessary for the firmness to change from F_{ref} to F_0. Eq. (4.14) expresses the postharvest firmness behavior as a function of the preharvest growing conditions with regard to firmness breakdown, the firmness at harvest, the storage time after harvest, and the biological age firmness at harvest (Fig. 4.8A and B).

4.4.2.2 *Biological variation and probability functions*

Another approach to obtain information about biological variation is to incorporate the finding that the biological age is apparently normally distributed. Information can be obtained in two ways. The first method is preferred when dealing with experimental data that have been classified into (quality) categories (relative frequency data), while the second approach is useful when no classification is used. The first method expresses the batch model as the Pr that measurements belong to a certain class (q_a, q_b) of the quality function Q. Assuming that the biological age (Δt) is normally distributed will result in the following batch model formulation (Eq. 4.15) (Schouten, Veltman, et al., 2004):

$$\Pr(Q(t) \in (q_a, q_b)) = \Pr\left(Q(\Delta t) \le q_b\right) - \Pr\left(Q(\Delta t) \le q_a\right) = \Phi\left(\frac{Q^{-1}(q_a) - \mu}{\sigma}\right) - \Phi\left(\frac{Q^{-1}(q_b) - \mu}{\sigma}\right) \tag{4.15}$$

with Φ the cumulative standard normal distribution function, μ the mean, and σ the standard deviation of the (biological age) distribution.

The second method is based on understanding how one variable is affected by the variation in another variable on which it depends. Let us assume that a quality function Q, as a function of biological age, is prone to biological variation. In that case, the Pr density $P(Q(t))$ can be

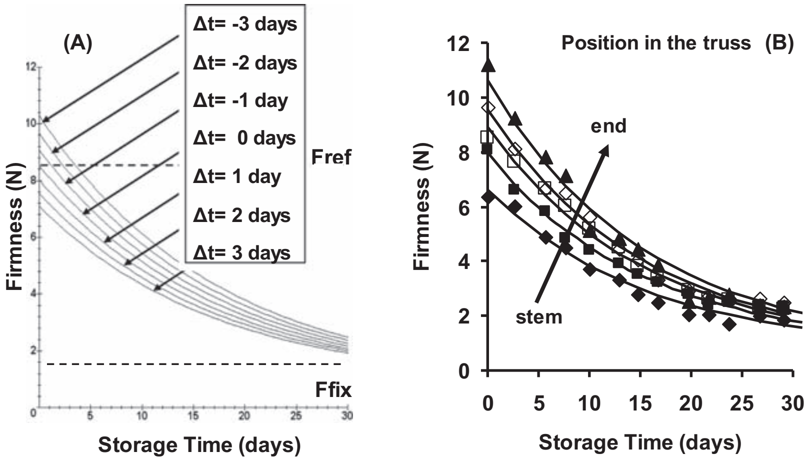


FIGURE 4.8 (A) Simulated firmness behavior over time of tomatoes stored at 16°C as a function of the maturity at harvest. Harvest maturity varies from −3 to +3 days, which reflects the normally encountered variation in harvested fruit. (B) The observed (measured) and expected (simulated) values for five individual tomatoes as a function of their location in the truss at the plant: the closer the tomatoes grow near the plant, the more mature they are compared to the tomatoes further away. Source: *Adapted from Schouten, R. E., Huijben, T. P. M., Tijskens, L. M. M. & van Kooten, O. (2007a). Modeling quality attributes of truss tomatoes: Linking color and firmness maturity.* Postharvest Biology and Technology, 45*(3), 298–306.*

expressed according to Eq. (4.16), assuming that the biological age is normally distributed with mean μ and σ the standard deviation (Hertog, Lammertyn, et al., 2004):

$$P(Q(t)) = P(Q^{-1}(q)) \cdot \frac{dQ^{-1}(q)}{dq} = \frac{1}{\sigma\sqrt{2\pi}} e^{-(1/2)(Q^{-1}-\mu/\sigma)^2} \cdot \frac{dQ^{-1}(q)}{dq} \tag{4.16}$$

From Eq. (4.16) it is clear that the shape of the distribution of measured variables such as color, firmness highly depends on the mechanism at work (Q^{-1}) and that it changes with time. The inference of the applicable dedicated equation for a logistic behavior (lower half) is shown in *Example 2*.

In the case of large amounts of individual fruits or vegetables in a batch, no differences between the two methods are expected in terms of batch or model parameters. However, when only a limited number of individuals in a batch are available, estimations will depend on the chosen class widths (q_a, q_b). In that latter case, the second method will likely result in improved descriptions of the batch variation. However, the first method provides results that are easier to interpret because they are expressed as Pr values between 0 and 1, instead of Pr density functions that have no upper limit and can easily exceed 1. Both methods are generic in nature, but limited to those quality functions with an inverse (Q^{-1}), which is the main problem in developing batch models.

Example 2: Method 2. Firmness batch model for tomatoes.

To create a batch model using the second method of firmness behavior, the inverse of the quality function (Eq. 4.14) has to be differentiated with regard to q. The

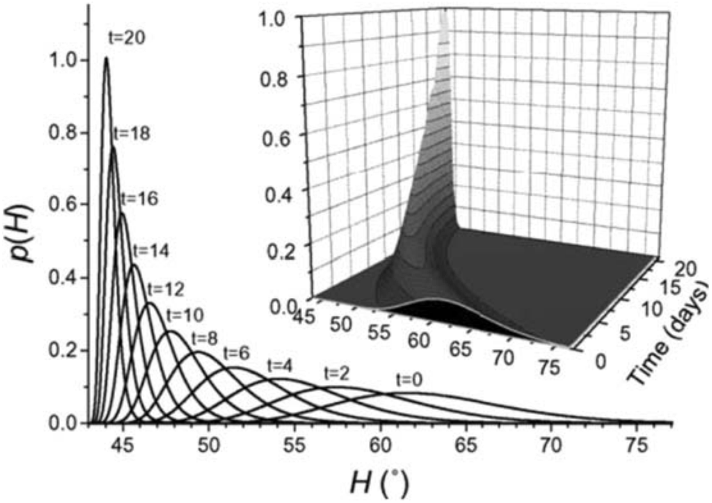


FIGURE 4.9 Propagation of the probability density function for the color p(H), expressed as Hue (H) for tomatoes stored at 15°C every other day (main plot), or as a gradually changing density over time (inset).

derivative with regard to q is applied in Eq. (4.17) and leads to the following equation:

$$P(F) = \frac{e^{-\frac{1}{2}\left(\frac{\frac{-\ln\left(\frac{F-F_{fix}}{F_{ref}-F_{fix}}\right)-k_{f,post}\cdot t}{k_{f,pre}}-\mu}{\sigma}\right)^2}}{\sigma\sqrt{2\pi}\cdot(F_{fix}-F)\cdot k_{f,pre}} \tag{4.18}$$

Fig. 4.9 shows an example of the propagation of the Pr density function assuming the logistic quality function rather than exponential. The distribution changes start ($t = 0$) as a symmetrical distribution that becomes skewed over time until all tomatoes show only little variation in color ($t = 20$).

4.4.2.3 *Biological variation and quantile functions*

An interesting procedure was presented by Jordan and Loeffen (2013), entirely based on the ranking of measured data for each measuring time (time sample), already proposed by Galton (1883). That ranking number is subsequently converted into a Pr as shown in the following equation:

$$\mathrm{Pr} = \frac{\mathrm{PN} - 1/2}{n_{\mathrm{obs}}} \tag{4.17}$$

where Pr is the probability, PN the ranking number, and n_{obs} the number of observations in each time sample. Applying the derived Pr in the quantile function (the inverse of the cumulative distribution, here a normal one, q_{norm} in the statistical package R), the mean and standard deviation of the parameter containing the biological variation (here Δt) can be estimated using normal nonlinear regression procedure. The main benefit of this system is that it is also not only applicable to longitudinal data (obtained by nondestructive measuring techniques) but also to cross-sectional data (obtained by destructive measuring techniques). Moreover, the results can directly be used to estimate dynamically in time the fraction of a batch of products that falls above or below a certain limit of acceptability. The disadvantage is that a large number of replicates need to be measured each time (preferably more than 50), and that the system relies more than usual on the (assumed) correctness of the model applied. Even with suboptimal models, this system provides high correlations. The previous system for estimating the biological variation, presented previously, fails almost completely when the model is not reflecting the processes occurring in the product. This analysis system has been successfully used to analyze cross-sectional data (Tijskens et al., 2017).

4.4.2.4 Multiple sources of variation

Schouten et al. (2007a) investigated whether the biological age based on (individual) color measurements and (individual) firmness measurements in tomatoes were linked. They found that the mean biological ages between batches from the same greenhouse were strongly linked. Apparently, the biological age based on mean color and biological age based on mean firmness of tomatoes are synchronized per grower, which points at links between the different metabolic pathways that result in synchronized quality attributes. This link between the biological age based on color and on firmness is also apparent when the chlorophyll-related absorption coefficient μ_a was linked to the biological age based on firmness of nectarines (Tijskens, Eccher Zerbini, Schouten, et al., 2007; Tijskens, Eccher Zerbini, Vanoli, et al., 2006). The viewpoint that multiple sources of variation may exist was investigated by De Ketelaere et al. (2006) who showed that within a batch of mangoes, next to the biological age based on firmness, also variation is present in the rate of the logistic firmness breakdown process. This is remarkable because in many deterministic quality models the rate constant of firmness breakdown is considered a constant that only varies between cultivars, not within batches.

Hertog, Scheerlinck, Lammertyn, and Nicolaï (2007) proposed an approach to generate batch models with two stochastic variables, for two different sources of biological variation. This was accomplished by extending the second method discussed earlier to the situation, where the quality function Q depends on two covarying sources of biological variation. The approach was demonstrated on postharvest stem growth data affected by biological variation in the mass of the head and initial length of the central stem of Belgian endive, applying a bivariate normal distribution.

The system based on quantile regressions (Jordan & Loeffen, 2013) can easily be extended to multiple sources of variation, one on the time axis (e.g., the biological shift factor Δt), and the other on the y-axis (i.e., technical variation or measuring error), as a geometric mean of both variations. With that approach, all variations can be assessed and estimated in one analysis. Frequently explained parts around 99% are obtained, since in principle all sources and types of variations are taken into account.

4.4.2.5 Application of batch models

Practical applications based on batch models are quickly becoming a reality. For instance, the (logistic) batch model describing the variation in the chlorophyll precursor in cucumbers was shown to have an upper limit in the cultivar-specific amount of this precursor (Schouten, Jongbloed, et al., 2004). This information could be used by cucumber breeders to create genotypes with a specific keeping quality. Another application for breeders and participants in tomato supply chains might be the combination of batch models for color and firmness batch behavior and combine these with consumer limits to provide the purchase period for consumers that starts when a tomato batch becomes acceptable (from unripe to ripe) and ends when the batch becomes unacceptable, (from ripe to overripe) (Schouten et al., 2007b; see also Section 4.4.2.6).

The quantile regressions system (Jordan & Loeffen, 2013) naturally presents the results as batch acceptability. The authors claim that the system is already in use commercially for some time.

4.4.2.6 Acceptance with biological variance

In both product properties (maturity) and consumer acceptance (liking) of these properties/attributes, biological variation is always present. With color as an example, the variation occurs according to the density function, associated with the logistic behavior (*black line* in the plots in Fig. 4.10). We have to bear in mind that this density function strongly depends on the mechanisms involved in the production and decay of the property under consideration.

Assuming that the variation in liking/acceptance in a large group of consumers is more or less normal (*dotted lines*) and that this liking shifts toward more mature fruit as the season progresses, the possibility to sell products to that group of people can be estimated/calculated as the cross section between the two density curves. When the product is green (immature, early season) none of the individual fruit is acceptable to any of the consumers (Fig. 4.10 top left). With progressing maturity (indicated by the time in the headers of

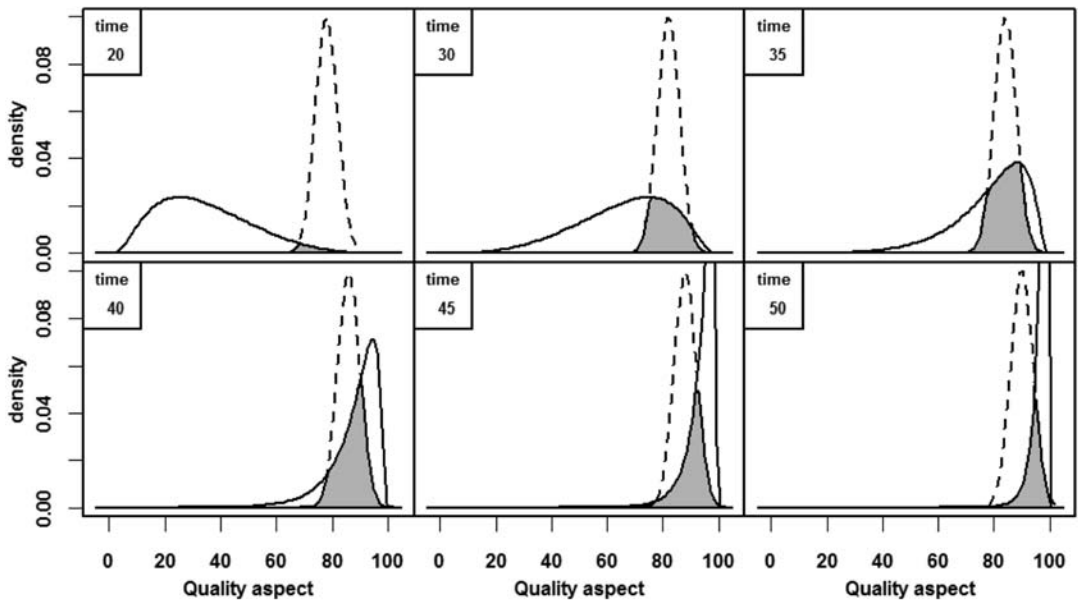


FIGURE 4.10 An example for the intersection (*gray area*) between product properties (e.g., color, *black line*) and consumer acceptance (liking, *dotted line*) at six different stages of maturity (biological age).

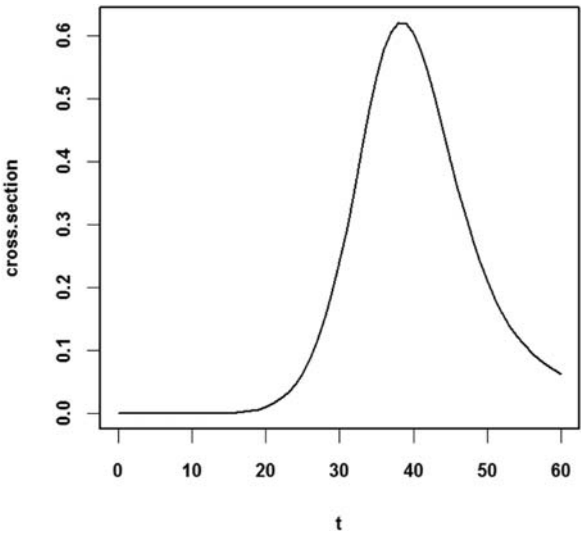


FIGURE 4.11 Behavior of cross section (*gray area*) between product properties and consumer acceptance as a function of maturation/ripening time.

Fig. 4.10), more and more fruits fall within the boundaries of consumer acceptance. At still higher maturity stages (overripe: Fig. 4.10 bottom row) the individual fruit also becomes unacceptable (to the right of the acceptance distribution).

The size of the area of the cross-sectional changes therefore with time. This is shown in Fig. 4.11. So, for every rate of development, and every moment of harvest, a maximum of liking exists, which can be optimized for the majority of people (in a group or segment of the population) to be acceptable. Assessing the variation in maturity of fruit has been successfully done in the last couple of decades. What needs to be assessed additionally is the variation in liking, or the variation in acceptance limit in the targeted group of people.

4.4.3 Models for growth

The modeling of quality attributes and quality-related product properties during growth is not well developed. In general, quality attributes important for postharvest handling of fruit and vegetables play a minor role in the production phase, except in floriculture. Attention is devoted to yield, the absence of defects, and the management of the plantation, orchard, or greenhouse. In fact, quality and taste is mainly reduced to selecting an appropriate cultivar. Hardly anything is known how postharvest quality actually grows.

However, the growing conditions in open field are highly variable due to weather and inability to control rainfall, sunlight, or day length. Open-field conditions make it very hard to pinpoint the active processes, to study them in isolation, and to construct from that knowledge mechanistic models. Nevertheless, preliminary trials (Tijskens & van Kooten, 2006) have revealed that progress can be expected from thorough problem decomposition and from modeling in a mechanistic way instead of the traditional statistical approach. The empirical temperature sum, frequently used in traditional growth models, has been used successfully and can be connected to summed rate constants of occurring reactions (Tijskens & Verdenius, 2000).

The diameters of apples (open field), tomatoes, and bell peppers (greenhouse) were assessed during growth and modeled as a first-order production reaction (von Bertalanffy model), based on the underlying assumption that photo-assimilates are transported to individual fruit. Not only the sink strength of the fruit is important but also the source strength of photosynthesis in the vicinity of the individual fruit (Tijskens et al., 2016).

4.4.4 Models for globalization

The globalization of fruit and vegetable supply chains has been occurring for quite some time. Globalization offers major advantages, but also considerable disadvantages (Phillips, 2006). However, the need to understand how the different regions and different seasons across the world affect quality and quality behavior (Banks, 2006; Tijskens, van Kooten, et al., 2006) has been neglected. The understanding and integration of variations from global sourcing require a fundamental approach that incorporates the relevant behavior of the product, both in the preharvest and in the postharvest realm. Quality differences induced by different cultivars, growing sites, soil types, climate, and weather have to be merged and combined into a single description to be applicable in a global supply chain. Because traditional modeling approaches are unsuitable to accommodate this integration of knowledge, we have to turn to modeling that is based on available knowledge on the processes that occur in the produce and initiate or cause the phenomena observed: a system's approach.

The concept of biological variation may, from a scientific point, be linked directly to certification issues. Food safety and product quality is increasingly controlled during the production process and in supply chains through the development and implementation of food safety and quality standards such as standard for farm management practice adopted in European Union, hazard analysis and critical control points, IFS, British Retail Consortium, or good harvesting practices. Traceability (see Chapter 12: Managing Product Flow Through Postharvest Systems) of batches is a prerequisite for these standards. Knowledge of how quality attributes or properties of batches change helps supply-chain partners understand why sometimes batch behavior differs from expectations based only on mean values.

The models elaborated earlier may seem over expanded and too complex for the intended simple target. An application targeting a global supply chain, however, has to account for effects of growing region, management, cultivar, and the influence of other conditions affecting the behavior of batches from all over the world. In addition, models for practical applications should include various preferences and likings (Schouten, Van Kooten, Van Der Vorst, Marcelis, & Luning, 2012; Van Kooten & Kuiper, 2009) of the different consumers (see also Section 4.4.2.6) across the world. The latter part is still largely out of reach although some interesting developments are taking place in combining process-oriented quality change models and models on consumer acceptance with economic aspects for the entire supply chain (Schepers & van Kooten, 2005; Schepers, van Henten, Bontsema, & Dijksterhuis, 2004).

A simple example of a model of the effects associated with different growing regions and management procedures on the quality and quality behavior in the globalized fruit and vegetable supply chain can be found in the maturity at harvest (Schouten et al., 2018).

The effects of harvest maturity on product behavior can be manifold. In its simplest form, harvest maturity induces a mere shift in the biological time, without altering fundamentally the behavior of the aspect studied (Tijskens, Heuvelink, et al., 2005). Based on a simple exponential breakdown (Eq. 15.14), the system of biological shift factors allows the standardization of graphical representations (see, e.g., Fig. 4.6 and Figs. 4.2 and 4.3 in Tijskens, Heuvelink, et al., 2005).

Venus et al. (2013) presented an extended application to assess and manage product losses in supply chains of tomatoes in Africa, based on remote sensing by satellites, and estimating the climate conditions inside open trucks. Remote sensing (e.g., NDVI and NAI levels) offers a huge potential in monitoring changes in all kinds of properties, important for agriculture and horticulture.

The principle of biological shift factor (Δt in Eq. 4.14) has been applied to firmness (Lana, Tijskens, & van Kooten, 2005) and color (Farneti et al., 2014; Lana, Tijskens, & van Kooten, 2006; Schouten et al., 2010) of fresh whole and cut tomatoes, the color of bell peppers (Tijskens, Heuvelink, et al., 2005), and apples (Tijskens et al., 2008, 2009; Tijskens, Schouten, et al., 2010; Unuk et al., 2012). The system of biological shift factors has the additional advantage that the values of the biological shift factor (encountered until now) are normally distributed. An exciting development is described in Tijskens, Eccher Zerbini, Vanoli, et al. (2006), Tijskens, Eccher Zerbini, Schouten, et al. (2007); Eccher Zerbini et al. (2009); Rizzolo et al. (2009) indicating that the actual biological shift factor of nectarines could be measured directly by time-resolved spectroscopy. In the long run the addition of biological variation resulting from the product that originates in different regions of the world will provide means to develop models applicable in globalized fruit and vegetable supply chains. Schouten et al. (2018) proposed a model on the postharvest firmness behavior of mangoes combining data from six different growing regions into a single description. Mangoes from each region had their own specific maturity stage after reefer transport to the Netherlands. The variable taught to be responsible for the differences was ethylene level and ethylene sensitivity.

A generic approach to generate a batch model that accounts for dynamic temperature scenarios, proposed by Hertog, Lammertyn, Scheerlinck, et al. (2007), provides an example of how to link biological variation methodology and globalization/certification into practical applications. The concept is based on the transformation of the actual time to "physiological time" or "biological time" that converts the batch model into a version based on differential equations. The conversion includes dynamic changes in temperature. The dynamic approach is important because temperature fluctuations in the supply chain are the norm (see Chapter 5: Models for Improving Fresh Produce Chains, for examples of dynamic simulation models). One application area can be telemetric monitoring (using radio-frequency identification technology and temperature loggers) in truck/reefer transport to inform chain managers about the quality status based on the current temperature and the effect it has on the propagation of the biological age distribution of each batch.

4.5 Conclusion and future developments

A decomposition of a problem into the constituting processes leads to the identification of plausible mechanisms occurring in the product. In using these mechanisms to build models, all available theoretical knowledge can be used. The application of fundamental rules, for example, chemical kinetics, allows these mechanisms to be expressed in the form of differential equations. These differential equations can (sometimes) be solved analytically under constant external conditions. When the conditions are not constant, or when the differential equations are too complex to be solved, the differential equations can be used to solve the problem in a numeric fashion. The practical and empirical knowledge and product expertise and available data are merely used to calibrate the developed models.

This chapter shows not only that problems in growing and handling horticultural products can and may be tackled by this approach, but it also shows that the method of process-oriented modeling opens new alleys to include the omnipresent biological variation into the system. To model supply chains and, especially global supply chains, the addition of the biological variation of product batches originating from a large number of growing conditions is of utmost importance.

The technical equipment to make this approach more feasible than it is currently will be developed further: more powerful computers, more powerful simulation packages, but especially important more suitable nondestructive measuring techniques to measure repeatedly the same individuals for a more extended set of attributes.

Moreover, statistical procedures are being developed and will be developed in the near future that account for the biological variation in the analysis of data gathered by destructive methods, which are currently by far the most abundant methods.

By applying process-oriented models in statistical analysis of experimental data, an increase in estimation reliability from for example, 70%−90% and higher, can be obtained frequently. The use of the technique of multiresponse−multivariate statistical analysis will increase and further improve the understanding of the problem and enhance the physiological basis of the systems approach in modeling.

References

Banks, N. (2006). Picking winners. *Acta Horticulturae*, *712*, 113−120, I.

Batt, P. J. (2006). Fulfilling customer needs in agribusiness supply chains. *Acta Horticulturae*, *699*, 83−89.

Bavay, C., Symoneaux, R., Maître, I., Kuznetsova, A., Brockhoff, P. B., & Mehinagic, E. (2013). Importance of fruit variability in the assessment of apple quality by sensory evaluation. *Postharvest Biology and Technology*, *77*, 67−74.

Bekaert, M., Edger, P. P., Hudson, C. M., Pires, J., & Conant, G. C. (2012). Metabolic and evolutionary costs of herbivory defense: Systems biology of glucosinolate synthesis. *New Phytologist*, *196*(2), 596−605. Available from https://doi.org/10.1111/j.1469-8137.2012.04302.x.

Benner, M., Geerts, R. F. R., Linnemann, A. R., Jongen, W. M. F., Folstar, P., & Cnossen, H. J. (2003). A chain information model for structured knowledge management: Towards effective and efficient food product improvement. *Trends in Food Science and Technology*, *14*(11), 469−477.

Berna, A. Z., Lammertyn, J., Buysens, S., Di Natale, C., & Nicolaï, B. M. (2005). Mapping consumer liking of tomatoes with fast aroma profiling techniques. *Postharvest Biology and Technology*, *38*, 115−127.

Botonaki, A., Polymeros, K., Tsakiridou, E., & Mattas, K. (2006). The role of food quality certification on consumers' food choices. *British Food Journal*, *108*(2), 77−90.

Brückner, B. (2006). Addressing consumer notions and individuality. *Acta Horticulturae*, *712*, 121−130.

Cook, D., Julias, M., & Nauman, E. (2014). Biological variability in biomechanical engineering research: Significance and *meta*-analysis of current modeling practices. *Journal of Biomechanics*, *47*(6), 1241−1250. Available from https://doi.org/10.1016/j.jbiomech.2014.01.040.

Cook, D. D., & Robertson, D. J. (2016). The generic modeling fallacy: Average biomechanical models often produce non-average results!. *Journal of Biomechanics*, *49*(15), 3609−3615. Available from https://doi.org/10.1016/j.jbiomech.2016.10.004.

Crisosto, C. H., Crisosto, G. M., & Metheney, P. (2003). Consumer acceptance of 'Brooks' and 'Bing' cherries is mainly dependent on fruit SSC and visual skin color. *Postharvest Biology and Technology*, *28*, 159−167.

Crisosto, C. H., Crisosto, G., & Neri, F. (2006). Understanding tree fruit quality based on consumer acceptance. *Acta Horticulturae*, *712*, 183−190.

De Ketelaere, B., Stulens, J., Lammertyn, J., Cuong, N. V., & De Baerdemaeker, J. (2006). A methodological approach for the identification and quantification of sources of biological variance in postharvest research. *Postharvest Biology and Technology*, *39*, 1−9.

de Wijk, R., Rasing, F., & Wilkinson, C. (2003). Texture of semi-solids 2: Sensory flavor-texture interactions for custard desserts. *Journal of Texture Studies*, *34*(2), 131−146.

de Wit, C. T. (1968). *Theorie en model (in Dutch). Inaugural speech* (p. 13) Wageningen, NL: Veenman.

de Wit, C. T., & van Keulen, H. (1972). *Simulation of transport processes in soils* (p. 100) Wageningen, NL: Pudoc.

Djekic, I., Radivojevic, D., & Milivojevic, J. (2019). Quality perception throughout the apple fruit chain. *Journal of Food Measurement and Characterization*, *13*(4), 3106−3118. Available from https://doi.org/10.1007/s11694-019-00233-1.

Eccher Zerbini, P., Vanoli, M., Rizzolo, A., Jacob, S., Torricelli, A., Spinelli, L., & Schouten, R. E. (2009). Time-resolved Reflectance Spectroscopy as a management tool in the fruit supply chain: An export trial with nectarines. *Biosystems Engineering*, *102*, 360−363.

Farneti, B., Schouten, R. E., Qian, T., Dieleman, J. A., Tijskens, L. M. M., & Woltering, E. J. (2014). 'Greenhouse climate control affects postharvest tomato quality. *Postharvest Biology and Technology*, *86*, 354−361.

Fearne, A., Barrow, S., & Schulenberg, D. (2006). Implanting the benefits of buyer-supplier collaboration in the soft fruit sector. *Supply Chain Management*, *11*(1), 3−5.

Galton, F. (1883). *Inquiries into human faculty and its development*. London: Macmillan.

Gwanpua, S. G., Verlinden, B. E., Hertog, M. L. A. T. M., Van Impe, J., Nicolai, B. M., & Geeraerd, A. H. (2013). Towards flexible management of postharvest variation in fruit firmness of three apple cultivars. *Postharvest Biology and Technology*, *85*, 18−29.

Heaton, J. W., & Marangoni, A. G. (1996). Chlorophyll degradation in processed foods and senescent plant tissues. *Trends in Food Science and Technology*, *7*, 8−15.

Hertog, M. L. A. T. M. (2001). Improving modified atmosphere packaging through conceptual models. In L. M. M. Tijskens, M. L. A. T. M. Hertog, & B. M. Nicolaï (Eds.), *Food process modeling*. Cambridge: Woodhead Publishing.

Hertog, M. L. A. T. M. (2002). The impact of biological variation on postharvest population dynamics. *Postharvest Biology and Technology*, *26*, 253−263.

Hertog, M. L. A. T. M., Lammertyn, J., De Ketelaere, B., Scheerlinck, N., & Nicolaï, B. M. (2007). Managing quality variance in the postharvest food chain. *Trends in Food Science and Technology*, *18*(6), 320−332. Available from https://doi.org/10.1016/j.tifs.2007.02.007.

Hertog, M. L. A. T. M., Lammertyn, J., Desmet, M., Scheerlinck, N., & Nicolaï, B. M. (2004). The impact of biological variation on postharvest behavior of tomato fruit. *Postharvest Biology and Technology*, *34*, 271−284.

Hertog, M. L. A. T. M., Lammertyn, J., Scheerlinck, N., & Nicolaï, B. M. (2007). The impact of biological variation on postharvest behavior: The case of dynamic temperature conditions. *Postharvest Biology and Technology*, *43*, 183−192.

Hertog, M. L. A. T. M., Nicholson, S. E., & Jeffery, P. B. (2004). The effect of modified atmospheres on the rate of firmness change of 'Hayward' kiwifruit. *Postharvest Biology and Technology*, *31*(3), 251−261. Available from https://doi.org/10.1016/j.postharvbio.2003.09.005.

Hertog, M. L. A. T. M., Peppelenbos, H. W., Evelo, R. G., & Tijskens, L. M. M. (1999). A dynamic and generic model of gas exchange of respiring produce: The effects of oxygen, carbon dioxide and temperature. *Postharvest Biology and Technology*, *14*, 335−349.

Hertog, M. L. A. T. M., Rudell, D. R., Pedreschi, R., Schaffer, R. J., Geeraerd, A. H., Nicolaï, B. M., & Ferguson, I. (2011). Where systems biology meets postharvest. *Postharvest Biology and Technology*, *62*, 223−237, vol. 3.

Hertog, M. L. A. T. M., Scheerlinck, N., Lammertyn, J., & Nicolaï, B. M. (2007). The impact of biological variation on postharvest behavior of Belgian endive: The case of multiple stochastic variables. *Postharvest Biology and Technology*, *43*, 78−88.

Hertog, M. L. A. T. M., Verlinden, B. E., Lammertyn, J., & Nicolaï, B. M. (2007). OptiPa, an essential primer to develop models in the postharvest area. *Computers and Electronics in Agriculture*, *57*, 99–106.

Heuvelink, E. (1999). Evaluation of a dynamic simulation model for tomato crop growth and development. *Annals of Botany*, *83*(4), 413–422. Available from https://doi.org/10.1006/anbo.1998.0832.

Hewett, E. W. (2006). Progressive challenges in horticultural supply chains: Some future challenges'. *Acta Horticulturae*, *712*, 39–49, I.

Jordan, R. B., & Loeffen, M. P. F. (2013). A new method for modelling biological variation using quantile functions. *Postharvest Biology and Technology*, *86*, 387–401.

Kramer, A., & Twigg, B. A. (1983). *Quality control in the food industry* (3rd ed.). Westport, CT: AVI Publishing Co.

Kyriacou, M. C., & Rouphael, Y. (2018). Towards a new definition of quality for fresh fruits and vegetables. *Scientia Horticulturae*, *234*, 463–469. Available from https://doi.org/10.1016/j.scienta.2017.09.046.

Lana, M. M., Tijskens, L. M. M., & van Kooten, O. (2005). Effects of storage temperature and fruit ripening on firmness of fresh cut tomatoes. *Postharvest Biology and Technology*, *35*, 87–95.

Lana, M. M., Tijskens, L. M. M., & van Kooten, O. (2006). Effects of storage temperature and stage of ripening on RGB color aspects of fresh-cut tomato using video image analysis. *Journal of Food Engineering*, *77*, 871–879.

Morris, C., & Young, C. (2000). 'Seed to shelf', 'teat to table', 'barley to beer' and 'womb to tomb': Discourses of food quality and quality assurance schemes in the UK. *Journal of Rural Studies*, *16*, 103–115.

Moskowitz, H. R. (2005). Psychophysical thinking in business: Products and concepts. *Journal of Sensory Studies*, *20*, 389–396.

Ostan, I., Poljšak, B., Simčič, M., & Tijskens, L. M. M. (2009). Nutrition for the Selfish Gene. *Trends in Food Science & Technology*, *20*, 355–365.

Ostan, I., Poljšak, B., Simčič, M., & Tijskens, L. M. M. (2010). Appetite for the Selfish Gene. *Appetite*, *54*, 442–449.

Passioura, J. B. (1996). Simulation models: Science; snake oil, education, or engineering? *Agronomy Journal*, *88*, 690–694.

Phillips, L. (2006). Food and globalization. *Annual Review of Anthropology*, *35*, 37–57.

Reay, P. F., & Lancaster, J. E. (2001). Accumulation of anthocyanins and quercetin glycosides in 'Gala' and 'Royal Gala' apple fruit skin with UV-B-visible irradiation: Modifying effects of fruit maturity, fruit side, and temperature. *Scientia Horticulturae*, *90*(1-2), 57–68. Available from https://doi.org/10.1016/S0304-4238(00)00247-8.

Rico, D., Martín-Diana, A. B., Barat, J. M., & Barry-Ryan, C. (2007). Extending and measuring the quality of fresh-cut fruit and vegetables: A review. *Trends in Food Science & Technology*, *18*, 373–386.

Rizzolo, A., Vanoli, M., Eccher Zerbini, P., Jacob, S., Torricelli, A., Spinelli, L., ... Tijskens, L. M. M. (2009). Prediction ability of firmness decay models of nectarines based on the biological shift factor measured by time-resolved reflectance spectroscopy. *Postharvest Biology and Technology*, *54*, 131–140.

Robertson, D., & Cook, D. (2014). Unrealistic statistics: How average constitutive coefficients can produce non-physical results. *Journal of the Mechanical Behavior of Biomedical Materials*, *40*, 234–239. Available from https://doi.org/10.1016/j.jmbbm.2014.09.006.

Schepers, H., & van Kooten, O. (2005). Profitability of ready to eat strategies: Towards model-assisted negotiation in a fresh produce chain. In C. J. M. Ondersteijn, J. H. M. Wijnands, R. B. M. Huirne, & O. van Kooten (Eds.), *Quantifying the agri-food supply chain proceedings of the frontis workshop on quantifying the agri-food supply chain*. The Netherlands: Wageningen. 22–24 October 2004 Frontis series. <http://library.wur.nl/frontis/quantifying_supply_chain/09_schepers.pdf>.

Schepers, H. E., van Henten, E. J., Bontsema, J., & Dijksterhuis, G. B. (2004). Tactics of quality management and promotions: Winning consumers for fresh exotic produce. In H. J. Bremmers, S. W. F. Omta, J. H. Trienekens, & E. F. M. Wubben (Eds.), *Dynamics in chains and networks* (pp. 568–582). Wageningen Academic Publishers.

Schouten, R., Farneti, B., Tijskens, L. M. M., Algarra Alarcón, A., & Woltering, E. (2014). Quantifying lycopene synthesis and chlorophyll breakdown in tomato fruit using remittance VIS spectroscopy. *Postharvest Biology and Technology*, *96*, 53–63. Available from https://doi.org/10.1016/j.postharvbio.2014.05.007.

Schouten, R., Van Kooten, O., Van Der Vorst, J., Marcelis, W., & Luning, P. (2012). Quality Controlled Logistics in vegetable supply chain networks: How can an individual batch reach an individual consumer in the optimal state? *Acta Horticulturae*, *936*, 45–52.

Schouten, R. E., Fan, S., Verdonk, J. C., Wang, Y., Kasim, N. F. M., Woltering, E. J., & Tijskens, L. M. M. (2018). Mango firmness modeling as affected by transport and ethylene treatments. *Frontiers in Plant Science*, *9*, 1647. Available from https://doi.org/10.3389/fpls.2018.01647.

Schouten, R. E., Huijben, T. P. M., Tijskens, L. M. M., & van Kooten, O. (2007a). Modeling quality attributes of truss tomatoes: Linking color and firmness maturity. *Postharvest Biology and Technology*, *45*(3), 298−306.

Schouten, R. E., Huijben, T. P. M., Tijskens, L. M. M., & van Kooten, O. (2007b). Modeling the acceptance period of truss tomato batches. *Postharvest Biology and Technology*, *45*(3), 307−316.

Schouten, R. E., Jongbloed, G., Tijskens, L. M. M., & van Kooten, O. (2004). Batch variability and cultivar keeping quality of cucumber. *Postharvest Biology & Technology*, *32*, 299−310.

Schouten, R. E., Natalini, A., Tijskens, L. M. M., Woltering, E. J., & van Kooten, O. (2010). Modelling the firmness behaviour of cut tomatoes. *Postharvest Biology and Technology*, *57*(1), 44−51.

Schouten, R. E., Tijskens, L. M. M., & van Kooten, O. (2002). Predicting keeping quality of batches of cucumber fruits based on a physiological mechanism. *Postharvest Biology & Technology*, *26*, 209−220.

Schouten, R. E., Veltman, R. H., De Wild, H. P. J., Koopen, T. J., Staal, M. G., & Tijskens, L. M. M. (2004). Determination of O_2 and CO_2 permeance, internal respiration and fermentation for a batch of pears (cv Conference). *Postharvest Biology and Technology*, *32*, 289−298.

Schouten, R. E., Woltering, E. J., & Tijskens, L. M. M. (2016). Sugar and acid interconversion in tomato fruits based on biopsy sampling of locule gel and pericarp tissue. *Postharvest Biology and Technology*, *111*, 83−92. Available from https://doi.org/10.1016/j.postharvbio.2015.07.032.

Schouten, R. E., Zhang, X., Tijskens, L. M. M., & Van Kooten, O. (2008). The propagation of variation in glucosinolate levels as effected by controlled atmosphere and temperature in a broccoli batch. *Acta Horticulturae*, *802*, 241−246.

Schouten, R. E., Zhang, X., Verkerk, R., Verschoor, J. A., Otma, E. C., Tijskens, L. M. M., & van Kooten, O. (2009). Modelling the level of the major glucosinolates in broccoli as affected by controlled atmosphere and temperature. *Postharvest Biology and Technology*, *53*(1-2), 1−10.

Simane, B., van Keulen, H., Stol, W., & Struik, P. C. (1994). Application of a crop growth model (SUCROS-87) to assess the effect of moisture stress on yield potential of durum wheat in Ethiopia. *Agricultural Systems*, *44*(3), 337−353.

Sloof, M. (2001). Problem decomposition. In L. M. M. Tijskens, M. L. A. T. M. Hertog, & B. M. Nicolaï (Eds.), *Food process modeling* (pp. 19−34). Cambridge: Woodhead Publishing.

Sloof, M., Tijskens, L. M. M., & Wilkinson, E. C. (1996). Concepts for modeling quality of perishable products. *Trends in Food Science & Technology*, *7*, 165−171.

Sugiyama, R., & Hirai, M. Y. (2019). Atypical myrosinase as a mediator of glucosinolate functions in plants. *Frontiers of Plant Science*, *10*, 1008. Available from https://doi.org/10.3389/fpls.2019.01008.

Thornley, J. H. M. (1976). *Mathematical models in plant physiology. A quantitative approach to problems in plant and crop physiology* (p. 318) London: Academic Press.

Tijskens, L. M. M. (1979). Texture of Golden Delicious apples during storage. *Lebensmittel-Wissenschaft-und-Technologie*, *12*(3), 138−142.

Tijskens, L. M. M. (1995). A model on the respiration of vegetable produce during postharvest treatments. In: *Proceedings international conference on AGRI-FOOD quality* (pp. 322−327), June 1995, Norwich, United Kingdom.

Tijskens, L. M. M. (2000). Acceptability. In R. L. Shewfelt, & B. Brückner (Eds.), *Fruit and vegetable quality: An integrated view* (pp. 125−143). Technomic Press.

Tijskens, L. M. M. (2004). *Discovering the future: Modeling quality matters* (Ph.D. thesis). Wageningen University. ISBN 90-8504-017-5.

Tijskens, L. M. M., & Luyten, H. (2004). Modeling food texture. In D. Kilcast (Ed.), *Texture in food. Vol. 1: Solid foods*. Cambridge: Woodhead Publishing.

Tijskens, L. M. M., & Polderdijk, J. J. (1996). A generic model for keeping quality of vegetable produce during storage and distribution. *Agricultural Systems*, *51*, 431−452.

Tijskens, L. M. M., & van Kooten, O. (2006). Theoretical considerations on generic modeling of harvest maturity, enzymes status and quality behavior. *International Journal of Postharvest Technology and Innovation*, *1*, 106−120.

Tijskens, L. M. M., & Verdenius, F. (2000). Summing up dynamics: Modeling biological processes in variable temperature scenarios. *Agricultural Systems*, *66*(1), 1−15.

Tijskens, L. M. M., Eccher Zerbini, P., Schouten, R. E., Vanoli, M., Jacob, S., Grassi, M., . . . Torricelli, A. (2007). Assessing harvest maturity in nectarines. *Postharvest Biology and Technology*, *45*(2), 204−213.

Tijskens, L. M. M., Eccher Zerbini, P., Vanoli, M., Jacob, S., Grassi, M., Cubeddu, R., . . . Torricelli, A. (2006). Effects of maturity on chlorophyll related absorption in nectarines, measured by non-destructive time-resolved reflectance spectroscopy. *International Journal of Postharvest Technology and Innovation*, *1*, 178−188.

Tijskens, L. M. M., Hertog, M. L. A. T. M., & Nicolaï, B. M. (2001). *Food process modeling*. Cambridge: Woodhead Publishing.

Tijskens, L. M. M., Hertog, M. L. A. T. M., Van Schaik, A. C. R., & De Jager, A. (1999). Modeling the firmness of Elstar apples during storage and transport', *International symposium on effect of preharvest and postharvest factors on storage of fruits and vegetables*, August 1997, Warsaw, Poland. *Acta Horticulturae*, *485*, 363−372.

Tijskens, L. M. M., Heuvelink, E., Schouten, R. E., Lana, M. M., & van Kooten, O. (2005). The biological shift factor. Biological age as a tool for modeling in pre- and postharvest horticulture. *Acta Horticulturae*, *687*, 39−46.

Tijskens, L. M. M., Konopacki, P., & Simčič, M. (2003). Biological variance, burden or benefit? *Postharvest Biology & Technology*, *27*, 15−25.

Tijskens, L. M. M., Konopacki, P. J., Schouten, R. E., Hribar, J., & Simčič, M. (2008). Biological variance in the colour of Granny Smith apples. Modelling the effect of senescence and chilling injury. *Postharvest Biology and Technology*, *50*(2−3), 153−163.

Tijskens, L. M. M., Konopacki, P. J., Schouten, R. E., Jongbloed, G., & Penchaiya, P. (2017). Assessing biological and technical variation in destructively measured experimental data. *Postharvest Biology and Technology*, *132*, 31−42. Available from https://doi.org/10.1016/j.postharvbio.2017.05.013.

Tijskens, L. M. M., Lin, W. C., & Schouten, R. E. (2005). Predicting harvest labour allocation in bell pepper production. *Acta Horticulturae*, *682*, 1435−1442.

Tijskens, L. M. M., Ostan, I., Poljšak, B., & Simčič, M. (2010). Consumers and food choice, quality, nutrition and genes. *Acta Horticulturae*, *880*, 29−38.

Tijskens, L. M. M., Schepers, H., & van Kooten, O. (2005). Modelling for quality assurance. In S. Kanlayanarat & W.B. McGlasson (Eds.), *Proceedings of the APEC symposium on assuring quality and safety of fresh produce* (pp. 23−33), August 1−3, 2005, Bangkok.

Tijskens, L. M. M., Schouten, R. E., Konopacki, P., & Jongbloed, G. (2015). Basic principles of analysing biological and technical variation in non-destructive data. *Computers and Electronics in Agriculture*, *111*, 121−126. Available from https://doi.org/10.1016/j.compag.2014.12.022.

Tijskens, L. M. M., Schouten, R. E., Konopacki, P. J., Hribar, J., & Simčič, M. (2010). Modelling the biological variance of the yellow aspect of Granny Smith apple colour. *Journal of the Science of Food and Agriculture*, *90*(5), 798−805.

Tijskens, L. M. M., Sloof, M., Wilkinson, E. C., & van Doorn, W. G. (1996). A model of the effects of temperature and time on the acceptability of potted plants stored in darkness. *Postharvest Biology & Technology*, *8*, 293−305.

Tijskens, L. M. M., Unuk, T., Okello, R. C. O., Wubs, A. M., Šuštar, V., Šumak, D., & Schouten, R. E. (2016). From fruitlet to harvest: Modelling and predicting size and its distributions for tomato, apple and pepper fruit. *Scientia Horticulturae*, *204*, 54−64. Available from https://doi.org/10.1016/j.scienta.2016.03.036.

Tijskens, L. M. M., Unuk, T., Tojnko, S., Hribar, J., & Simčič, M. (2009). Biological variation in the colour development of Golden Delicious apples in the orchard. *Journal of the Science of Food and Agriculture*, *89*(12), 2045−2051.

Tijskens, L. M. M., van Kooten, O., & Schouten, R. E. (2006). Modeling for globalization, Conference MQUIC, 7 August 2006, Bangkok *Acta Horticulturae*, *712*, 51−58.

Tomlins, K., Manful, J., Gayin, J., Kudjawu, B., & Tamakloe, I. (2007). Study of sensory evaluation, consumer acceptability, affordability and market price of rice. *Journal of the Science of Food and Agriculture*, *87*, 1564−1575.

Unuk, T., Tijskens, L. M. M., Germšek, B., Zadravec, P., Vogrin, A., Hribar, J., . . . Tojnko, S. (2012). Effect of location in the canopy on the colour development of three apple cultivars during growth. *Journal of the Science of Food and Agriculture*, *92*(12), 2450−2458.

van Boekel, M. A. J. S. (1999). Testing of kinetic models: Usefulness of the multiresponse approach as applied to chlorophyll degradation in foods. *Food Research International*, *32*, 261−269.

van Boekel, M. A. J. S. (2000). Kinetic modeling in food science: A case study on chlorophyll degradation in olives. *Journal Science Food Agriculture*, *80*, 3−9.

van Boekel, M. A. J. S., & Tijskens, L. M. M. (2001). Kinetic modeling. In L. M. M. Tijskens, M. L. A. T. M. Hertog, & B. M. Nicolaï (Eds.), *Food process modeling*. Cambridge: Woodhead Publishing.

Van Dijk, C., & Tijskens, L. M. M. (2000). Mathematical modeling of enzymatic reactions as related to the texture of fruits and vegetables after storage and mild preheat treatments. In S. M. Alzamora, S. M. Tapia, & A. López-Malo (Eds.), *Design of minimal processing technologies for fruit and vegetables* (pp. 127−152). Aspen Publishers Inc.

van Keulen, H., de Wit, C. T., & Lof, H. (1976). The use of simulation models for productivity studies in arid regions. In O. L. Lange, L. Koppen, & E. D. Schulze (Eds.), *Ecological studies analysis and synthesis* (19, pp. 408−420). Verlag, Heidelberg: Springer, ISSN 0070-8356.

Van Kooten, O., & Kuiper, E. (2009). Consumer acceptability in flower chains: How can we determine what the final customers really want? *Acta Horticulturae*, *847*, 17–26.

Venus, V., Asare-Kyei, D. K., Tijskens, L. M. M., Weir, M. J. C., de Bie, C. A. J. M., Ouedraogo, S., … Smaling, E. M. A. (2013). Development and validation of a model to predict postharvest losses during the transport of tomatoes in West Africa. *Computers and Electronics in Agriculture*, *92*, 32–47.

Verbeke, G., Molenberghs, G., & Rizopoulos, D. (2010). Random effects models for longitudinal data. In K. van Montfort, J. Oud, & A. Satorra (Eds.), *Longitudinal research with latent variables*. Berlin, Heidelberg: Springer. Available from http://doi.org/10.1007/978-3-642-11760-2_2.

Wierenga, P. J., & De Wit, C. T. (1972). Simulation of heat transfer in soils. *Soil Science Society of America Proceedings*, *34*, 845–848.

Wittstock, U., & Burow, M. (2007). Tipping the scales—Specifier proteins in glucosinolate hydrolysis. *IUBMB Life*, *59*(12), 744–751. Available from https://doi.org/10.1080/15216540701736277.

Zhang, L., Zhang, B., Zhou, J., Gu, B., & Tian, G. (2017). Uninformative biological variability elimination in apple soluble solids content inspection by using Fourier transform near-infrared spectroscopy combined with multivariate analysis and wavelength selection algorithm. *Journal of Analytical Methods in Chemistry*, *2017*. Available from https://doi.org/10.1155/2017/2525147, art. no. 2525147.

This page intentionally left blank

CHAPTER

5

Models for improving fresh produce chains

Deepak Aggarwal[1] *and Stanley E. Prussia*[2]

[1]Department of Engineering, Sam Higginbottom University of Agriculture, Technology and Sciences, Allahabad, India [2]College of Engineering, University of Georgia, Athens, GA, United States

Abbreviations

CLD	causal loop diagrams
CSP	critical systems practice
FFVV	fresh fruit and vegetable value
GUI	graphical user interface
HAS	human activity system
MIT	Massachusetts Institute of Technology
PAM	purposeful activity model
PAS	purposeful activity system
RD	root definition
SOSM	system of systems methodology
SSM	soft systems methodology

Models facilitate learning in three ways. Developing a model requires knowledge and understanding of the interactions by the object or system with its surroundings and internal parts. Research is often necessary to fill information gaps that often are discovered. Then, users of the model learn by experimenting with extreme conditions and by visualizing and understanding events that normally happen too fast or too slow or are too large or too small to observe in real life.

More models of fresh produce chains are needed for integrating plant physiology, technology, and management practices for improving each business link and entire chains. Most chapters in this book use one or more types of models.

"Based on current trends, it is therefore highly likely that models will increasingly become part of the everyday toolkit used in agriculture, food processing, and distribution." (Holger, 2019).

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00005-1

5.1 Background

Models are part of our everyday lives more than we realize. "For example, maps and plans are models of the layout of the roads, rivers, buildings or other features of our physical environment. An architect's sketch, or an engineering drawing is a model of some artefact which is to be constructed. Prior to constructing that artefact, we may be shown a scale model of it to test our reactions, or to see how it might operate." (Lane, 2019).

Some models are as simple as the equation for a spring, $f = k \times d$ where f is force, k is a constant multiplied by d, the distance moved. Other models, like those predicting weather patterns, are very complex. The size scales of models range from representing subatomic particles to the movement of galaxies. Time-lapse and high-speed photography help us visualize how plants grow and to see how hummingbirds fly. Simulations and gaming models can make learning enjoyable.

"Models are explicit, simplifying interpretations of aspects of reality relevant to the purpose at hand. They seek to capture the most important variables and interactions giving rise to system behavior. They are used as surrogates for real-world systems for the purpose of carrying out experiments." (Jackson, 2019). A premise of this chapter is that models can help us understand how to improve fresh fruit and vegetable value (FFVV) chains.

Fresh produce passes through various links of refrigerated (see also Chapter 15) or non-refrigerated value chains from the farmer's plot to the consumer's plate (see also Chapters 2, 5, 6, and 11). Extensive research since the 1960s has focused on deciphering the ideal postharvest handling conditions to maximize product shelf life for different produce species. However, ideal conditions are seldom met in real-life value chains as the produce travels from field to sorting area, packaging, loading, transportation, unloading, retail display, the car, and home. Further, retail and food service managers often are not provided information about previous handling that affects the remaining shelf life at their link of a value chain (Prussia & Mosqueda, 2006).

The ideal storage temperature and humidity conditions recommended to increase shelf life are rarely followed during the true-life cycle of fresh produce shipments (see Chapter 16). In addition, the storage conditions generally recommended by researchers are those which maximize the shelf life, which might not be the intended requirement of consumers. Rather, the primary goals of consumers might be firmness, color, ripeness, rupture strength, and taste (see also Chapter 3, 17, 19, and 21).

Models predicting postharvest quality changes could help decision makers alter shipment destinations and storage conditions so that fresh produce arrives with the desired characteristics. Examples are provided below for models that can help reduce loss and waste and provide consumers with desired fresh produce attributes. Tijskens and Schouten (Chapter 4) describe the development of models to predict postharvest changes based on fundamental plant physiology, advanced data measurement and analyses, and innovative modeling methods.

5.2 Model types

Many types of models have been developed for different purposes and systems. Authors have different ways of presenting various types of models based on the systems they are intended to support. Three authors committed to improving organizations have three different lists for types of models (Ackoff, 1999; Jackson, 2019, Lane 2019). The point is that even within one field of application there is a wide range of terminologies.

5.2.1 Contrasting model pairs

Lane (2019) discusses his list of four types of models by stating that "each of the different modelling techniques can be more or less appropriate for different situations, and for different types of systems which have been identified." Managers and leaders who increase their knowledge and understanding of many types of models will be better able to incorporate advances in postharvest handling into their daily operations.

5.2.1.1 Table listing contrasting model types

One way to organize selected types of models is to list them as pairs of contrasting types as shown in Table 5.1. Only a few of many possible pairs are listed. Descriptive words are given for each model type in the table. More details are provided for some of the model types in the following sections.

Some of the models from Table 5.1 are described later to illustrate diverse or novel types. Combinations of different model types often occur. Iconic models are most often tangible and dynamic. Conceptual models are often qualitative and soft. More details are given in Section 5.2.2 for some models that have been used or have potential for adaption for improving postharvest handling of fresh produce.

TABLE 5.1 A list of selected contrasting types of models with related keywords.

Contrasting types of models	
Iconic, physical	*Mental, conceptual*
Scale, breadboard	Visual, verbal, metaphors
Real, tangible	*Virtual*
Photos, sculptures, mockups	Stories, role play, drawings
Quantitative, analytic, math	*Qualitative, judgment*
Logic, graphs, financial	Visual, rich pictures, opinion
Deterministic	*Stochastic*
Known in/predicable out	Distributions of data in/out
Hard, unitary	*Soft, pluralist, purposeful activity*
Known goals, agreement	Social, differing worldviews
Static	*Dynamic, simulations*
Fixed over time	Changing, output becomes input
Batch	*Interactive, gaming*
One data set per input/output	Outside monitor and control

5.2.1.2 Iconic models

Iconic models use physical materials to give a strong visual resemblance between the original and the model but with different materials or size scales that have similar shapes or patterns. Small plastic blocks, a fraction of full-size equipment, could be used to evaluate alternative layouts for a new packinghouse. Stacking patterns for marine-refrigerated shipping containers could be demonstrated using scale model paper containers, pallets, and boxes.

5.2.1.3 Mental models

Mental models are qualitative conceptualizations that help us simplify the complex world around us. We have mental models of how we expect people to react if we say or do certain things. We also have expectations of how physical objects respond to different inputs. Implicit mental models can limit how we perceive the world about us (Lane, 2019). Most people only think about a value chain that starts with a grower pushing fresh produce into a chain that ends with a consumer. Starting with consumers that pull product through a chain changes how we understand the people, organizations, and problems.

5.2.1.4 Conceptual models

Most of the models listed in Table 5.1 are conceptual models. Iconic/similitude and real/tangible are exceptions because they are intended to be models of the real world. A model of a concept is quite different because to be a good model, it need not have this real-world correspondence. Checkland (1999) defines conceptual models (CMs) with very narrow terminology because his conceptual models are an integral part of soft systems methodology (SSM). CMs for SSM are visual diagrams with a boundary containing subsystems representing activities necessary for the human activity system (HAS) to function. The subsystems are identified with verbs to indicate actions that can actually be taken. So, admonishments like "succeed" and "improve" must be avoided. Figure 5.2 is an example of a CM with the purpose to "simulate holistically".

5.2.1.5 Hard systems models

Hard systems are hard in the sense that participants have defined firm objectives with known goals. Stakeholders are in unity about what is needed. Jackson (2019) states "Participants defined as being in a unitary relationship have similar values, beliefs, and interests. They share common purposes and are all involved, in one way or another, in decision-making about how to realize their agreed objectives." This unity can be true for a single business link in an FFVV chain but is unlikely to apply to the total chain.

5.2.1.6 Soft systems models

A free lesson on systems engineering from the open university (Anon, 2019) explains that the hard systems approach is used when problems and opportunities can be clearly defined while the soft systems approach is used when there is little or no agreement about the problem. Soft systems have stakeholders with a plurality of viewpoints about the system to be modeled. Jackson (2019) explains that people in a pluralist relationship have the same basic interest, but they do not have the same values and beliefs. They can overcome their differences if both sides are allowed to participate in decisions that are made. Longer lasting marketing arrangements can be expected if produce buyers and packinghouse owners/managers are involved in the details for new arrangements such as developing a quality management system.

5.2.1.7 Summary

Ackoff (1999) points out that it can be harmful to use models developed for physical systems for management systems. So, models and methodologies such as SSM need to be used for learning how to improve decisions made by managers and leaders of links in FFVV chains.

5.2.2 Models with applications for postharvest

The models described in this section have been adapted or have potential to be adapted for FFVV chains. Most of the models discussed are included in one or more of the 11 methodologies in Jackson's (2019) system of systems methodology (SOSM) diagram. New models can be expected to also fit into one or more of the methodologies described by Jackson.

5.2.2.1 Bond graphs

Bond graphs are not mentioned in Jackson's (2019) SOSM but would be included in his hard systems thinking methodology. Diagrams representing the dynamics of a physical system can be drawn using bond graphs. "In bond graphs, elements are connected by *bonds* through *power ports*. Each bond represents an effort-flow pair that when multiplied give the power entering or leaving the attached ports." (Kypuros, 2013). The components of one system can be connected together by power that flows through one or more domains identified as translational, rotational, electrical, and hydraulic domains.

A common example of a single translational domain is the suspension system of a truck consisting of a mass (vehicle), spring (usually a coil, air bag, or leaf), and dashpot (shock absorber). The power (effort × flow) moving through each port of a translational domain is force × velocity. All four domains exist for hydraulic bin dumpers at packinghouses. Power (effort × flow) moves through electrical cables (volts × amperes), to an electric motor (torque × angular velocity), to a hydraulic pump (pressure × flow rate), and to a hydraulic cylinder (force × velocity). Thus the bin dumper can be analyzed quantitatively as a system.

Established procedures are followed to write differential equations directly from bond graphs that represent the dynamics of the system. Otherwise, equations are written based on experience or general principles. Rather than obtaining one high-order differential equation that is difficult or impossible to solve, the process gives multiple first-order equations. For the truck suspension example, two first-order equations rather than one second-order differential equation can be written directly from the bond graph diagram. The equations are then solved using matrices to give values for the state of variables such as force, acceleration, and displacement as a function of time. Results are the status of the state variables for the system as a function of time.

Kypuros (2013) gives details about how the bond graphs can be used to model and analyze dynamic systems. A more recent book *An Introduction to Bond Graph Modeling with Applications* (Tenreiro Machado & Cunha, 2021) presents a reader-friendly introduction to bond graph modeling tools. They give an in-depth theoretical background and provide numerous exercises and problems.

Bond graphs would be an ideal model for learning ways to reduce mechanical damage to fruits and vegetables during their many modes of handling and transport from farm to fork. Results from bond graphs could quantify the amount of energy transmitted from rough roads to individual fruits through suspension systems and packaging. Fruits and vegetables bruise when the force from the energy exceeds their elastic limit. Bond graph models are especially well suited for identifying harmful vibration frequencies (resonance) that damage fruits and vegetables during transport. Enterprising researchers and students are encouraged to explore additional opportunities for applying bond graphs to FFVV chains.

5.2.2.2 System dynamics models

Systems dynamics is one of the most common applications of systems thinking. Jay Forrester was a professor at the Massachusetts Institute of Technology (MIT) when he developed systems dynamics. When he published the first book on the subject, Forrester (1961) used the term "Industrial Dynamics."

In the 1960s, Professor Jay Forrester at the MIT developed The Beer Game as a board game to help improve the management of supply chains (Dizikes, 2012; Martinez-Moyano, Rahn, & Spencer, 2014; Snyder, 2021; Sterman,1989). The System Dynamics Society (2021) began selling Beer Game kits for the board game version in 1992. The Society sold about 20 kits that year; in 2004, it sold over 1100 kits (Martinez-Moyano et al., 2014).

One purpose of the Beer Game is to learn about the structure of systems and the processes that occur within the structure. Instructors at executive workshops use it to demonstrate the Bullwhip Effect, the impact of hidden information, and the importance of coordination across supply chains. Another point learned is that operations must be managed as a system, not as a set of isolated activities. Thompson and Badizadegan (2015) make the point that difficulties managing inventory when playing the Beer Game "suggests that perfect information about demand is not the real issue, and that poor performance results from failure to understand the system and individual and organizational behavior."

Learning about the Beer Game motivated researchers at the University of Georgia to develop a computerized Peach Game, as described in Section 5.3.2. The purpose of the Peach Game is to help retail produce managers and others improve their understanding of the consequences of their ordering decisions. Causal loop diagrams (CLD) in Fig. 5.1 are one of the hallmarks of system dynamics that were used for the Peach Game. The Delay built into its Reinforcing Loop shown in the CLD is what makes the game challenging.

A second hallmark of system dynamics is stock and flow diagrams that are also used in the Peach Game. Stocks are the reservoir and flows are the rate of removal or input of stocks. Equations that describe stocks, flows, and the state of the stocks can be simulated in discrete or continuous time intervals. Terms from system dynamics that have become common include "unintended consequences," "leverage points," and "archetypes."

Senge (2006) published a business management book that includes extensive descriptions and examples of systems thinking, system dynamics, and CLD. System dynamics is also

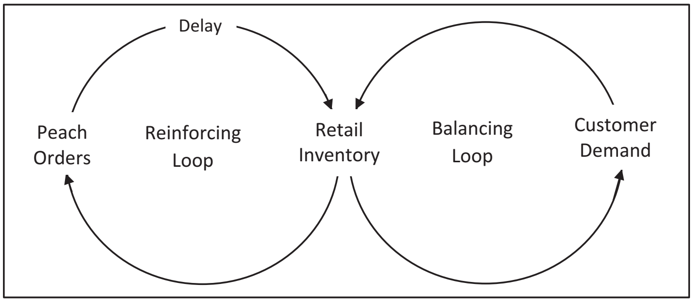


FIGURE 5.1 CLD with reinforcing and balancing loops. *CLD*, Causal loop diagrams.

described in a very understandable way by Meadows, Randers, and Meadows (2008). Her previous book, *Limits to Growth* (Meadows, Meadows, Randers, & Behrena, 1972), made her well known for the system dynamic models predicting that existing world economic growth is unstainable.

At the time of this writing (April, 2021) MIT Management Executive Education plans to offer business leaders a 1-week program where organization leaders "will be introduced to a variety of tools, including mapping techniques, simulation models, and MIT's management flight simulators—such as the Beer Game—which they can apply to their own business environment as soon as they complete the program" (MIT, 2021b).

5.2.2.3 *Simulation and gaming models*

This section discusses simulation and gaming models in general. Simulations are included in the annual Cornell University, SC Johnson College of Business five-day Food Executive Program (2021). Two of the 10 instructors for the 2021 class will use a "simulation exercise on strategic turnaround" to "guide teams through a computerized competition operating a retail food company in a very dynamic and competitive market." Such high-level interest indicates that additional computer simulation models and games developed specifically for FFVV chains could be beneficial to a wide range of users (see Sections 5.3 and 5.5.2.3).

5.2.2.3.1 Simulation models

Sterman (2021) at The MIT Sloan School of Management states "Deep actionable knowledge and decision-making skills develop when people have the chance to apply classroom theory in the real world, with its messy complexity, time pressures, and irreversible consequences... Management simulation games bring an *experiential* aspect to learning about complex systems." (emphasis added).

One of the books describing simulation models (Smith, Sturrok, & Kelton, 2018) includes details for using the simulation package SIMIO. Another book on simulation modeling (Law, 2015) gives a comprehensive description of simulation models. Topics with special application to FFVV chains include modeling, simulation software, model verification and validation, and analysis of simulation experiments.

The web site for Simio (2021a) describes a competition sponsored for college students using SIMIO to improve real-world businesses and organizations. Each year the top three winning teams prepared videos describing their models. Over the several years of the competition, very few of the winners had modeled anything about food production, handling, or marketing. One video was about improving the operations at a restaurant. Another team simulated supply chains for an international manufacturer (nonfood). A third team modeled processing operations at a hybrid seed company.

FFVV chains could benefit from simulations based on software such as SIMIO in similar ways as the businesses described by all the student winners. A free download of SIMIO is available (Simio, 2021b). Another source of free simulation software is from MIT (2021a). Forio (2021) is a company (in partnerships with MIT and other business schools) that develops custom and many ready-to-run simulations (for purchase). The closest simulation to FFVV chains is one for the global supply chain for coffee beans that includes activities for the creation of a cost-effective and flexible supply chain, forecasting, building production plans based on a probabilistic demand forecast, and evaluating process performance measures.

5.2.2.3.2 Simulation video games

SimFarm® is a managerial/business simulation video game first released in 1993 by Maxis. Single players build and manage a virtual farm. The game included a teacher's guide, masters for student worksheets, and a user's guide. SimFarm is the "country cousin" to SimCity that was published 4 years earlier. One of the many other spin-offs from SimCity is The Sims, now at version four, The Sims 4. The parent company, Electronic Arts, Inc., claims to have more than 300 million registered players around the world (Electronic, 2021).

SimFarm simulates a real farm from one of nine climatic regions in the USA selected by the player who places buildings, buys and sells livestock, and plants crops. Weather and seasons present real-world challenges, including tornadoes, droughts, pests, and dust storms. The four types of livestock have specific food and water requirements and produce offspring. Maximizing profits for each crop requires players to select the necessary season, farm equipment, and management practices related to water requirements, temperature requirements, and resistance to pests, weeds, and diseases. Sales of crops and livestock are the main revenue-raising items in SimFarm®. The player lives in a homestead that can be expanded after each simulated year if enough money is made by the end of the year.

Farming Simulator® is another managerial/business simulation video game series developed by Giants Software and published by Focus Home Interactive (Farming Simulator, 2021). Recent versions have a multiplayer mode and online mode with other players. Giants, 2021 claims to have sold more than 25 million copies and has been downloaded 90 million times on mobile applications during its first 11 years.

Farming Simulator® simulates locations that are based on American or European environments. Players are able to farm, breed livestock, grow crops, and sell assets generated from farming. In career mode, the player's task is to update initial farm and machinery. The main goal of the players is to produce crops and sell them to expand their fields, animals, and buildings. The player can choose from several crops to grow and can invest money in additional fields and equipment. Livestock may be purchased and cared for. In mission mode the player performs various tasks such as mowing grass or delivering cargo within a time frame that is dynamically generated. Players who complete the task are rewarded with a sum of money and a bonus based on how quickly the task was completed.

Neither SimFarm nor Farming Simulator has options to grow fruits or vegetables (except potatoes). Players could add to their valuable learning experiences if the companies developed similar simulations of growing multiple fresh fruit and vegetable crops and preparing them for various markets.

5.2.2.4 Models for soft systems methodology (SSM)

Models are central in the description of SSM by Checkland and Poulter (2006). SSM provides a way for improving fresh produce value chains by viewing them as if they are systems. Checkland (1999) describes the conceptual models used in SSM to represent a HAS (human activity system). In the updated version of SSM (Checkland & Poulter, 2006), the term HAS is replaced with the term "purposeful activity system (PAS)." Models representing a PAS are called purposeful activity models (PAMs).

Before developing a model for a PAS, a root definition (RD) is needed. RDs are a verbal statement (model) describing the PAS to be modeled. The RD can be checked for completeness by using the mnemonic: customers, actors, transformation, weltanschauung, owner, environment (Checkland & Poulter, 2006):

C	Customers:	The victims or beneficiaries of T
A	Actors:	Those who would do T
T	Transformation process:	The conversion of an input to an output
W	Weltanschauung:	The worldview which makes this T meaningful in context
O	Owner(s):	Those who could stop T
E	Environmental constraints:	Elements outside the system which are taken as given

One of the purposes for developing the postharvest quality simulator described in Section 5.3.1 was to learn how much consumption quality was reduced by delays in cooling blueberries and peaches after harvest. An interdisciplinary team was organized at the University of Georgia to use a systems approach for the purpose of improving business links in a typical value chain for the products. When considering the various activities for the development of the postharvest quality simulator, it can be considered a learning system called "simulate holistically." In retrospect, we used the three Ss that were identified later for systems thinking as a way to learn unknowns—Select models, Simulate holistically, and Share results (See Chapter 2).

One possible RD for the learning system that resulted is

A learning system owned by college academic departments developed by individual researchers to guide their interdisciplinary team for taking a holistic approach to simulate FFVV chains to improve quality for consumers, reduce losses, and increase farmer profits.

The CATOWE for the RD is

C—Consumers and business links in FFVV chains

A—Interdisciplinary team members
T—The team's need for research guidelines was provided by the 3 Ss model
W—Simulations have the potential to result in changes that improve postharvest handling
O—academic departments of the researchers
E—Academic departments have different learning paradigms and expectations that could complicate team communications and cooperation.

Checkland and Poulter (2006) provide preparations for building PAMs (2006), give five logical steps for building PAMs, describe a model for building PAMs, and give instructions for building models for PASs. These include:

- Show a boundary to delineate what activities are included in the system and those outside.
- Use verbs to describe activities that can be done by the actors.
- Use between five and nine activities.
- Make sure hierarchies are correct by outlining subsystems of the activities in additional models.
- Use arrows to indicate interactions and communications among activities and their sequence.
- Include a manage activity that includes plan, monitor, and control.
- Show the transformation from the RD.

The model in Fig. 5.2 illustrates the activities described in the previous RD. The activity in the center, simulate systems, is described in more detail in Section 5.3.1. The activity labeled "Verb" indicates all activities must be verbs. All activities need to have separate RDs and be modeled as subsystems. A key to SSM is to develop more than one RD and PAM for the different worldviews of customers, owners, actors, or other stakeholders.

5.2.2.5 Models for critical systems practice

Critical systems practice (CSP) is a multimethodology developed by Jackson (2019) to achieve improvements over time in complex organizations like the businesses in FFVV chains. Chapter 2 describes CSP and suggests applications for postharvest handling. The 11 methodologies that Jackson (2019) deems the most important for management practice are described in Chapters 9–18 of this book. "CSP helps managers to evaluate the usefulness to them, in their situation, of different management solutions and, particularly, different systems methodologies and methods, and to use them in combination if necessary."

5.3 Models developed for fresh produce at the University of Georgia

This section focuses on models developed specifically for FFVV chains. Aggarwal and Prussia were the developers of the first two models presented here, so more details were available for describing them than for the other models in this section.

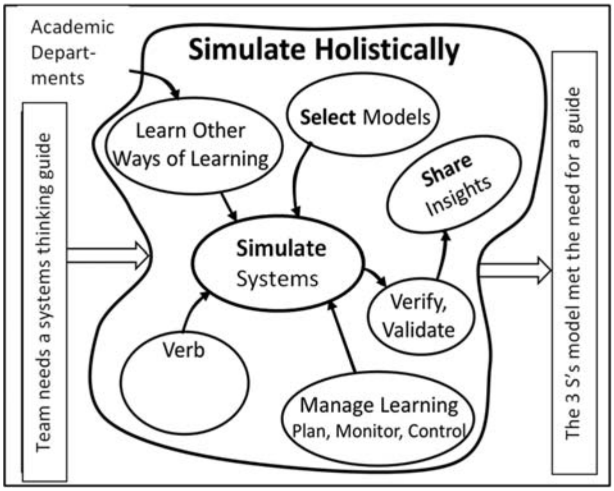


FIGURE 5.2 A conceptual model based on Soft systems methodology (SSM) that represents activities needed to "simulate holistically."

5.3.1 The postharvest quality simulator

5.3.1.1 Background

One motivation for developing a model for postharvest changes in quality was to quantify the old adage "Cool fruits and vegetables as soon as possible." Also, there was interest to have an interactive model for easily evaluating the difference in the quality that was available for consumers after different combinations of time and temperature at each link in a chain.

5.3.1.2 Model development

A research team at the University of Georgia desired to model postharvest changes in the quality of blueberries and peaches (Aggarwal, Prussia, Prussia, et al., 2003). They started by conducting storage studies at temperatures typical for links in FFVV chains. Firmness and mass were selected as attributes of interest to consumers and because nondestructive measurement instruments were available for both. Repeated measurements of the same items over time also allowed smaller sample sizes (25), thus enabling evaluation of more cultivars with the available resources. The seven cultivars of blueberries and nine for peaches were available locally, as was needed for cooling the fruit within a few minutes after harvest. Samples of fruit were stored at four temperatures (1°C, 12°C, 22°C, and 32°C) at 95% relative humidity until no longer consumable.

The development of equations for predicting loss of firmness and mass for all cultivars was similar to the following example for "Tifblue" blueberries. Fig. 5.3 shows the average rate of firmness loss of berries when stored at 12°C was linear with a slope of 0.066% per hour. The same value is circled in Table 5.2 where slopes are shown for all seven blueberry cultivars at four storage temperatures.

Firmness $F(t)$ at the end of a storage time (t) at a fixed temperature (Temp) was calculated by using the regression equation for each cultivar. Eq. (5.1) is for "Tifblue." $F_{(t=0)}$ is the initial firmness at the start of one of the storage times. The initial firmness was reduced by the time of storage multiplied by the regression equation from Fig. 5.4, the circled term in Eq. (5.1). The

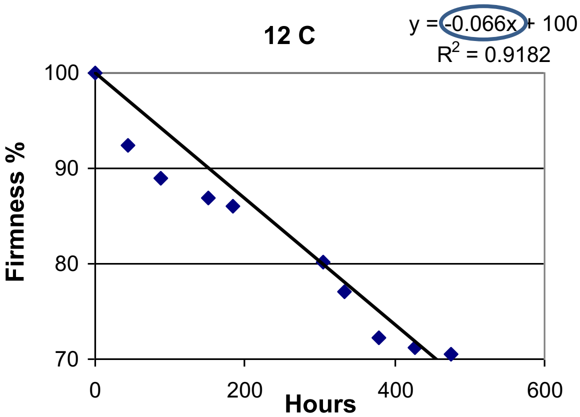


FIGURE 5.3 Linear regression model of firmness for "Tifblue" blueberries stored at 12°C.

TABLE 5.2 Slopes for seven cultivars at four temperatures.

	Rate of percent firmness loss (%/h)			
Cultivar	**1°C**	**12°C**	**22°C**	**32°C**
Climax	0.0311	0.0431	0.0721	0.1196
Premier	0.1317	0.1495	0.1683	0.2593
Tifblue	0.0402	0.0660	0.0901	0.1908
Brightwell	0.043	0.0487	0.0517	0.0654
Powder blue	0.0206	0.0316	0.112	0.3957
Yadkin	0.042	0.075	0.1172	0.2519
Baldwin	0.0523	0.066	0.123	0.2121

The slopes were then plotted as a function of the four storage temperatures (Fig. 5.4) with the data point of 0.066 circled at 12°C. Exponential regressions gave good fits for all the cultivars between y and x. Thus a value for y (the rate of firmness loss, %) could be calculated for any value of x (temperature, °C) within the temperature range.

firmness and mass calculated for the end of each link was the input for the next link in a value chain. The first link started at 100% firmness. Eq. 5.1 enables calculation of firmness based on initial firmness and as a function of the time held at a specified temperature. A similar equation was developed for mass.

$$F(t) = F_{(t=0)} - t\,(0.0366\,e^{0.0483\,\mathrm{Temp}}) \tag{5.1}$$

The simulation models were then applied to each link in typical value chains. The initial mass and firmness at harvest and the time and temperature in the field were the variables used for calculating the percentage change in quality values for the first link. Inputs to subsequent links were the outputs from the previous links (Aggarwal, Prussia, Prussia,

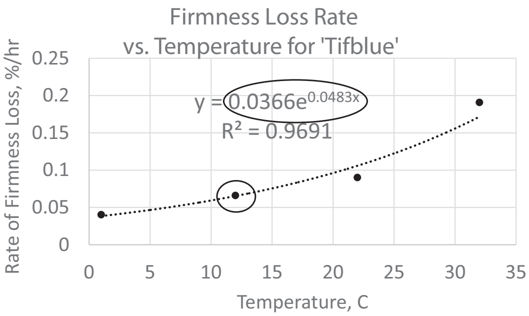


FIGURE 5.4 Firmness loss rate versus temperature for "Tifblue."

FIGURE 5.5 Dashboard for postharvest quality simulator showing "Tifblue" blueberries.

et al., 2003). Eq. (5.1) represents a transition from the scientific method to systems thinking in the form ready to develop a simulation model.

Fig. 5.5 shows the user-friendly graphical user interface (GUI) that was developed (Aggarwal, Prussia, Florkowski, & Lynd, 2011a) for running simulation models. The equations for predicting changes in mass and firmness of blueberries and peaches were entered into spread sheets. A column of cells was reserved for entering the time duration selected by a user for each of the eight rows reserved for links in a hypothetical value chain. Likewise, a column was reserved for entering the temperature selected for the link. A reference column enabled entering temperatures that gave nearly ideal results for comparing with the simulated chain. Visual basic provided an interactive GUI that covered details of the spreadsheet that were not needed by the user.

Worksheets at the start of the simulation enable selecting blueberries or peaches and the cultivar desired. The "back" buttons return to the previous screens. Users tap in desired values for time and temperature (reference and main) for each link in the value chain. Updated values are immediately displayed on plots for the total duration the fruit was in the chain. Blueberries have plots for both mass and firmness that include lines for "eating quality threshold." Plots for peaches show only firmness. Peaches are climacteric (ripen after harvest) so two lines are shown for firmness; one for retail "ready to sell" and the other for consumers "ready to eat." Repeated simulations were done for different conditions to learn the consequences of different times and temperatures at each link in the simulated chain.

The model can simulate the quality of blueberries and peaches during their journey through the various links of a value chain. A noteworthy result is the visibility of rapid mass and firmness losses for the short times at high temperature such as at a loading dock and in a car. The model is user-friendly and can show the residual shelf life of the produce. The models developed were suitable for evaluating practical postharvest situations such as the impact of different delay times before cooling. Likewise, producers can quantify the benefit of lowering temperatures during cooling delays or the benefit of reducing cooling delays.

5.3.1.3 Results

In general, the loss of mass and firmness during storage for 1 h at 34.2°C = 1 day at 2°C. Other simulations showed that lowering temperature by 10°C in the field for 1 h extended shelf life by 15 h. For "Tifblue" berries, lowering the field temperature from 40°C to 20°C extended shelf life by 4 days in the home. These results demonstrate latent damage; the loss of shelf life at one link does not become evident until a later link. Each cultivar differed in shelf life. All simulations ran showed that expediting delivery through the entire chain would benefit consumers.

Users of the postharvest quality simulator have included many college students, university graduate students and faculty, researchers at government agencies, and managers of links in a FFVV chain. Everyone quickly learned how to use the simulation and liked the ease of evaluating different combinations of times and temperatures links in value chains.

5.3.1.4 Discussion

A user-friendly simulation model makes it possible to replace the common adage "cool as soon as possible" with verifiable answers on the benefits for lowering temperatures and reducing distribution times for the blueberry and peach cultivars studied. A copy of the postharvest quality simulator model is available from the authors. Others are encouraged to develop and publish similar simulations for other fruits and vegetables. A nagging question remains, "Who pays the farmer for the costs of extending shelf life for consumers?"

5.3.2 The Peach Game

The Peach Game developed at the University of Georgia (Aggarwal, Prussia, Florkowski, & Lynd, 2011b) was patterned after the Beer Game originally developed at the MIT by Professor Jay Forrester in the 1960s as described by Dizikes (2012) and Martinez-Moyano et al. (2014).

5.3.2.1 Background

Fresh produce orders made by grocery stores need to be timely and in response to consumer demand to minimize postharvest losses and maximize profits. A computer simulation game for ordering peaches was developed to help produce managers improve their understanding about peach value chains (Aggarwal et al., 2011b). The principles learned are intended to help them when ordering other fresh fruits and vegetables.

The quality and availability of fresh produce at retail grocery stores are determined by ordering decisions made by produce managers. Quality is lowered when excess product is ordered that cannot be sold for several days. Ordering less than customers demand results in empty displays, unhappy customers, and loss of revenue. A simulation game would enable produce managers to enhance their ordering skills by experimenting with different strategies without the risk of disrupting their actual operations. The Peach Game was developed as an entertaining approach for learning about fresh produce retailing.

5.3.2.2 Development

The Peach Game is a computer simulation based on the four-stage board game Sterman (1989) developed from the original Beer Game. The Peach Game was developed for fresh produce retail managers and others interested in improving value chains. Players assume the role of a fresh produce manager at a retail grocery store. Their goal is to minimize peach inventory without running out of stock. This game accounts for the complexity of the sector, combining system dynamics and systems thinking to model and simulate the essential elements responsible for meeting consumer demand.

A visual graphic user interface software (STELLA, n.d.) was used to model typical peach value chains and to develop the necessary equations. The game simulates the Consumer, Retailer, Wholesaler, and Farmer links in a peach value chain. The game emphasizes the importance of correct ordering based on deterministic or stochastic consumer demand, inventory management, delays in produce delivery, perishability, and initial capital. Success in the game is assessed as the financial performance of the retailer and not ending the session due to depleted inventory. The game has eight levels, each with increasing complexity.

Specifically, the simulation requires weekly input decisions at the retail link of a chain. It is designed to help retailers improve fresh produce ordering decisions without risking the actual consequences of suboptimal decisions or unpredictable outcomes in an actual market environment. The simulation in the form of a game provides an interactive, hands-on experience to understand the concepts and to develop skills desired in the fresh produce industry. The developed game combines the individual perception of systems with the mechanics of change in the chain and combines the flexibility associated with adaptation to the emerging circumstances with the rigidity imposed by the time sequence of operating systems.

Like most programs, Stella opens with a blank window. A screen shot of the completed development for the introductory level for version 1.0 of the Peach Game is shown in Fig. 5.6. The icons in the tool bar at the top were dragged to desired positions as needed to build the dynamic systems model. The four boxes at the top of the work area contain the functions for Consumer, Retailer, Wholesaler, and Farmer. Transport between the links was represented by delays in delivery. The interconnections between the functions established the logic and dynamics of the model. The arrows on the far-left toggle between the diagram shown and screens with lines of code that were automatically written as the connections were made. Additional code was added manually for labels, data input, and other details.

When the game is first opened, a title screen appears with a button for going to the system description screen that explains the main functions of the four FFVV chain links. Then a button opens the game description screen that lists YOUR GOALS, INITIAL STATUS, and TIME HORIZON. The next screen gives instructions for interacting with the dashboard. For example, one click on the run button simulates 1 week. The number of boxes ordered that week is set by a sliding button. Displays show current status of the quantity

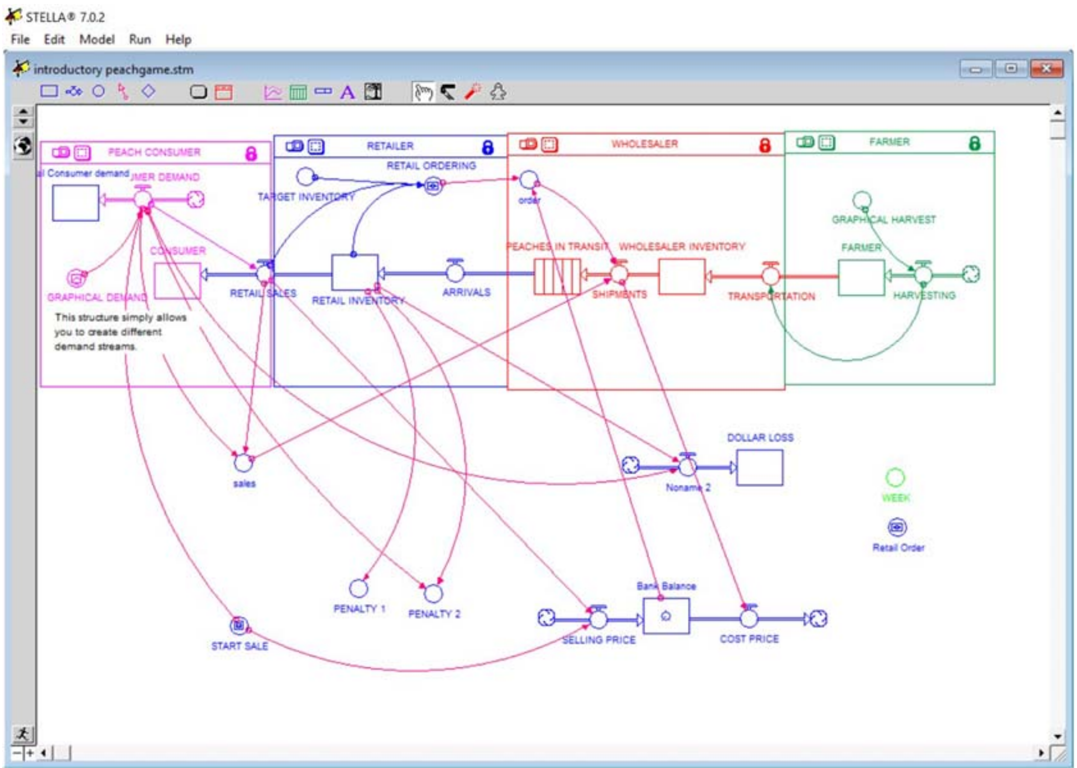


FIGURE 5.6 Stella development window for the introductory level Peach Game.

demand and the retail inventory. Finally, buttons are available for going to the introductory level or all the other levels of the game.

Players of the introductory level are given a diagram for consumer demand that starts with one box per week on week 13 as shown in Fig. 5.7. Consumer demand increases by one box per week until reaching a maximum of 15 boxes on day 27 before returning to zero at the same rate. Peaches become available at the same increasing rate from the farmer starting on week 7. The peach season ends after week 42. The number of boxes ordered by the player each week is automatedly sent to the wholesaler, and on to the farmer. There is a 2-week delay from when the retailer places an order until the boxes arrive. The retail inventory and consumer demand traces on the plot are extended each time a week is simulated. The "conclude" button goes to a screen with some debriefing questions and a list of five evaluations from "good" to "perfect" based on the dollar loss scores shown.

Based on experience with the first Peach Game, a second version was developed with four additional features available as shown in Fig. 5.8. The second version also has an updated introductory level of play that does not have the four new features, A—D.

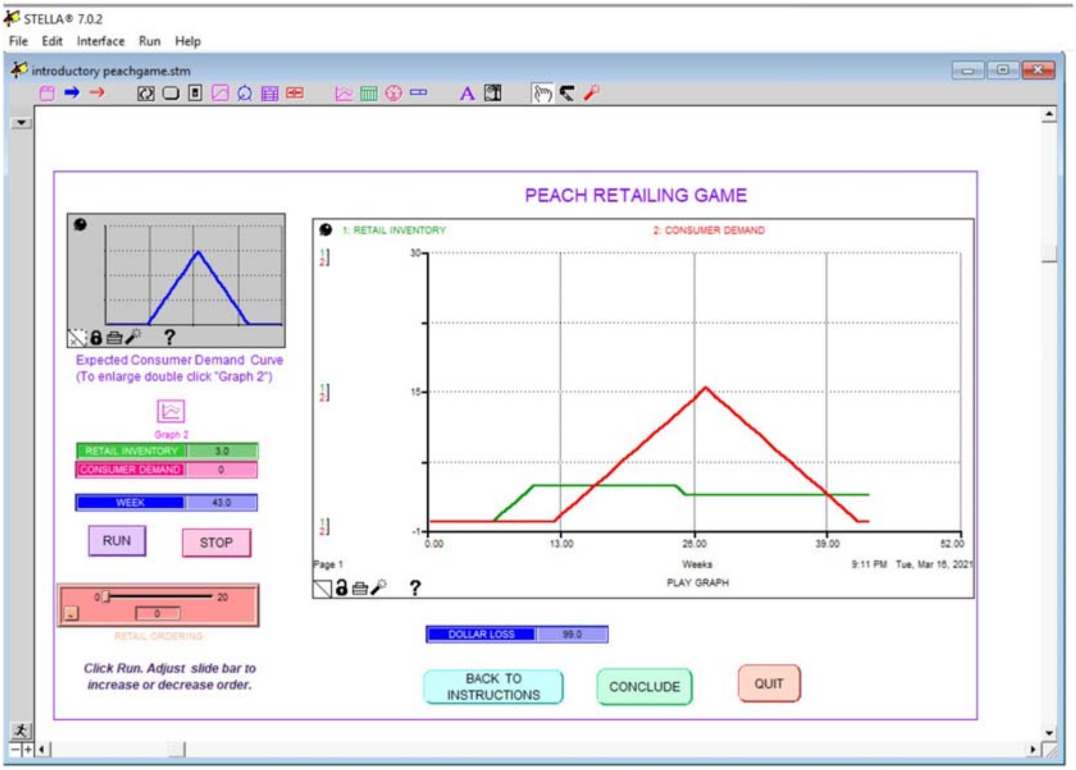


FIGURE 5.7 A screenshot of the dashboard of introductory level for the first version of the Peach Game.

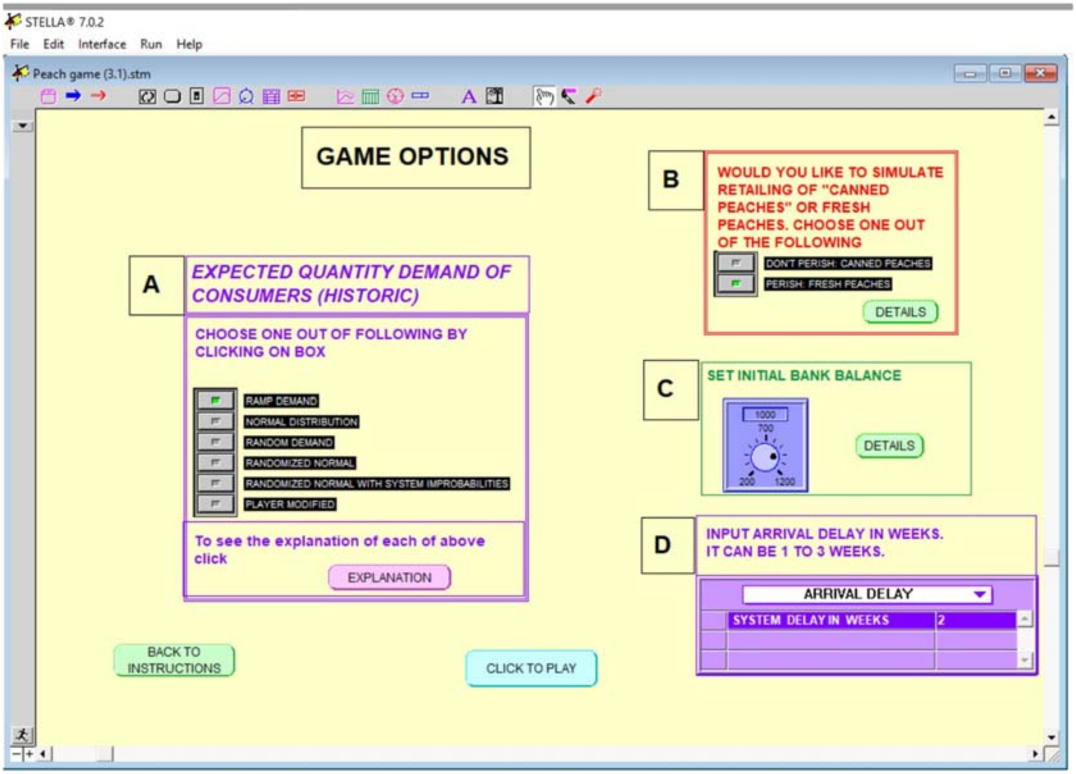


FIGURE 5.8 Game options for the multiple level Peach Game.

The dashboard for "Game Options" for multiple levels of the second version of the Peach Game is shown in Fig. 5.9. A button can be toggled to start or end a sale that is available to lower excessive inventory. When peaches are on sale the quantity demanded doubles, but the profit is reduced from 50% to 20%. The CLICK TO SEE PLAY HISTORY button goes to a screen with three plots; QUANTITY DEMAND, BANK BALANCE, and RETAIL ORDER. A button is provided for deleting data from all the three plots.

5.3.2.3 *Results*

Preliminary plans for developing the Peach Game were shared at an international symposium in New Zealand (Prussia, Florkowski, Sharan, Naik, & Deodhar, 2001). Descriptions of the completed game were published (Aggarwal, Prussia, Florkowski, & Lynd, 2003, 2004). The second edition of the Encyclopedia of Agricultural, Food, and Biological Engineering (Aggarwal et al., 2011b) includes the same article that was in the first edition published in 2004.

The Peach Game (mostly the introductory level for the two versions) has been played by a wide range of users in different settings. All were able to quickly learn to run it and to understand its output. Produce managers confirmed it represented the difficulty of

FIGURE 5.9 Dashboard for the introductory level of play for version 2 of the Peach Game.

ordering fresh produce. The Peach Game has been played by several hundred users at postharvest workshops conducted in the USA in Georgia (four venues), Florida, and California. It was played at international workshops or seminars in Thailand, The Netherlands, Mexico, and The Philippines (seven venues—at government research agencies, universities, and professional societies). Only one person of the hundreds of players calculated the exact number of cases needed each week and had a zero inventory each week and always met the quantity demanded.

A typical Bullwhip Effect is shown in Fig. 5.10 that results from overreaction to the risks of the game ending due to zero retail inventory. Retail orders (trace 3) were made in steady steps of increase and decrease. Initial orders were 5 cases until inventory (trace 2) started to level off (week 15), triggering a jump to 10 cases. A second decrease in retail inventory triggered the player to double the retail orders on week 24 that resulted in the spike in retail inventory that did not occur until week 30. The player had reduced orders from 20 back to 10 on week 28, but it was too late to avoid the bullwhip effect.

Both the lack of inventory (game over) and the bullwhip effect occur frequently, even when playing the introductory level with a simple ramp demand that is known and with plots visible each week (trace 1). The consequence of overordering to avoid ending the

FIGURE 5.10 Peach Game results illustrating the Bullwhip Effect.

game is excess inventory that causes extended storage and the resulting loss of quality shown in the Postharvest Quality Simulator (Section 5.3.1).

Feedback from stakeholders and other groups confirmed that the game provides a hands-on, interactive tool to learn about complex concepts in postharvest fresh produce retailing. Players were surprised at the difficulty of maintaining low inventory without running out of stock, even at the easiest level. The simulation game provides an interesting way to help retail managers and others understand the dynamics of postharvest marketing systems. The desired outcome will be more fresh produce without the risk of empty shelves indicating the loss of revenue opportunity.

5.3.2.4 Discussion

The lessons taught by the simulation emphasize a few issues in fresh produce supply chains: (1) the stochastic nature of the consumer demand as measured by the quantity consumed in each time period; (2) the need to minimize current inventories; (3) the effects of delays in the delivery inherent in the system; (4) the perishability of fresh produce; (5) the placement of produce on sale as a tool for managing inventories and meeting demand, and (6) structure (delay) is more important than process.

As per the systems thinking analysis, one of the greatest factors that may affect the fresh produce consumption is the retail and retail displays. The decisions made by the retailer not only impact the consumer's eating experience but also are instrumental in impacting the efficiency, longevity, and finances of whole value chains.

5.3.3 Models for soft systems

Soft system models are necessary when attention is focused on management and leadership rather than plant physiology and technology. The interdisciplinary team at the University of Georgia took a systems approach from the beginning by working with different links in FFVV chains. After several years, we realized that it could be interesting to assemble representatives from major business links for discussions on how to reduce losses and improve the quality available to consumers.

5.3.3.1 Background

A 1-day workshop was organized at the University of Georgia for managers and owners of business links for FFVV chains (Prussia & Werner, 2000). The 20 participants at the first workshop represented consumers, restaurants, supermarkets, fresh-cut processors, wholesale dealers, truckers, packinghouses, growers, and researchers. Teams were formed at the first workshop to discuss how links in fresh produce chains affect quality/safety/loss. The teams then shared their observations with the whole group.

5.3.3.2 Development

The participants at the first workshop requested a second workshop. It was conducted 4 months later with mostly the same individuals. PAM's were explained to them as presented in Section 2.2.4. The full group participated to identify the verbs and interactions representing a PAM for consumers. Teams were then formed to identify six to eight verbs to describe the main activities of the other links [Market (Retail), Market (Restaurant), Distribute, Process, Transport, Pack, and Grow]. Each team then presented to the rest of the group the activities they identified for their link.

5.3.3.3 Results

At the end of the first workshop an important comment was that it was the first meeting they knew about that had been specifically organized for all the businesses in fresh produce chains to meet with the purpose of discussing ways to improve fresh produce quality and to reduce losses. Fig. 5.11 shows the results from the beginning of the second workshop when the full group listed the verbs and interactions for consumer activities, including the linking interactions of the subsystems represented by the verbs. The PAM diagram shown was drawn later based on the input at the workshop. The results of the

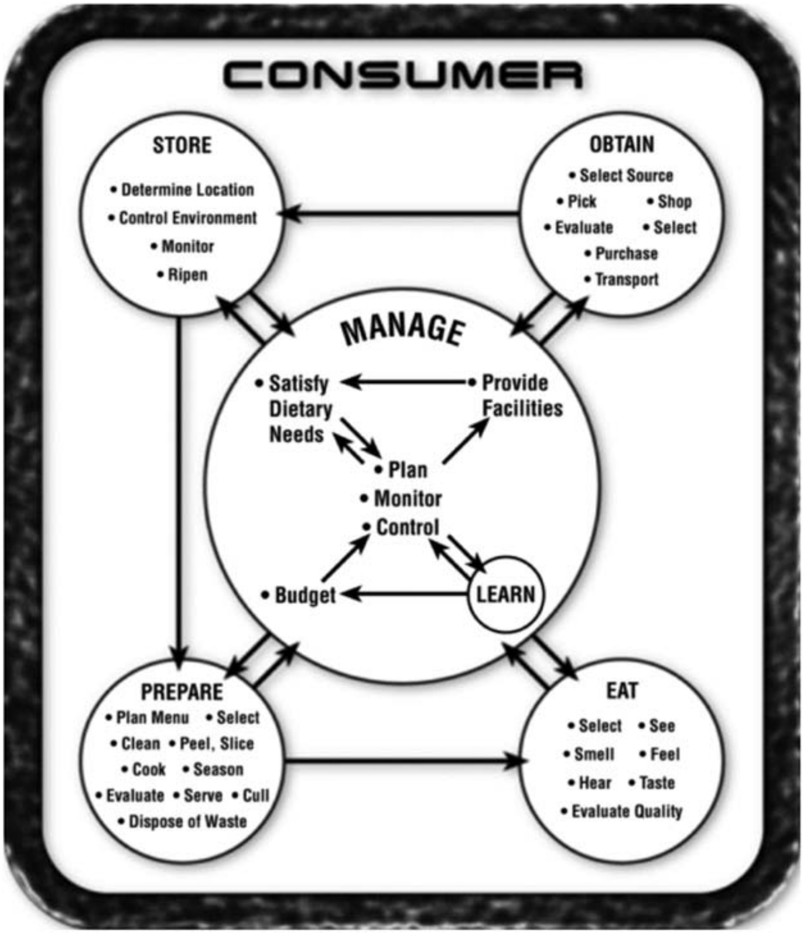


FIGURE 5.11 Purposeful activity model for consumers.

teams developing PAM's for separate links was published (Prussia & Werner, 2000; Prussia, 2000a; 2000b).

5.3.3.4 Soft systems methodology discussion

Fresh-cut processors were found to have the most interactions with other links because they purchase, arrange transport, and market to restaurants, institutions, grocery stores, and other retailers. One result of the workshop was the visualization of the need for a better understanding of the roles that each link has with other businesses. One participant from a business link recognized the need to improve their understanding of other employees in their own link. The simple requirement from SSM for using verbs to represent the activities for a system was very effective for organizing group discussions and developing models representing each link in fresh produce chains.

5.3.4 Discussion

The models and simulations presented in this section are only a tiny start for what could and should be done with models to better understand FFVV chains. A few more models by other researchers are presented in the next section.

5.4 Selected models for fresh fruit and vegetable value chains by others

The first two models presented here for FFVV chains are similar to the Peach Game. The third model simulates the impact of decisions made at a single link on the whole food ecosystem. The final model estimates quality changes of individual items throughout a cold chain.

5.4.1 The Tomato Game

A board game was developed for selling and buying of tomatoes in a marketing chain with links for growers, cooperatives, wholesalers, and retailers (Van Haaften, Lefter, Lukosch, van Kooten, & Brazier, 2020). Researchers and representatives from the chain participated in the development of the interactive game. Players could request cards with information about the link in the chain they had selected to play. Volumes traded were determined by rolling dice. Players had a limited time to negotiate the volume and price for their deals. The researchers concluded, "Involving stakeholders from the field in the design, development and execution of the gaming simulation (sessions) enables explication of tacit knowledge from participants, independent of the field of application."

5.4.2 The Fruit Game

Researchers in Italy (Busato & Berruto, 2006) expanded on the Peach Game using an object-oriented simulation language, Extend to develop the *Fruit Game*. It simulates decisions required for links of value chains for strawberries, zucchini, and tomatoes. It allows testing of diverse logistic and transport solutions. "The FruitGame simulate[s] all the activities in the supply chain, like production, packaging and transportation between the links. The model tracks all the events that occur to each box of product. In this way it is possible to evaluate the shelf life and other quality parameters in great detail."

5.4.3 The food value chain gaming-simulation

Accorsi, Bortolini, Baniffaldi, Pilati, and Ferrari (2017) explain their gaming-simulation tool that was developed within LabVIEW Integrated Development Environment. They start with market demand to simulate value flows that started with the agricultural/production stage and progress through distribution/transport, storage, consumption, and waste/disposal stages. They adopted a pull paradigm that enabled "lead companies to better understand their processes and the interdependencies with other actors, to simulate their supply chain operations, to identify bottle necks or quantify the benefits from adopting some monitoring, traceability and real-time control technologies."

This gaming-simulation tool (Accorsi et al., 2017) enabled the users and planners to experience the effect of a decision on a given link of the network to the whole food ecosystem. Such a method is called gaming, because the users and planners play the levers of the network and experience the impact of their choices on the overall sustainability of a whole ecosystem.

5.4.4 Virtual cold chains

Fruit quality loss is dependent on the temperature control throughout a postharvest cold chain. Previous research has mainly focused on optimizing the cooling performance of single unit operations. However, assessing fruit temperature history throughout an entire cold chain is crucial to determine the end quality (see also Chapter 16: Investigating Losses Occurring During Shipment: Forensic Aspects of Cargo Claims). Wu et al. (2018) proposed a virtual cold chain (VCC) method to predict the temperature history and quality loss of packaged fresh fruit, down to each individual fruit, throughout the entire cold chain.

The VCC method is based on computational fluid dynamics and kinetic quality modeling. Results show that the difference in quality loss among individual fruits in a carton could reach 11% for a specific cold chain. The maximum difference in the remaining quality at the end of the cold chain between different cold chain scenarios is 23%. The VCC method has a potential to track temperature history and to estimate quality loss of individual fruit in the cargo throughout a cold chain.

5.4.5 Discussion

Valuable examples are available of system dynamics methodologies applied to FFVV chains in a recent book edited by Accorsi and Manzini (2019). Table 5.1 lists the chapters, describes the issues modeled for different phases of a food value chain, and lists the disciplines involved. Fig. 5.1 shows the physical flows of food from farm to consumer and important parts of the network contributing to the food ecosystem.

The recent examples in this section of developing simulations are encouraging. Yet, many more models need developed for a wide range of crops, locations, and approaches. Especially needed are models that integrate physiology and technology with management decisions.

5.5 New models needed for fresh fruit and vegetable value chains

Models help us make sense of the inputs we receive from the world around us. Simulation models help us evaluate potential improvements without the costs and risks of changing actual systems. The models, simulations, and games presented in Sections 5.3 and 5.4 were examples that illustrate ways to learn how to improve FFVV chains. Models are needed for many more crops, functions, decision options, and other system features before major benefits can be expected.

Models related to plant physiology and technical innovations have facilitated improvements in FFVV chains for most crops. However, Chapter 2 documents that three global needs have persisted for over five decades:

- Low per capita consumption of fruits and vegetables (see also Chapter 3,17, and 21),
- Losses and wastes are high, and
- Low family farm income.

Decisions by managers and leaders of businesses in each link of chains and organizations supporting chains hold the future for improving these three Ls. Expanded use of models like the ones shown in Sections 5.3 and 5.4 will be a necessary start. Then, different types of models than those used in the past are needed to improve individual businesses in an FFVV chain.

The most important need is to implement new methodologies for improving chains that consist of multiple businesses. Consultancies (interventions) using the complete SSM is an established way to improve organizations. CSP expands the choices of methodologies to 11 and provides overall guidance for interventions. Simulations and video games provide entertaining ways for learning the consequences to the entire chain from decisions made at any link.

5.5.1 Additional crops and functions

The postharvest quality simulators described in Sections 5.3 and 5.4 were only for a limited number of crops, cultivars, seasons, and other variables. Additional inputs are required to develop, verify, and validate more general models.

5.5.1.1 Postharvest quality simulation models

Many more models similar to the postharvest quality simulator need developed for both climacteric and nonclimacteric fruits and vegetables. Rather than using regression analyses, new plateaus would be reached by basing interactive postharvest quality simulations on the recommendations of Tijskens and Schouten (see Chapter 4).

5.5.1.2 Management simulation video games

New simulations and games are needed of fresh produce retail departments to help managers gain experience with a full range of decisions and actions necessary to maintain product quality, reduce waste, and satisfy customers. Similar simulations and games could help each business link in FFVV chains and related organizations.

5.5.2 Models for organizations and chains of organizations

Lasting systemic improvements in FFVV chains will require the development of models that decision makers can use to integrate management science approaches with existing and new plant physiology and technological developments. One of the largest challenges is to develop ways to improve interactions among links in chains that are not systems. They are not systems because they do not have one person or group with overall responsibility and authority. The methodologies in this section can provide progress for improving the organizations and chains of organizations related to fresh produce.

5.5.2.1 Soft systems methodology

SSMs would enable researchers to learn essential activities and interactions in fresh produce chains. Section 5.2.2.4 provides an overview of models based on SSM. All the resources available through SSM should be applied to study existing links in postharvest chains. Then, a suggested approach is to develop models and simulations of all the links in a chain as if it is one organization or system. Activities, interactions, and communications necessary for effective operations could then be determined. Any missing, duplicate, or ineffective activities or flows would then need the application of innovative ways to make improvements.

Discussions should include how changes to improve one link might affect other links. A top priority would be serious proposals for ways to make sure farmers receive fair compensation. Likewise, any other links in a chain that makes an investment benefiting consumers or other links in a chain must be assured they are rewarded.

Another recommended application of using SSM to model multiorganizational FFVV chains is to have managers/owners for each link in a chain develop an RD for the complete chain based on their worldview. All the resulting PAMs for each worldview would most likely be different. Discussions of the differences could help identify changes needed to improve interactions and flows of product, money, and information.

Comprehensive models of postharvest chains will greatly enhance the ability of researchers and managers to identify needs and develop recommended changes based on Checkland's law of conceptualization "A system which serves another cannot be defined and modeled until a definition and a model of the system served are available" (Checkland, 1999).

5.5.2.2 Critical systems practice

CSP developed by Jackson (2019) and described in Section 5.2.2.5 could guide the learning needed to fill knowledge gaps about the management of postharvest links and chains. Jackson recognizes that even his broad-based CSP is not yet prepared to guide interventions in chains of organizations (such as FFVV chains). "This thinking will have to be adapted in other contexts such as multiorganizational settings."

Experienced practitioners will be needed to do comprehensive interventions (consultancies) for selected FFVV chains using CSP. Multiple methodologies, methods, models, tools, and techniques can be expected to be applied. Results can be expected that will provide inputs on how CSP can be applied to other multiorganization.

5.5.2.3 Simulation video games for fresh fruit and vegetable value chains

Video games have reached a level of technology and popularity that makes it realistic to develop video games connecting the links for FFVV chains. Most of the content in this chapter and other chapters in this book would be needed to develop comprehensive video games that function like the Farming Simulator or SimCity described in Section 5.2.2.3. Additional inputs would be needed to model all the business links in selected chains. Benefits would include new understanding of chains that would be needed to develop video games and the experience gained by managers, leaders, researchers, students, and others who play the games.

Video games like SimCity could add activities in a home that included purchasing fruits and vegetables. Consumption modeling could include meal planning according to recommendations in "My Plate" (USDA, 2021) or other guidelines. Future health results of good nutrition could be visually compared with poor nutrition choices made earlier in the game. Children eagerly eating good tasting fruit could be simulated and compared with frustrated parents trying to get children to eat fruit with poor taste. The flow of money entering a chain could reflect the purchase appeal to the customer/consumer. Decisions made by retail grocery stores, schools, restaurants, hospitals, and other institutions could be simulated in a video game to show consequences of decisions causing poor storage, excess inventory, no stock, or other factors that affect quality or profit.

Players could also establish strategic and tactical infrastructure and decision policies of simulated food service providers that would determine the quality and costs of produce they deliver. Players could design, build, and operate packinghouses based on the player's understanding of sorting, packaging, cooling, and other options available in the game. For example, signal detection theory (see also Chapter 13) could help players learn if high defect rates were due to technical or personnel problems. The existing Farming Simulator, SimFarm, or other games would need to add fruits and vegetables to their choices of products to grow and sell.

Multiplayer, real-time gaming would be ideal with one or more players establishing and operating each simulated business and consumer in an FFVV chain. Chains could be simulated as if they are systems so interactions and communications among the links could be better understood.

5.5.3 Discussion

Playing simulation video games would be an entertaining method for everyone interested in fresh fruits and vegetables to experience the challenges and satisfactions of learning the consequences of decisions they make while playing the role of manager at each link in a selected chain. Developing a comprehensive simulation video game as described would require extensive knowledge of the activities in all the links for selected chains and the interactions within the links, with other links, and with organizations beyond the chain. When developing models, researchers often discover knowledge gaps that require specialized research.

Lack of models by SimFarm, Farming Simulator, or other sources represents an opportunity for them or others to develop simulation games for fresh produce chains. Simulation video games could be a capstone for integrating the research necessary to understand the complex interactions among and within the links of FFVV chains. Many types of models would be required ranging from iconic to soft. Learning about value chains would result from the process of developing the models, the research necessary to fill information gaps, and users of the model as they experiment with extreme conditions not possible in real life.

Public funding for developing models and for sponsoring interventions for improving FFVV chains should come from national and international agencies (such as USDA and

FAO) because the main beneficiaries will be farmers and consumers (see also Chapters 18 and 20). Simulations and games could show how large retail grocery stores and restaurant chains would benefit by paying for investments made by farmers and packers for improvements like superior genetics, gentler field transport, earlier cool, upgraded sorting equipment, and adequate packaging.

Granting agencies could encourage research projects that have interdisciplinary teams, including systems thinkers for the development of models using methodologies such as SSM and CSP. The development of managerial/business simulation video games needs to be prioritized with online, multiplayer games representing the links in typical FFVV chains.

5.6 Recommendations

A systems approach to postharvest handling of fresh fruits and vegetables needs to include models that help decision makers in each business link in value chains to understand the interactions among all the businesses in a chain. Decisions at every link need to be based on an understanding of plant physiology and the engineering technology that ensures that consumer expectations are satisfied or exceeded. Chapter 2 provides a framework for developing models needed by postharvest businesses.

Three recommendations for developing models intended to improve FFVV chains are:

- Develop models of several diverse fruit and vegetable chains using the SSM to learn details about their activities, interconnections, flows of information, and political and social environments to understand how they could function as if they were systems.
- Use the critical systems thinking methodology as a guide for learning the technical, managerial, and social changes necessary to increase per capita consumption, reduce losses and waste, improve profits for family farms and other global issues related to postharvest handling of fresh produce.
- Develop simulation models and games that enable a single decision maker to understand the consequences resulting from their decisions when managing a simulated single link in a chain or for a group of decision makers to learn how to improve a complete simulated chain.

References

Accorsi, R., & Manzini, R. (Eds.), (2019). *Sustainable food supply chains*. Academic Press. Available from https://doi.org/10.1016/B978-0-12-813411-5.00003-X.

Accorsi, R., Bortolini, M., Baniffaldi, G., Pilati, F., & Ferrari, E. (2017). Internet-of-things paradigm in food supply chains control and management. *Procedia Manufacturing*, *11*, 889–895, 27th International Conference on Flexible Automation and Intelligent Manufacturing, FAIM2017, 27–30 June 2017, Modena, Italy.

Ackoff, R. L. (1999). *Ackoff's best: His classic writings on management*. New York: John Wiley.

Aggarwal, D., Prussia, A. J., Prussia, S. E., Nunez, A., NeSmith, D. S., Florkowski, W. J., & Lynd, D. (2003). Predicting fresh produce quality in supply chains. *Acta Horticulturae*, *604*, 179–188.

Aggarwal, D., Prussia, S. E., Florkowski, W. J., & Lynd, D. (2003). Simulation game for fresh produce retailing. *Focus on Biological Engineering Features Resource*, *10*(5), 12. Available from https://link-gale-com.proxy-remote.

galib.uga.edu/apps/doc/A101889234/AONE?u = uga&sid = AONE&xid = 7163a457. Gale Academic One File. Accessed 09.04.20.

Aggarwal, D., Prussia, S. E., Florkowski, W. J., & Lynd, D. (2004). Simulation game for peach retail ordering systems. *Interactive Multimedia Electronic Journal of Computer-Enhanced Learning*, *6*(1).

Aggarwal, D., Prussia, S. E., Florkowski, W. J., & Lynd, D. (2011a). Produce quality simulator. In D. R. Heldman, & C. I. Moraru (Eds.), *Encyclopedia of agricultural, food and biological engineering* (2nd ed.). New York: Marcel Dekker Inc.

Aggarwal, D., Prussia, S. E., Florkowski, W. J., & Lynd, D. (2011b). Produce retailing simulation, in. In D. R. Heldman, & C. I. Moraru (Eds.), *Encyclopedia of agricultural, food, and biological engineering* (2nd ed.). New York: Marcel Dekker Inc.

Anon. (2019). *Systems engineering: Challenging complexity*. <Systems engineering: Challenging complexity: 3.7 Systems methodologies for managing change—OpenLearn—Open. University—T837_1>.

Busato, P., & Berruto, R. (2006). FruitGame: Simulation model to study the supply chain logistics for fresh produce. In F. Zazueta, J. Kin, S. Nimomiya, & G. Schiefer (Eds.), *Computers in agriculture and natural resources: Proceedings of the 4th world congress conference* (pp. 488−493). ASABE Publication, Number 701P0606.

Checkland, P. (1999). *Systems thinking, systems practice, includes a 30-year retrospective*. Chichester: Wiley.

Checkland, P., & Poulter, J. (2006). *Learning for action*. Chichester: John Wiley & Sons.

Cornell. (2021). *Food executive program*. Cornell Dyson. https://dyson.cornell.edu/outreach/fimp/programs/food-executive-program/ Accessed 11/30/2021.

Dizikes, P. (2012). *The secrets of the system*. MIT News Office, MIT News, Massachusetts Institute of Technology. <The secrets of the system | MIT News | Massachusetts Institute of Technology> Accessed 19.03.21.

Electronic Arts. (2021). *Maxis studios – official EA sites*. < Maxis Studios−Official EA Sites> Accessed 02.04.21.

Farming Simulator. (2021). *Official website | farming simulator*. <farming-simulator.com> Accessed 02.04.21.

Forio. (2021). *Global supply chain: Management simulation – Simulation ready-to-run*. Forio. <Global Supply Chain: Management Simulation−Simulation Ready-to-Run | Forio> Accessed 31.03.21.

Forrester, J. W. (1961). *Industrial dynamics*. Cambridge, MA: Productivity Press.

Holger, M. (2019). Chapter 3: *The role of modeling and systems thinking in contemporary agriculture*. In R. Accorsi, & R. Manzini (Eds.), *Sustainable food supply chains* (pp. 39−47). Academic Press, ISBN 9780128134115. Available from https://doi.org/10.1016/B978-0-12-813411-5.00003-X.

Jackson, M. C. (2019). *Critical systems thinking and the management of complexity*. Hoboken, NJ: Wiley.

Kypuros, J. (2013). *System dynamics and control with bond graph modeling* (1st ed.). Boca Raton, FL: CRC Press.

SDS. (2021). *The Beer Game: A production-distribution game*. System Dynamics Society. <The Beer Game: A Production-Distribution Game - System Dynamics Society> Accessed 23.04.21.

Giants Software. (2021). *Giants software on the quiet, surprising success of farming simulator*. VentureBeat. <GIANTS Software | Home (giants-software.com)> Accessed 29.01.21.

Lane, D. (2019). *Systems modelling*. OpenLearn Lesson by The Open University, Walton Hall, Milton Keynes, United Kingdom, MK7 6AA. Systems modelling—OpenLearn—Open University—T553_1. Accessed 26.02.21.

Law, A. M. (2015). *Simulation modeling and analysis* (5th (ed.)). McGraw-Hill Series in Industrial Engineering and Management.

Martinez-Moyano, I. J., Rahn, J., & Spencer, R. (2014). *The Beer Game: Its history and rule changes* (13). <researchgate.net> Accessed 01.04.21.

Meadows, D. H., Meadows, D. L., Randers, J., & Behrena, W. W. I. I. I. (1972). *The limits to growth: A report for the club of Rome's project on the predicament of mankind*. New York: Universe Books.

Meadows, D. H., Randers, J., & Meadows, D. L. (2008). *Limits to growth: The 30-year update*. White River Junction, VT: Chelsea Green Publishing Company.

MIT. (2021a). *About | MIT Sloan*. <About Teaching Resources Library | MIT Sloan> Accessed 03.04.21.

MIT. (2021b). *Business dynamics: MIT's approach to diagnosing and solving complex business problems*. Offered by Massachusetts Institute of Technology, Management Executive Education. June 7−15, 2021. Complex Business Problem Solving. <mit.edu>. <Management Simulations | MIT Sloan> Accessed 19.03.21.

Prussia, S. E. (2000a). Methods and examples of integration. In R. L. Shewfelt, & B. Bruckner (Eds.), *Fruit and vegetable quality: An integrated view* (pp. 267−284). Lancaster, PA: Technomic Press.

Prussia, S. E. (2000b). Soft systems methodologies for modeling postharvest chains. *Acta Horticulturae*, *536*, 653−660.

Prussia, S. E., Florkowski, W., Sharan, G., Naik, G., & Deodhar, S. (2001). Management simulation game for improving food chains. *Acta Horticulturae*, *566*, 231−236. Available from https://doi.org/10.17660/

ActaHortic.2001.566.28. Available from https://doi.org/10.17660/ActaHortic.2001.566.28. Management Simulation Game for Improving Food Chains. actahort.org.

Prussia, S. E., & Mosqueda, M. R. P. (2006). Systems thinking for food supply chains: Fresh produce applications. *Acta Horticulturae*, *712*, 91–104.

Prussia, S. E., & Werner, J. E. (2000). Roles and interactions of business links in postharvest chain. In W. J. Florkowski, S. E. Prussia, & R. L. Shewfelt (Eds.), *An integrated view of fruit and vegetable quality* (pp. 31–38). Lancaster, PA: Technomic Press.

Senge, P. M. (2006). *The fifth discipline: The art & practice of the learning organization*. New York: Doubleday.

Simio. (2021a). *Simio Software products for simulation and production scheduling*. Simio. <Supply Chain Simulation and Scheduling Software | Simio> Accessed 03.02.21.

Simio. (2021b). *Free simulation software—Simio personal edition*. Simio. <Free Simulation Software - Simio Personal Edition | Simio> Accessed 28.01.21.

Smith, J. S., Sturrok, D. T., & Kelton, W. D. (2018). *Simio and simulation: Modeling, analysis, applications* (5th Ed.). CreateSpace Independent Publishing Platform.

Snyder, L. (2021). *A brief history of the Beer Game*. < A Brief History of the Beer Game. by Larry Snyder|by Opex Analytics|The Opex Analytics Blog|Medium>. Accessed 19.03.21.

STELLA. *Systems thinking for education and research*. (n.d.). <http://www.iseesystems.com/softwares/Education/StellaSoftware.aspx>.

Sterman, J. (2021). *Management simulation games [WWW Document]*. *Manag. Simul*. MIT Sloan. Management Simulations | MIT Sloan, Accessed 08.02.21.

Sterman, J. D. (1989). Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science*, *35*(3), 321–339.

Tenreiro Machado, T. F. A., & Cunha, V. M. R. (2021). *An introduction to bond graph modelling with applications*. Chapman and Hall/CRC.

Thompson, K., & Badizadegan, N. D. (2015). *Valuing information in complex systems: An integrated analytical approach to achieve optimal performance in the beer distribution game*. IEEE. Available from https://doi.org/10.1109/ACCESS.2015.2505730 Accessed 19.03.21. http://authors.library.caltech.edu/65681/1/07360108.pdf Accessed 11/30/2021.

Van Haaften, M. A., Lefter, I., Lukosch, H., van Kooten, O., & Brazier, F. (2020). *Do gaming simulations substantiate that we know more than we can tell? Simulation & gaming* (pp. 1–23). Sagepub. Available from http://doi.org/10.1177/1046878120927048. Available from sagepub.com.

Wu, W., Cronjé, P., Nicolai, B., Verboven, P., Opara, U. L., & Defraeye, T. (2018). Virtual cold chain method to model the postharvest temperature history and quality evolution of fresh fruit – A case study for citrus fruit packed in a single carton. *Computers and Electronics in Agriculture*, *144*, 199–208. Available from https://doi.org/10.1016/j.compag.2017.11.034.

USDA. (2021). *MyPlate*. U.S. Department of Agriculture. <MyPlate|U.S. Department of Agriculture> Accessed 24.04.21.

PART 2

Product

This page intentionally left blank

CHAPTER

6

Challenges in handling fresh fruits and vegetables

Robert L. Shewfelt[1] *and Stanley E. Prussia*[2]

[1]Food Science and Technology, University of Georgia, Athens, GA, United States [2]College of Engineering, University of Georgia, Athens, GA, United States

Abbreviations

1-MCP	methylcyclopropene
DA	Difference in Absorbance
FAO	Food and Agricultural Organization
MSG	Management Simulation Games
RH	Relative Humidity

6.1 Introduction

Since the publication of the first edition of this book, we have seen advances in the understanding of postharvest handling from field to consumer. The efficiency of handling has improved as has an emphasis on quality as delivered to the consumer (Prusky, 2011). Issues like reduction of food waste and improving sustainability have gained more attention (FAO, 2015; FAO, 2019; Porat, Lichter, Terry, Harker, & Buzby, 2018). The general public is becoming more aware of the intricacies of value chains and why each business in the chain is important in delivering high-quality items to the market. The importance of health and nutritive properties of fruits and vegetables is being recognized, but not enough fruits and vegetables are being grown around the world (Mason-D'Croz et al., 2019) to fulfill the recommendations for a healthy diet (WHO, 2018). Another problem is the lack of access to fresh produce in low-income neighborhoods of metropolitan areas or in rural areas. These areas of low access to fresh, whole foods are known as food deserts (Parasecoli, 2019).

This edition continues our quest to merge the fields of postharvest physiology, postharvest technology, and systems thinking to develop a better appreciation of how to deliver fresh fruits and vegetables at levels of better quality and to prevent food loss and waste.

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00006-3

Advances in postharvest handling will require applied technological solutions. When we first introduced the topic over 30 years ago, few scientists and technologists had any appreciation for what could be achieved through a systems approach to postharvest handling. We are gratified that this approach has gained an appreciation from many colleagues around the world. We hope, through this edition, to extend the use of systems thinking to achieve a greater integration of handling operations. This chapter:

- outlines current approaches to postharvest handling,
- describes progress for integrating basic knowledge in physiology with technological advances,
- emphasizes the importance of systems thinking in advancing postharvest value chains, and
- illustrates continuing challenges to postharvest handling with particular emphasis on sustainability and managing postharvest chains.

6.2 Consumer-focused handling of fruits and vegetables from the consumer back to the farm

Fruits and vegetables don't appear all by themselves in homes or salad bars. Most of them travel through numerous steps from the growing location to the point of sale. This progression is referred to as the supply chain or value chain. In the early 1980s as a new research team, we introduced a new way of looking at these chains for fresh fruits and vegetables by viewing the steps as components of a system rather than focusing on them as individual, unrelated entities (Prussia, Jordan, Shewfelt, & Beverly, 1986).

At the time, we benefited from looking at chains as if they were systems, but Chapter 2 explains why they fail to meet the requirements necessary to be a system as defined by Wilson and Morren (1990). Recent reviews trace avocados (Bill, Sivakumar, Thompson, & Korsten, 2014) and sweet cherries (Habib, Bhat, Dar, & Wani, 2017) in postharvest chains. Money and (ideally) information about needs and desires flow through value chains from consumers to each business along the way. With the ultimate goal of satisfying the consumer, our journey begins in the home and works its way back to the farm.

6.2.1 Home handling and storage

Not all produce is taken to a home environment. Some items are consumed where they are purchased, and all handling stops at that point. Many items, however, are temporarily stored prior to consumption. Frequently, the weakest link in handling fresh fruits and vegetables is in the home because the consumer has limited information on how to best handle and store fresh items to maintain optimal quality (Shewfelt, Prussia, & Dooley, 2000). Too often, chilling-susceptible fruits and vegetables, such as bananas, are stored in the refrigerator when they should be held at room temperature.

Home refrigerators offer means to vary humidity and temperature within specific drawers and locations in the unit, but failure to take advantage of these features can lead to lowered quality. Storage in plastic containers or bags separates sensitive produce from ethylene and helps to maintain moisture (home refrigerators are good dehumidifiers).

In the home, shelf-life extension is usually not as important as maintaining acceptable quality for an item's expected life. Performance of a fruit or vegetable in the home depends upon its condition when bought from the retail outlet.

6.2.2 Retail sales, restaurants, and institutions

Fresh fruits and vegetables are sold to many different types of retail venues including supermarkets/grocery stores, corner stores/quick-stop gas stations, restaurants, open-air markets, produce stands, pick-your-own farms, outdoor festivals, and other sales locations. Supermarket chains are most likely to receive fresh items at large distribution centers and then assemble mixed loads for transport to individual stores. Such shipments may be to a single store or to many stores. If the load is small and the trip is relatively short, the temperature, ethylene, and Relative Humidity (RH) restrictions may not be as critical as for larger loads of longer duration.

Specialized food service companies buy fresh produce from packers or more often from distribution centers and sell to restaurants, schools, colleges, hospitals, military, prisons, nursing homes, cruise ships, caterers, and other institutions. Other paths are through processing companies that prepare fresh-cut, minimally processed, and prepared food (coleslaw, carrot and raisin salads, etc.). In the United States the percentage of total food expenditures purchased outside the home increased from 50.1% in 2009 to 54.4% in 2019 (USDA, ERS, 2020).

Most supermarket stores, restaurants, and institutions have limited storage space. Timely ordering and proper stock rotation are critical for maintaining fresh quality. To prevent cross-contamination, all fresh fruits and vegetables must be stored separately from raw meats, even case-ready (prepackaged) meat which could leak. Such operations may or may not have the adequate facilities to maintain separate temperatures for chilling-sensitive items or to keep ethylene-generators from those that are sensitive to the gaseous plant hormone. Most display cases are not necessarily optimal for storage of fresh produce.

Major losses of fruits and vegetables leading to food waste occur during retail operations and in the home after purchase (Porat et al., 2018). *Shrink* is the term used in the trade to assess the success of a produce operation. It refers to the economic loss incurred due to the loss of fresh items as they are sold at a lower than expected price or become unsalable. Estimates of shrink tend to be lowest for sweet corn and bananas but highest for turnip greens and papayas (Buzby, Bentley, Padera, Ammon, & Campuzano, 2015). Quick sales of items that begin to show blemishes can help recoup losses. *Shatter* refers to loss of items like grapes that become detached from the vine or disappear through customer grazing. Melons and other fruits that begin to show signs of deterioration can be salvaged by removing the rind followed by cutting and packaging in the back of the store under sanitary conditions (Barrett, Beaulieu, & Shewfelt, 2010). Perishability at retail is a function of proper handling during storage usually in a distribution center.

6.2.3 Storage at distribution centers

As in other links of a fresh produce chain, transport, temperature, presence of ethylene, and relative humidity are important factors in maintaining fresh quality. USDA Handbook Number 669 by the Agricultural Marketing Service (Ashby, 1995) lists recommended storage conditions for a wide range of products. Appendix II has eight load compatibility groups including recommended temperatures, relative humidity, and other important details when transporting fresh produce. USDA published a 780 page handbook in 2016 that includes a chapter (page 54) specifically on storage of fresh fruits and vegetables at distribution centers, along with many other chapters important for postharvest handling. (The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks). Chilling-sensitive commodities should be kept at a higher temperature than those that are not sensitive. Frequently, the innermost rooms of storage facilities are kept at the lowest temperature and separated from the outer rooms by doors or thick-slatted curtains that permit ready access to forklifts. It is crucial that the low temperatures are not so low that they cause freezing which can be very destructive to quality. Separate rooms are also necessary to keep ethylene-sensitive produce away from ethylene generators.

Climacteric fruits like apples or tomatoes may be held in an unripe state in a chamber low in ethylene until ready for market at which time they are treated by catalytically generated ethylene for artificial ripening (Zhang, Cheng, Wang, Khan, & Ni, 2017). The use of the ethylene inhibitor 1-MCP (1-methylcyclopropene) is effective in maintaining fruit quality during storage (Golding & Singh, 2016). Some operators carefully watch the market in an attempt to maximize profits. Rapidly respiring leafy vegetables may be cooled with ice, which also serves to keep up RH (relative humidity) as the ice melts and helps prevent shriveling due to loss of moisture. Fumigation with 1-MCP is an alternative means of maintaining green color in leafy greens (Al Ubeed, Wills, Bowyer, & Golding, 2018). Smart storage techniques are being developed to trace quality changes during storage (Wang, Zhang, Gao, & Adikhari, 2018). Performance in storage is a function of how an item was handled during transport.

6.2.4 Transportation

Transport of fresh produce varies widely based on distance to market. Local delivery may occur via open-air, small vehicles such as a pickup truck or larger vehicles containing mixed loads of various crops. The longer the time between harvest and point of sale, the more important it is to maintain temperature control (Negi & Anand, 2015; Ndraha, Hsiao, Vlajic, Yang, & Lin, 2018; Singh, Gunasekaran, & Kumar, 2018) (See also Chapter 15). A long-distance shipment is more likely to be confined in compartments containing a single crop in a controlled environment (Falagan & Terry, 2018; Vaycheslavovich, Adilovna, & Xasanovich, 2016). Refrigeration is not always recommended as some fruits such as bananas are susceptible to chilling injury and should not be transported or stored below their optimal temperature. Pretreatment with heat prior to storage can improve performance of chilling-sensitive fruits and vegetables when stored at lower than optimal temperatures (Yamauchi, 2013).

Ethylene-sensitive produce such as lettuce must be kept away from ethylene generators such as climacteric fruits and diesel-powered forklifts. Green leafy vegetables like kale and collards do not fare well in environments with low RH. During transportation by truck, mechanical damage can be induced by harmonic vibrations that can be mitigated by air-ride suspensions and proper packaging (Fernando, Fei, Stanley, & Eshaei, 2018). In trans-continental shipments, the side of the truck facing the sun will reach higher temperatures than the side receiving less sunlight. Likewise, floors have higher temperatures due to heat radiating from road surfaces. Careful handling during loading and unloading helps reduce damage in shipments. Such efforts are only as good, however, as proper operations in the packing facility.

6.2.5 Packing

After a crop is harvested it is typically transported to a packing facility where it is separated from trash, washed, cooled, sorted, and packed in boxes for shipment to a distribution center. Some items like lettuce and celery are packed in the field during harvest, but most crops go to a packing facility. The excessive depth of soft fruit in a transit wagon or vehicle can lead to bruising which may not become evident until a later handling step. Quick cooling is necessary for most items to remove the field heat and to slow respiration. Separating removes foreign materials and items not suitable for sale (see also Chapter 5).

Fruit that is acceptable for sale but too ripe for long-distance shipping is generally culled and sold locally. Traditionally, separating and sorting has been done by humans (Londhe, Nalawade, Pawar, Atkari, & Wandkar, 2013), but advancements are being made through optical-based scanning techniques (Vijayarekha, 2012; Zhang et al., 2018) (See also Chapter 13). Special care must be taken in how the items are packed in boxes prior to shipment. Many fruits and vegetables are packed into boxes with holes to facilitate forced air cooling after packing and to ensure refrigerated air in trucks can circulate through the box to maintain refrigerated temperatures during transport (see also Chapter 15). Fruits susceptible to bruising are packed in flexible trays to restrict movement and keep them from touching each other. The ability to withstand shipment after packing depends on the maturity of an item at harvest.

6.2.6 Harvest

Harvest is a critical time in determining the quality of a fruit or vegetable when purchased or consumed (Prusky, 2011). Climacteric fruits continue to ripen after harvest. If picked too early, these fruits are unlikely to reach full flavor. Picked too late and they are too fragile and are likely to arrive to the consumer with noticeable bruises. Maturity indices have been developed for certain fruits to guide proper harvest, with readings to estimate the presence of chlorophyll using a DA (Difference of Absorbance) meter instead of the standard color chips (Gonçalves, Couto, & Almeida, 2016). Nonclimacteric fruits must be allowed to reach peak maturity prior to harvest. Certain vegetables such as sugar snap peas if harvested too early are tender and succulent but very susceptible to bruising and mechanical damage.

With growing concerns over field labor, increased interest is being shown in mechanical harvesting of many forms of produce. The challenges in use of machines include the necessity for once-over harvesting, removal of more than just the target fruit or vegetable, and bruising of fruit that may not be evident at harvest but becomes noticeable at a later handling step. Quality maintenance of fruits and vegetables from harvest to the consumer can be influenced by a number of factors during growth and development in the field or orchard, many of which are difficult to trace.

6.2.7 Production phase operations

Although the emphasis of this book is on the crop after it is harvested, what happens to the plant before harvest affects the quality and stability of the fruit or vegetable as it wends its way through the chain. Early research by the University of Georgia postharvest team identified the interface between preharvest factors and postharvest quality as a critical area that needed exploration. Most studies in this area provide insight into how a specific preharvest factor affects a specific quality attribute for a specific fruit or vegetable. The ability to determine interaction effects of multiple independent preharvest variables on multiple dependent postharvest variables has not been achieved to date due to the complexity of necessary experimental designs.

Both general climate conditions and specific weather events such as rain, excess wind, hail, and frost can all affect purchase characteristics such as appearance and possibly even consumption characteristics such as flavor and texture (Bisbis, Gruda, & Blanke, 2019; Houston et al., 2018; Bisbis, Gruda, & Blanke, 2018). Selection of the cultivar can have profound effects on the quality and acceptability of an individual item at harvest, purchase, and consumption. The grower can manipulate conditions in the field through plant spacing, pruning and culling, fertilization, irrigation, or application of agricultural chemicals such as pesticides and growth regulators.

6.3 Toward a more integrated approach to handling

A systems approach to postharvest handling of fresh fruits and vegetables was taken from the beginning by the University of Georgia team. We realized the need to focus on consumers, as described in the introduction of Chapter 2. We were aware that it is natural for each group to blame others in a chain for their problems. And we viewed the trip from harvest to consumption as an integrated whole rather than a series of independent steps in value chains. To this end, we traced individual crops including southern peas (Jordan, Shewfelt, Hurst, & Prussia, 1985; Prussia & Shewfelt, 1985), tomatoes (Shewfelt, Prussia, Resurreccion, Hurst, & Campbell, 1987), peaches (Jordan, Meyers, Prussia, & Shewfelt, 1987), snap beans (Resurreccion, Hurst, Shewfelt, & Prussia, 1987), and blueberries (Aggarwal et al., 2003) through particular handling chains. Through systematic studies we learned that:

- to understand a handling system the specific steps needed to be diagramed from harvest to consumer (Shewfelt et al., 1987),
- the most difficult aspects to understand in any handling chain were the *preharvest effects* on postharvest quality and the effect of *purchase quality* at the point of sale on *consumption quality* by the consumer (Prusky, 2011; Shewfelt & Henderson, 2003),
- rough handling at an early step in a handling chain might not become evident until a later step in the chain. We called it *latent damage* (Campbell, Prussia, & Shewfelt, 1986; Lurie, 2009),
- since many commodities changed ownership in each handling chain, there was little monetary incentive for modifications early in the chain to improve quality later as it arrived at the market,

- the driving force in any produce handling chain was the *point of integration* such as regional distribution centers of supermarkets or purveyors for restaurant corporations (Brookes, 1995),
- the primary criteria used by the buyers of produce was price and not quality,
- branding offered players early in a handling chain the opportunity to establish quality standards and command a specific price (Shewfelt, 2006), and
- there was no single handling system for any commodity that was identifiable; rather handling chains varied at the beginning, middle, and end of any value chain, thus requiring higher level systems thinking (Prussia, 2006).

Such understanding led to more in-depth approaches to various aspects of produce handling and the integration of seemingly unrelated aspects of the value chains as described in the next section.

The center of attention in Fig. 6.1 is the person who consumes fruits and vegetables. Circles with verbs identify typical activities at common links in various value chains. The double circles labeled “Sell” and “Prepare and Sell” indicate a consumer might buy fresh produce from a grocery store or from a business or institution that buys produce and prepares it for consumers. The other double circles labeled “Process” and “Distribute” indicate businesses that repack products like bananas or tomatoes and ones that prepare food products such as coleslaw or fresh cut fruits and vegetables. Money flows from the consumer to the business links in each chain. Value is added at each link as the product flows in the opposite direction as the money.

The dotted boundary indicates the value chain is not a system (see Chapter 2 for details). No one, including the consumer, is the CEO of any value chain. However, each business link is a system with the authority to change its subsystems. Systems thinking suggests that information flows should exist directly between consumers and each link in the chain. Existing information flows between other links and entities are not shown to emphasize flows with consumers. Double arrows indicate information should flow both ways. The diagram represents a complex network by showing flows of information, product, and money between entities inside and outside the pseudosystem.

Focus groups and consumer panels provide information that can be exchanged with other systems in value chains, trade associations, researchers, extension workers, groups writing standards, and others in the network.

The main challenge for improving fresh produce networks is to learn how to apply systems thinking to individual systems and to the value chain where products flow to consumers. The most basic fact is that the network is not a system. Even a value chain is not a system.

6.4 Challenges amenable to systems solutions

6.4.1 Marketing and in-store handling

Although most studies of fresh-produce value chains follow fruits and vegetables to the supermarket (Dunning, 2016; Hingley & Sodano, 2010; Lin & Wu, 2011; Porat et al., 2018) or restaurant (Givens & Dunning, 2019; Pigatto, 2017; Rimal, 2016), other channels include institutions, farmers markets (Curtis, Yeager, Black, Drost, & Ward, 2014; Kim, Curtis, & Yeager, 2014), community-supported agriculture (Lagane, 2015; Vasquez, Sherwood, &

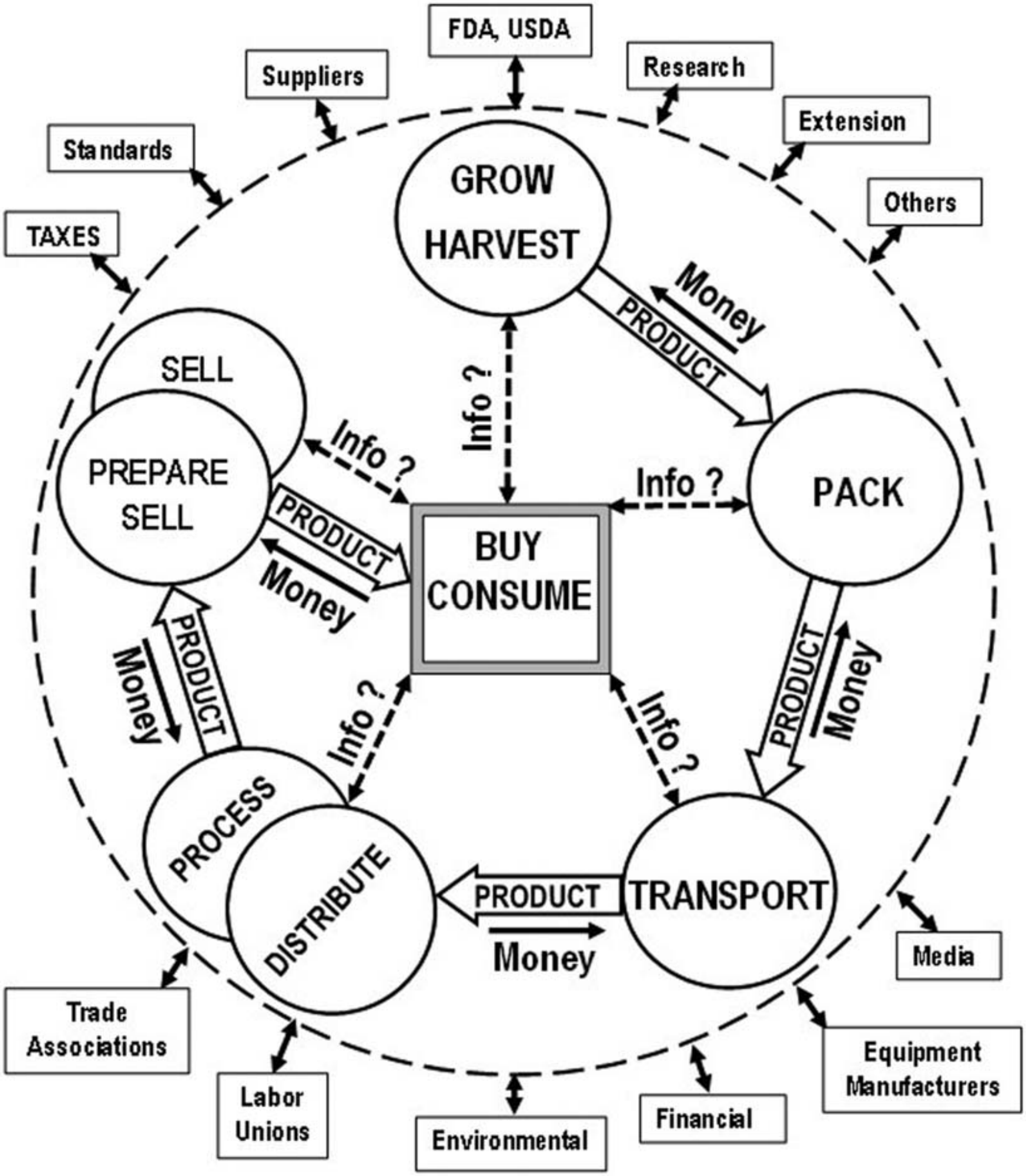


FIGURE 6.1 The final consumer should be the focus for all decisions by all links of all fresh fruit and vegetable value chains.

Larson, 2017), department stores where food is not a primary category, and street vendors (Aggrawal, Manjereka, & Aggrawal, 2011). Corner stores provide limited access to fresh produce in food deserts (Reese, 2019; Weatherspoon, Oehmke, Dembele, & Weatherspoon, 2015) (see also Chatper 12).

Challenges associated with fresh produce include losses within value chains (Porat et al., 2018), shrink at retail (Buzby et al., 2015; Mattsson, Williams, & Berghel, 2018), the logistics of dealing with numerous growers/suppliers (Givens & Dunning, 2019; Hingley & Sodano, 2010), seasonal availability (Rimal, 2016), consistency of supply (Lin & Wu, 2011), and low consumer demand (Weatherspoon et al., 2015). Smaller, regional retail grocery chains tend to be more flexible in direct farm-to-store delivery than larger national distributors (Dunning, 2016). Factors that shape consumer perceptions of quality and choice include availability, freshness (Rimal, 2016), price (Hingley & Sodano, 2010), accessibility, convenience, and store image (Aggrawal et al., 2011). Consumers perceive fresh fruits and vegetables as healthy alternatives to processed food, but fresh items can present a food safety hazard if not handled properly as demonstrated by occasional food borne illnesses caused by fresh produce.

6.4.2 Food safety

Food safety begins in the growing area (Parker, Wilson, LeJeune, & Doohan, 2012; (Thakur & Kniel, 2018) using recognized good agricultural practices and should be monitored through value chains (Dan, Keuchelaere, & Uyttendaele, 2015; Zoellner, Al-Mamun, Grohn, Jackson, & Worobo, 2018) including employee handling in retail and food service operations (Choi, Norwood, Seo, Sirsat, & Neal, 2016). Food quality standards are being developed throughout handling chains as demanded by and funded by retail operations (Jacxsens et al., 2015). Best management practices have been developed for food safety evaluation (Bill et al., 2014; Noor and Feroz, 2016; Tzamalis, Panagiotakos, & Drosinos, 2016).

The most serious food-safety concern for fresh foods is an outbreak due to food pathogens resulting in hospitalization and death (Strawn, Schneider, & Danyluk, 2011; Yeni, Yavas, Alpas, & Soyer, 2016). Presence of pathogenic microbes documented on fresh produce include *Escherichia coli* (Martinez-Vaz et al., 2014), *Listeria monocytogenes* (Marik, Zuchel, Schaffner, & Strawn, 2020), and *Salmonella* species (Hernandez-Reyes & Schikora, 2013; Miller, Rigdon, Robinson, Hedberg, & Smith, 2013; Gurtler, Harlee, Smelser, & Schneider, 2018). Washing with or without soap is even less effective at removing microbial hazards from fresh fruit and vegetables (Bhilwadikar, Pounraj, Manivannan, Rastogi, & Negi, 2019) than removing pesticides. Fresh-cut fruits and vegetables are particularly susceptible to microbial contamination (De Corato, 2020) and sanitation must be carefully monitored throughout the handling chain (Artés, Gómez, Aguayo, Escalona, & Artés-Hernández, 2009). Food safety is just one of a number of checks that must be made within handling chains to assure product quality.

When used properly, pesticides do not pose a health risk. Governmental regulations provide for appropriate procedures for application and premarket holding times of fresh produce to ensure consumer safety (Buchanan, 2000). Organic plant-based foods are likely to have lower pesticide residues, but they are not necessarily considered to be of less risk than their conventional counterparts (Mie et al., 2017). An extensive series of reviews of health risks posed by specific pesticides such as glyphosate (EFSA, 2015) is being conducted by the European Food Safety Authority (EFSA). Contrary to court findings in California (Erickson, 2018), the EFSA does not consider glyphosate as a carcinogenic threat

(EFSA, 2015). Simple household methods of decontamination such as washing with water alone or with added soap are not considered to be effective in removing pesticides in contaminated fruits or vegetables (Bhilwadikar et al., 2019).

6.4.3 Quality management

Quality assurance has been an integral program in food processing operations for over a century. Quality management programs are essential to ensure adequate quality and safety practices are established and consistently applied at all links in fresh produce chains. These principles are now being applied more widely within fresh produce operations. The primary reason for such adoption is the growing number of produce associated outbreaks leading to illness and death (Gurtler et al., 2018; Miller et al., 2013; Yeni et al., 2016; Martinez-Vaz, Fink, Diez-Gonzalez, & Sadowsky, 2014; Carstens, Salazar, & Darkoh, 2019). Management of microbial quality is critical (Noor & Feroz, 2016; Tzamalis et al., 2016; He, Huang, Li, Shi, & Wu, 2018a).

Programs are being developed by many organizations that extend beyond traditional separating and sorting operations to monitor quality through supply chains to ensure acceptable color, flavor, and texture of produce items as purchased and consumed by the ultimate consumer (Porat et al., 2018). Practical applications of quality management were described for several links in fresh produce chains in the first edition of this book (Lidror & Prussia, 1993). Quality management programs have been described for avocado (Bill et al., 2014), leafy vegetables (Mampholo, Sivakumar, & Thompson, 2016), pomegranate (Caleb, Fawole, Mphahlele, & Opara, 2015), and tomatoes (Arah, Amaglo, Kumah, & Ofori, 2015). Supermarket chains are placing greater emphasis on quality checking of produce labeling for accuracy (Smith-Spark, Katz, Wilcockson, & Marchant, 2018). Quality monitoring and maintenance can be compromised if handling chains are constrained.

6.4.4 Constrained handling chains

The challenges facing handlers of fresh fruits and vegetables in countries that lack infrastructure and advanced postharvest technologies are different from those who have these advantages. Most postharvest research has been directed at complex interacting chains which deliver fresh produce to mass markets. Differing circumstances require differing solutions. A systems perspective is useful in the successful transfer of technology developed in one country to meet the needs of another (Sparks, 2013). Extensive training of a small group to train the trainers throughout a host country can be very effective (Holcroft & Kitinoja, 2018). Factors leading to postharvest losses of fresh produce in countries lacking advanced infrastructure include low seed quality, poor farm practices, harvest losses, rough road conditions, and inadequate storage and cooling facilities (Kumar, Underhill, & Kumar, 2016; Kitinoja, Odeyemi, Dubey, Musanase, & Gill, 2019).

Development of grower cooperatives can improve infrastructure both on the farm and at the market (Balaji, 2016; Mphafi, Oyekale, & Ndou, 2019). Integrated crop management systems have also been introduced to improve profitability for households with smallholders (Kowornu et al., 2018; Silitonga, Hartoyo, Sinaga, & Rusastra, 2017). Many of these operations have little or no mechanization, relying primarily on human labor. Even small investments in limited technology can improve profitability (Priscilla & Singh, 2015) and human welfare (Babhulkar, Raut, & Jibhakate, 2018). Unlike processed foods, fresh produce is composed of living, respiring plant tissue. As such, fresh items require special handling. An understanding of the response of fresh fruits and vegetables to environmental stress is critical to maintain quality and reduce food loss and waste.

6.4.5 Stress physiology

When a whole plant or detached, edible organ of that plant undergoes stress, it elicits a physiological response. In most cases this response has an undesirable effect on food quality, but occasionally the response results in improved quality. Stresses to plant tissues can be biological, physical, or mechanical, and they can occur to the whole plant before harvest or the harvested fruit or vegetable during handling and storage. Preharvest stresses can include weather events (Bisbis et al., 2018) such as too much sunlight (Mupambi et al., 2018), too much heat or cold (Askari-Khorasgani & Pessarakli, 2019), or too much or too little rain during developmental stages of the fruit or vegetable. Biological attack by microbes or insects (Manja & Aoun, 2019) can also promote a physiological response by the plant as can inadequate mineral nutrition for the plant (He, Yu, Li, Du, & Guo, 2018b). Toxic buildup of heavy metals can be absorbed by the plant when grown in contaminated soils which in turn are transported to the fruit or vegetable before harvest (Edelstein & Ben-Hur, 2018). Eustressors are chemical or physical treatments during plant growth to induce favorable changes in the quality of harvested vegetables (Vasquez-Hernandez et al., 2019).

Response to postharvest stress can include freezing, CO_2 injury, chilling injury (Valenzuela et al., 2017), and bruising (Hussein, Fawole, & Opara, 2018; Hussein, Fawole, & Opara, 2019). Exposure to ethylene can also induce postharvest damage in susceptible fruits and vegetables (Hu, Sun, Pu, & Wei, 2019). Fresh-cut items are particularly sensitive to microbial attack (Francis et al., 2012). Heat treatment of chilling sensitive items before storage can decrease susceptibility during storage at low temperatures (Lurie, 2016). Molecular techniques show promise in genetically modifying plant genetics to minimize adverse physiological responses in harvested produce (Khandagale & Nadaf, 2016; Kumar & Srivistava, 2016).

Note that a stress may occur at one step in a handling chain but not become evident until a later step. Such latent damage can then incur a monetary loss for the "owner" of the item when it is discovered, even though preventative action can only be initiated by the previous "owner." Exact causes of latent damage are difficult to determine and prevent unless the monetary consequences are sufficient to motivate feedback among links of a chain. The overall monitoring of postharvest quality helps prevent food loss and waste, contributing to environmental sustainability of individual crops.

6.4.6 Sustainability

Since the first edition of this book, no topic has gained in prominence as much as the issue of sustainability. With increased concern about global climate change, efforts have been instituted in produce growing areas to minimize resource inputs and maximize yield. The contribution of fruits and vegetables to plant-based diets have a lower carbon footprint than ones incorporating animal products (Martin & Danielsson, 2016; Gonzalez-Garcia, Esteve-Llorens, Moreira, & Feijoo, 2018). Overuse and unwise land-use practices lead to loss of soil fertility and productivity to crop land (Baijukya, de Ridder, Masuki, & Giller, 2005). Life cycle analysis is one method growers are using to minimize inputs (Ingrao, Matarazzo, Tricase, Clasadonte, & Huisingh, 2015), and buyers use to assess the environmental impact of specific handling chains (Gama Caldas & Neto, 2018; Parajuli, Thoma, & Matlock, 2019). Assessing resource inputs in the growing area is a very difficult undertaking and clear-cut solutions are rarely uncovered (Cerutti, Bruun, Beccaro, & Bounous, 2011; Thorn, 2016).

In value chains, techniques are being developed for efficient distribution through the handling steps to maintain quality of delivered items while minimizing food decay and food loss (Mattsson et al., 2018). In wealthier nations with more advanced distribution channels, much of the waste is generated by the consumer after it is purchased (Ghosh, Fawcett, Sharma, & Poinern, 2016). Whenever an item is wasted by the consumer, the accumulation of the value of resource inputs are lost (Shewfelt, 2017; Zeide, 2019). In countries with poorer infrastructure, more food is lost between harvest and market (FAO, 2015; Parfitt, Barthel, & Macnaughten, 2010; Berjan, Capone, Debs, & El-Bilali, 2018). Chains are being developed in less wealthy nations to improve the efficiency of distribution with particular emphasis on traditional vegetables (Chagomoka, Afari-Sefa, & Pitoro, 2014). To ensure sustainability we must understand what happens at chain interfaces.

6.4.7 Working at the interfaces of postharvest chains

Postharvest chains are typically visualized as following fresh produce from harvest to market. It became apparent to the University of Georgia postharvest team early in our research, however, that the weakest links in understanding supply chains are at the interfaces between preharvest operations and postharvest handling and between the market and the consumer (Shewfelt & Prussia, 1993a). Critical questions that still need answers include:

- What preharvest factors play critical roles in postharvest quality and perishability of items during postharvest handling?
- Can chemical markers be identified in fresh items to predict postharvest performance (Shewfelt & Prussia, 1993b)?
- How well do traditional measures of produce quality predict consumer acceptability?
- Is it possible to design handling chains to move away from extending shelf life to maintaining quality within an expected life?

Extremely valuable results have been achieved in recent decades from research of fresh produce physiology and technology. Now the overriding need is to develop innovative managerial approaches that compel managers at each link of a chain to make decisions that focus on consumers and to reduce food loss and waste for economic and environment benefits.

6.4.8 Managerial considerations

Implicit in any analysis of postharvest handling chains is the need for a management function to ensure value as delivered to the consumer and to minimize food loss and waste. Unlike processed food products, fresh fruit and vegetables pose a moving target because when they are detached plant organs that are physiologically active and perishable. Knowing the ownership of a shipment is likely to change hands more than once from field to consumer, it is difficult to maintain continuity of that shipment. Further complicating matters are the confluence of streams of different shipments with different handling requirements the closer the items get to the consumer.

In addition to the flow of product from the grower to the consumer, the flow of money from the consumer back to the grower deserves attention. Value is determined by the ultimate consumer with respect to price, convenience, quality, and perishability (see also Chapter 10). Intermediate handlers within a value chain expect to receive a fair price from their customer for the value of the item they deliver. Demand for increased value by that customer will likely require an increase in the price paid to make necessary improvements.

Reducing postharvest losses of fruits and vegetables is a global challenge that has continued for many decades. The regions that have over 50% loss of fresh produce are the same regions of the world with the greatest food shortages (Chapter 2). Wilson (2013), page 2 asks the question "Why are we putting 95% of our resource into food production and only 5% into the postharvest preservation of food?" He also states "... production of these crops will increase 38–67 percent by 2050 which falls far short of the 60–100 percent needed to provide food security for the world at that time" (Wilson, 2013, page 1). He advocates increasing food availability by decreasing losses.

Even in regions where fresh produce is available and affordable, the challenge is to find ways to encourage consumers to eat the recommended daily servings of fruits and vegetables. Chapter 2 (also, Jackson, 2019 and Lane, 2020) discusses systems approaches that have potential to make progress on reducing food losses and increasing consumption of fresh produce by integrating social, managerial, sustainability, and political issues along with biological and technical improvements. The Food and Agriculture Organization of the United Nations is moving forward in the direction of a holistic approach for reducing food loss and waste (FAO, 2019).

The challenge is for large numbers of business leaders, researchers, educators, extension specialists, and other value chain participants to become motivated to learn systems thinking. Then, multitudes of systems practitioners are needed around the world to use appropriate systems approaches to better understand specific value chains.

The modeling methods presented in Chapter 5 are examples of tools that could be used by teams learning about individual value chains with the purpose of making desirable and feasible changes. Teams need to include participants from each link in the chain and selected representatives from other businesses and agencies. It is important for teams to include the workers doing the various tasks at all the links, so they can share their perspective with owners, managers, supervisors, and other leaders. Especially important are team members that represent consumers.

Management simulation games, MSG, have become established tools for executive management workshops (McLaughlin, 2020; Sterman, 2020). MSG enable managers to evaluate the consequences of their decisions much like airplane pilots use flight simulators to evaluate decisions under circumstances too risky to attempt in actual aircraft. Examples of MSG are available from the Sloan Business School web site (MIT, 2020). More examples and instructions for developing MSG are available (Senge, Kleiner, Roberts, Ross, & Smith, 1994, page 537–549).

The Peach Game and the Produce Quality Simulator described in Chapter 5, are early examples of postharvest MSG for fresh produce. The development of these MSG required extensive learning about value chains. "Sim Farmer" is a computer game first released in 1993 that is still available (Anon, 2020). The YouTube site has several time-lapse videos that show the game being played in fast motion.

Imagine the benefits of a game called "Sim Food" that could be developed where consumers, value chain leaders, and others could play games that accurately predict consequences of decisions for all parts of selected fresh produce chains. A wide variety of new structures and management decisions could be tested to learn how they affect losses, consumer nutrition levels, sustainability, environments, and other issues.

The primary challenge is motivating consumers, leaders, and others interested in postharvest handling of fruits and vegetables to increase their learning and applications of systems approaches. Typically, another challenge is the funding of projects such as for consultants to study fresh produce supply chains. Chapter 10 describes an example of a self-organizing and self-funding project in Australia where links of supply chains were integrated into a successful organization.

6.5 Summary

To understand the challenges in handling of fresh fruits and vegetables, a systems approach focuses on consumer-driven quality and value. It is this perspective that turns a supply chain that emphasizes money to a value chain that emphasizes consumer satisfaction. Participants in a value chain must cooperate with each other to create value. Produce flows in one direction while money and information flow in the opposite direction. These flows are not static. Rather, they are modified as more accurate information on consumer requirements becomes available and is communicated through the links in a chain. A weak point in produce handling is the lack of a clear understanding of how factors during growth and production of a specific fruit or vegetable affect its performance and durability within the chain. Management within the chain seeks to identify causes of damage occurring at early links in the chain that do not become evident until a later link and then rectify them. It is at the point of integration where chains of different produce lines intersect that price and quality standards are set providing guidance to participants. In successful chains, quality of individual fruits or vegetables match marketing claims, food safety is assured, storage and handling conditions meet the physiological constraints of living items, and the chain is managed in a sustainable fashion.

References

Aggrawal, A., Manjereka, P., & Aggrawal, A. (2011). Consumer behaviour in retail food patronage: A study of Navi Mumbai. *BVIMR Management Edge*, *4*(1), 11–14.

Aggarwal, D., Prussia, A. J., Prussia, S. E., Nunez, A., NeSmith, D. S., Florkowski, W. J., & Lynd, D. E. (2003). Predicting fresh produce quality in supply chains. *Acta Horticulturae*, *604*, 179–188.

Al Ubeed, H. M. S., Wills, R. B. H., Bowyer, M. C., & Golding, J. B. (2018). Comparison of hydrogen sulphide with 1-methylcyclopropene (1-MCP) to inhibit senescence of the leafy vegetable, Pak choy. *Postharvest Biology and Technology*, *137*, 129–133.

Anon (2020). https://www.youtube.com/channel/UCuMdIDoNRo32T5mTzCmsW-Q, Accessed 11.05.20.

Arah, I. K., Amaglo, H., Kumah, E. K., & Ofori, H. (2015). Preharvest and postharvest factors affecting the quality and shelf life of harvested tomatoes: A mini review. *International Journal of Agronomy*, *2015*, Article ID 478041, 6 pages. Available from http://doi.org/10.1155/2015/478041.

Artés, F., Gómez, P., Aguayo, E., Escalona, V., & Artés-Hernández, F. (2009). Sustainable sanitation techniques for keeping quality and safety of fresh-cut commodities. *Postharvest Biology and Technology*, *51*, 287–296.

Ashby, B. H. (1995). Protecting perishable foods during transport by truck. *Agricultural marketing service, transportation and marketing programs*. Available from https://www.ams.usda.gov/sites/default/files/media/TransportPerishableFoodsbyTruck%5B1%5D.pdf. accessed 6 April 2020.

Askari-Khorasgani, O., & Pessarakli, M. (2019). Relationship between signaling and metabolic pathways of grapevines under temperature and light stresses—A review. *Journal of Plant Nutrition*, *42*, 2164–2175.

Babhulkar, H. S., Raut, A. A., & Jibhakate, R. A. (2018). Design modification and analysis of head loading share apparatus for farm workers and vegetable vendors—Literature review. *International Journal for Research in Applied Science and Engineering Technology*, *6*, 2921–2924.

Baijukya, F. P., de Ridder, N., Masuki, K. F., & Giller, K. E. (2005). Dynamics of banana-based farming systems in Bukoba district, Tanzania: Changes in land/use, cropping and cattle keeping. *Agriculture, Ecosystems & Environment*, *106*, 395–406.

Balaji, P. (2016). Retailing of vegetables in peri-urban market in Tamil Nadu. *International Journal of Commerce and Business Management*, *9*, 242–246.

Barrett, D. M., Beaulieu, J. C., & Shewfelt, R. L. (2010). Color, flavor, texture and nutritional quality of fresh-cut fruits and vegetables: Desirable levels, instrumental and sensory measurement, and effects of processing. *Critical Reviews in Food Science and Nutrition*, *50*, 369–389.

Berjan, S., Capone, R., Debs, P., & El-Bilali, H. (2018). Food losses and waste: A global overview with a focus on Near East and North Africa region. *International Journal of Agricultural Management and Development*, *8*(1), 1–16.

Bhilwadikar, T., Pounraj, S., Manivannan, S., Rastogi, N. K., & Negi, P. S. (2019). Decontamination of microorganisms and pesticides from fresh fruits and vegetables: A comprehensive review from common household processes to modern techniques. *Comprehensive Reviews in Food Science and Food Safety*, *18*, 1003–1038.

Bill, M., Sivakumar, D., Thompson, A. K., & Korsten, L. (2014). Avocado fruit quality management during the postharvest supply chain. *Food Reviews International*, *30*, 169–202.

Bisbis, M. B., Gruda, N., & Blanke, M. (2018). Potential impacts of climate change on vegetable production and product quality—A review. *Journal of Cleaner Production*, *170*, 1602–1620.

Bisbis, M. B., Gruda, N. S., & Blanke, M. M. (2019). Securing horticulture in a changing climate—A mini review. *Horticulturae*, *5*(3), 56.

Brookes, R. (1995). Recent changes in the retailing of fresh produce: Strategic implications for fresh produce suppliers. *Journal of Business Research*, *32*, 149–161.

Buchanan, R. L. (2000). The development of science-based food safety regulations in the United States. *Irish Journal of Agricultural and Food Research*, *39*, 331–342.

Buzby, J. C., Bentley, J. T., Padera, B., Ammon, C., & Campuzano, J. (2015). Estimated fresh produce shrink and food loss in U.S. supermarkets. *Agriculture*, *5*, 626–648.

Caleb, O. J., Fawole, O. A., Mphahlele, R. R., & Opara, U. L. (2015). Impact of preharvest and postharvest factors on changes in volatile compounds of pomegranate and minimally processed arils—Review. *Scientia Horticulturae*, *188*, 106–114.

Campbell, D. T., Prussia, S. E., & Shewfelt, R. L. (1986). Evaluating postharvest injury of fresh market tomatoes. *Journal of Food Distribution Research*, *17*, 16–25.

Carstens, C. K., Salazar, J. K., & Darkoh, C. (2019). Multistate outbreaks of foodborne illness in the United States associated with fresh produce from 2010 to 2017. *Frontiers in Microbiology*, *2019*. Available from https://doi.org/10.3389/fmicb.2019.02667.

Cerutti, A. K., Bruun, S., Beccaro, G. L., & Bounous, G. (2011). A review of studies applying environmental impact assessment methods on fruit production systems. *Journal of Environmental Management*, *92*, 2277–2286.

Chagomoka, T., Afari-Sefa, V., & Pitoro, R. (2014). Value chain analysis of traditional vegetables from Malawi and Mozambique. *International Food and Agribusiness Management Review*, *17*, 59–85.

Choi, J., Norwood, H., Seo, S., Sirsat, S. A., & Neal, J. (2016). Evaluation of food safety related behaviors of retail and food service employees while handling fresh and fresh-cut leafy greens. *Food Control*, *67*, 199–208.

Curtis, K. R., Yeager, I., Black, B., Drost, D., & Ward, R. (2014). Market and pricing potential for extended season fresh produce sales: An intermountain West example. *Journal of Food Distribution Research*, *45*(2), 46–65.

Dan, L., Keuchelaere, Ade, & Uyttendaele, M. (2015). Fate of foodborne viruses in the "farm to fork" chain of fresh produce. *Comprehensive Reviews in Food Science and Technology*, *14*, 755–770.

De Corato, U. (2020). Improving the shelf-life and quality of fresh and minimally-processed fruits and vegetables for a modern food industry: A comprehensive critical review from the traditional technologies into the most promising advancements. *Critical Reviews in Food Science and Technology*, *60*, 940–975.

Dunning, R. (2016). Collaboration and commitment in a regional supermarket supply chain. *Journal of Agriculture, Food Systems, and Community Development*, *6*(4), 21–39.

Edelstein, M., & Ben-Hur, M. (2018). Heavy metals and metalloids: Sources, risks and strategies to reduce their accumulation in horticultural crops. *Scientia Horticulturae*, *234*, 431–444.

EFSA (European Food Safety Authority). (2015). Conclusion on the peer review of the pesticide risk assessment of the active substance glyphosate. *EFSA Journal*, *13*(11), 4302.

Erickson, B. E. (2018). 11 states fight California's listing of glyphosate as a Prop 65 carcinogen. *C&EN Global Enterprise*, *96*(3), 1.

Falagan, N., & Terry, L. A. (2018). Recent advances in controlled and modified atmosphere of fresh produce post-harvest technologies to reduce food waste and maintain fresh produce quality. *Johnson Matthey Technology Review*, *62*, 107–117.

FAO (2015). Global initiative on food loss and waste reduction. http://www.fao.org/3/a-i4068e.pdf.

FAO (2019). The state of food and agriculture 2019. Moving forward on food loss and waste reduction. Rome. License: CC BY-NC-SA 3.0 IGO. http://www.fao.org/3/ca6030en/ca6030en.pdf#page = 48. Accessed 12 May, 2020.

Fernando, I., Fei, J., Stanley, R., & Eshaei, H. (2018). Measurement and evaluation of the effect of vibration on fruits in transit—Review. *Packaging Technology and Science*, *31*, 723–738.

Francis, G. A., Gallone, A., Nychas, G. J., Sofos, J. N., Amodio, M. L., & Spano, G. (2012). Factors affecting quality and safety of fresh-cut produce. *Critical Reviews in Food Science and Nutrition*, *52*, 595–610.

Gama Caldas, M., & Neto, B. (2018). The use of green criteria in the public procurement of food products and catering services: A review of EU schemes. *Environment, Development and Sustainability*, *20*, 1905–1933.

Ghosh, P. R., Fawcett, D., Sharma, S. B., & Poinern, G. E. J. (2016). Progress towards sustainable utilisation and management of food wastes in the global economy. *International Journal of Food Science*, *2016*. Available from https://doi.org/10.1155/2016/3563478.

Givens, G., & Dunning, R. (2019). Distributor intermediation in the farm to food service value chain. *Renewable Agriculture and Food Systems*, *34*, 268–270.

Golding, J. B., & Singh, S. P. (2016). Use of 1-MCP in the storage life extension of fruit. *Reference Module in Food Sciences* (pp. 1–10). Elsevier. Available from https://dx.doi.org/10.1016/B978-0-08-100596-5.21006-8.

Gonçalves, R. G., Couto, J., & Almeida, D. P. F. (2016). On-tree maturity control of peach cultivars: Comparison between destructive and nondestructive harvest indices. *Scientia Horticulturae*, *209*, 293–299.

Gonzalez-Garcia, S., Esteve-Llorens, X., Moreira, M. T., & Feijoo, G. (2018). Carbon footprint and nutritional quality of different human dietary choices. *The Science of the Total Environment*, *644*, 77–94.

Gurtler, J. B., Harlee, N. A., Smelser, A. M., & Schneider, K. R. (2018). *Salmonella enterica* contamination of market fresh tomatoes: A review. *Journal of Food Protection*, *81*, 1193–1213.

Habib, M., Bhat, M., Dar, B. N., & Wani, A. A. (2017). Sweet cherries from farm to table: A review. *Critical Reviews in Food Science and Nutrition*, *57*, 1638–1649.

He, Y., Huang, H., Li, D., Shi, C., & Wu, S. J. (2018a). Quality and operations management in food supply chains: A literature review. *Journal of Food Quality*, *2018*, Article ID 7279491, 14 pages. Available from https://doi.org/10.1155/2018/7279491.

He, L., Yu, L., Li, B., Du, N., & Guo, S. (2018b). The effect of exogenous calcium on cucumber fruit quality, photosynthesis, chlorophyll fluorescence, and fast chlorophyll fluorescence during the fruiting period under hypoxic stress. *BMC Plant Biology*, *18*. Available from https://doi.org/10.1186/s12870-018-1393-3.

Hernandez-Reyes, C., & Schikora, A. (2013). *Salmonella*, a cross-kingdom infecting humans and plants. *FEMS Microbiology Letters*, *343*, 1–7.

Hingley, M., & Sodano, V. (2010). Channel management and differentiation strategies in the supply chain for fresh produce. *Journal of Food Products Marketing*, *16*, 129–146.

Holcroft, D., & Kitinoja, L. (2018). The Postharvest Education Foundation's role in reducing postharvest losses. *Julius-Kuhn-Archiv*, *463*, 963–968.

Houston, L., Capalbo, S., Seavert, C., Dalton, M., Bryla, D., & Sagli, R. (2018). Specialty fruit production in the Pacific Northwest: Adaptation strategies for a changing climate. *Climate Change*, *146*(1/2), 159–171.

https://www.ars.usda.gov/arsuserfiles/oc/np/commercialstorage/commercialstorage.pdf. 2016. (Accessed 4 November 2021).

Hu, B., Sun, D.-W., Pu, H., & Wei, Q. (2019). Recent advances in detecting and regulating ethylene concentrations for shelf-life extension and maturity control of fruit: A review. *Trends in Food Science and Technology*, *91*, 66–82.

Hussein, Z., Fawole, O. A., & Opara, U. L. (2018). Preharvest factors influencing bruise damage of fresh fruits—A review. *Scientia Horticulturae*, *229*, 45–58.

Hussein, Z., Fawole, O. A., & Opara, U. L. (2019). Harvest and postharvest factors affecting bruise damage of fresh fruits. *Horticultural Plant Journal*, *6*. Available from https://doi.org/10.1016/j.hpj.2019.07.006.

Ingrao, C., Matarazzo, A., Tricase, C., Clasadonte, M. T., & Huisingh, D. (2015). Life Cycle Assessment for highlighting environmental hotspots in Sicilian peach production systems. *Journal of Cleaner Production*, *92*, 109–120.

Jackson, M. C. (2019). *Critical systems thinking and the management of complexity*. John Wiley & Sons, 728 pages.

Jacxsens, L., van Boxstael, S., Nanyunja, J., Jordaan, D., Luning, P., & Uyttendaele, M. (2015). Opinions on fresh produce food safety and quality standards by fresh produce supply chain experts from the global South and North. *Journal of Food Protection*, *78*, 1914–1924.

Jordan, J. L., Meyers, S. C., Prussia, S. E., & Shewfelt, R. L. (1987). Quality of fresh-market peaches within the postharvest handling system. *Journal of Food Science*, *52*, 361–364.

Jordan, J. L., Shewfelt, R. L., Hurst, W. C., & Prussia, S. E. (1985). A systems approach to the evaluation of changes in quality during postharvest handling of southern peas. *Journal of Food Science*, *50*, 769–772.

Khandagale, K., & Nadaf, A. (2016). Genome editing for targeted improvement of plants. *Plant Biotechnology Reports*, *10*, 327–343.

Kim, M.-K., Curtis, K. R., & Yeager, I. (2014). An assessment of marketing strategies for small-scale produce growers. *International Food and Agribusiness Management Review*, *17*, 187–204.

Kitinoja, L., Odeyemi, O., Dubey, N., Musanase, S., & Gill, G. (2019). Commodity assessment studies on the postharvest handling and marketing of tomatoes in Nigeria, Rwanda and Maharashtra, India. *Journal of Horticulture and Postharvest Research*, *2*, 1–14.

Kumar, P., & Srivastava, D. K. (2016). Biotechnological advancement in genetic improvement of broccoli (*Brassica oleracea* L. var Italica) an important vegetable crop. *Biotechnology Letters*, *38*, 1049–1063.

Kumar, S., Underhill, S., & Kumar, S. (2016). *Postharvest physical risk factors along the tomato supply chain: A case study in Fiji. Proc. Crawford Fund* 59–64.

Kuwornu, J. K. M., Oduro, E., Amegashie, D. P. K., Fening, K. O., Yangyouru, M., MacCarthy, D. S., . . . Datta, A. (2018). Cost-benefit analysis of conventional and integrated-crop management for vegetable production. *International Journal of Vegetable Science*, *24*, 597–611.

Lagane, J. (2015). When students run AMAPs: Towards a French model of CSA. Agric. *Human Values*, *32*, 133–141.

Lane, A. (2020). *Mastering systems thinking in practice*. The Open University. Walton Hall, Milton Keynes, United Kingdom, MK7 6AA. https://www.open.edu/openlearn/ocw/mod/oucontent/view.php?id = 65641&section = 2, 12 May 2020.

Lidror, A., & Prussia, S. E. (1993). Quality management: An industrial approach to produce handling. In R. L. Shewfelt, & S. E. Prussia (Eds.), *Postharvest handling: A systems approach*. Orlando, FL: Academic Press.

Lin, P.-C., & Wu, L.-S. (2011). How supermarket chains in Taiwan select suppliers of fresh fruit and vegetables via direct purchasing. *Service Industries Journal*, *31*, 1237–1255.

Londhe, D., Nalawade, S., Pawar, G., Atkari, V., & Wandkar, S. (2013). Grader: A review of different methods of grading for fruits and vegetables. *Agricultural Engineering International*, *15*, 217–230.

Lurie, S. (2009). Stress physiology and latent damage. In W. J. Florkowski, R. L. Shewfelt, B. Brueckner, & S. E. Prussia (Eds.), *Postharvest handling: A systems approach*. San Diego.: Elsevier.

Lurie, S. (2016). Prestorage heat stress to improve storability of fresh produce: A review. *Israel Journal of Plant Sciences*, *63*, 17–21.

Mampholo, B. M., Sivakumar, D., & Thompson, A. K. (2016). Maintaining overall quality of fresh traditional leafy vegetables of southern Africa during the postharvest chain. *Food Reviews International*, *32*, 400–416.

Manja, K., & Aoun, M. (2019). The use of nets for tree fruit crops and their impact on the production: A review. *Scientia Horticulturae*, *246*, 110–122.

Marik, C. M., Zuchel, J., Schaffner, D. W., & Strawn, L. K. (2020). Growth and survival of *Listeria monocytogenes* on intact fruit and vegetable surfaces during postharvest handling: A systematic literature review. *Journal of Food Protection*, *83*, 108–128.

Martin, M., & Danielsson, L. (2016). Environmental implications of dynamic policies on food consumption and waste handling in the European Union. *Sustainability*, *8*, 282–296. Available from https://doi.org/10.3390/su8030282.

Martinez-Vaz, B. M., Fink, R. C., Diez-Gonzalez, F., & Sadowsky, M. J. (2014). Enteric pathogen-plant interactions: Molecular connections leading to colonization and growth and implications for food safety. *Microbes and Environments*, *29*, 123–135.

Mason-D'Croz, D., Bogard, J. R., Susler, T. B., Cenacchi, N., Dunston, S., Herrero, M., & Wiebe, K. (2019). Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: An integrated modelling study. *Lancet Planetary Health*, *3*, e318–e329.

Mattsson, L., Williams, H., & Berghel, J. (2018). Waste of fresh fruit and vegetables at retailers in Sweden—Measuring and calculation of mass, economic cost and climate impact. *Resources, Conservation and Recycling*, *130*, 118–126.

McLaughlin, E. (2020). *Food executive program*. Cornell University. https://dyson.cornell.edu/outreach/fimp/programs/food-executive-program/, Accessed 12 May 2020.

Mie, A., Andersen, H. R., Gunnarsson, S., Kahl, J., Kesse-Guyot, E., Rembiakowska, E., ... Grandjean, P. (2017). Health implications of organic food and organic agriculture: S comprehensive review. *Environmental Health: A Global Access Science Source*, *16*, 111–132.

Miller, B. D., Rigdon, C. E., Robinson, T. J., Hedberg, C., & Smith, K. E. (2013). Use of global trade item numbers in the investigation of a *Salmonella* Newport outbreak associated with blueberries in Minnesota, 2010 *Journal of Food Protection*, *76*, 762–769.

MIT (2020). Massachusetts Institute of Technology, Sloan School of Management. https://mitsloan.mit.edu/LearningEdge/simulations/Pages/Overview.aspx, accessed 6 April 2020.

Mphafi, K., Oyekale, A. S., & Ndou, P. (2019). Effect of enterprise development support program on market participation and profit efficiency of indigenous vegetable production in South Africa. *Applied Ecology and Environmental Research*, *17*, 6853–6864.

Mupambi, G., Anthony, B. M., Layne, D. R., Musacchi, S., Serra, S., Schmidt, T., & Kalcsits, L. A. (2018). The influence of protective netting on tree physiology and fruit quality of apple: A review. *Scientia Horticulturae*, *236*, 60–72.

Ndraha, N., Hsiao, H.-I., Vlajic, J., Yang, M.-F., & Lin, H.-T. V. (2018). Time-temperature abuse in the food cold chain: Review of issues, challenges, and recommendations. *Food Control*, *89*, 12–21.

Negi, S., & Anand, N. (2015). Cold chain: A weak link in the fruits and vegetables supply chain in India. *IUP Journal of Supply Chain Management*, *12*, 48–62.

Noor, R., & Feroz, F. (2016). Requirements for microbiological quality management of agricultural products. *Nutrition & Food Science*, *46*, 808–816.

Parajuli, R., Thoma, G., & Matlock, M. D. (2019). Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: A review. *The Science of the Total Environment*, *650*(Part 2), 2863–2879.

Parasecoli, F. (2019). *Food*. Cambridge, MA: The MIT Press.

Parfitt, J., Barthel, M., & Macnaughten, S. (2010). Food waste within supply chains: Quantification and potential for change to 2050. *Philosophical Transactions of the Royal Society B*, *365*, 3065–3081.

Parker, J. S., Wilson, R. S., LeJeune, J. T., & Doohan, D. (2012). Including growers in the 'food safety' conversation: Enhancing the design and implementation of food safety programming based on farm and marketing needs of fresh fruit and vegetable producers. *Agriculture and Human Values*, *29*, 303–319.

Pigatto, G. (2017). Supply chain of perishables: How restaurants choose and relate with suppliers of vegetables. *Economia & Região*, *5*, 7–30.

Porat, R., Lichter, A., Terry, L. A., Harker, R., & Buzby, J. (2018). Postharvest losses of fruits and vegetables during retail and in consumers' homes: Quantifications, causes, and means of prevention. *Postharvest Biology and Technology*, *139*, 135–149.

Priscilla, L., & Singh, S. P. (2015). Economics of vegetable production in Manipur. Indian. *Journal of Development Economics*, *11*, 933–938.

Prusky, D. (2011). Reduction of the incidence of postharvest quality losses, and future prospects. *Food Security*, *3*, 463–474.

Prussia, S. E., Jordan, J. L., Shewfelt, R. L., & Beverly, R. B. (1986). *A systems approach for interdisciplinary postharvest research on horticultural crops. Research report*. University of Georgia, College of Agriculture, Experiment Stations 514.

Prussia, S. E., & Mosqueda, M. R. P. (2006). Systems thinking for food supply chains: Fresh produce applications. *Acta Horticulturae*, *712*, 91–104.

Prussia, S. E., & Shewfelt, R. L. (1985). Ventilation cooling of bulk shipments of shelled southern peas. *Transactions of the ASAE. American Society of Agricultural Engineers*, *28*, 1704–1708.

Reese, A. M. (2019). Black food geographies: Race, self-reliance, and food access in Washinton, DC. Chapel Hill, NC: University of North Carolina Press.

Resurreccion, A. V. A., Hurst, W. C., Shewfelt, R. L., & Prussia, S. E. (1987). Relationships between sensory and objective measures of postharvest quality of snap beans as determined by cluster analysis. *Journal of Food Science*, *52*, 113–116.

Rimal, A. (2016). Purchasing locally produced fresh vegetables: National franchise vs. locally owned and operated restaurants. *Journal of Food Distribution Research*, *47*, 98–108.

Senge, P. M., Kleiner, A., Roberts, C., Ross, R., & Smith, B. (1994). The fifth discipling fieldbook. *Strategies and tools for building a learning organization*. New York: Doubleday.

Shewfelt, R. L. (2006). Defining and meeting consumer requirements. *Acta Horticulturae*, *712*, 31–37.

Shewfelt, R. L. (2017). How can we eat more sustainably to save our earth for our children and grandchildren? In *Shewfelt: In Defense of processed food* (pp. 143–160). Cham: Springer Nature.

Shewfelt, R. L., & Henderson, J. D. (2003). The future of quality. *Acta Horticulturae*, *604*, 49–60.

Shewfelt, R. L., & Prussia, S. E. (1993a). Challenges in handling fresh fruits and vegetables. In R. L. Shewfelt, & S. E. Prussia (Eds.), *Postharvest handling: A systems approach*. New York.: Academic Press.

Shewfelt, R. L., & Prussia, S. E. (1993b). Interdisciplinary solutions to challenges in postharvest handling. In R. L. Shewfelt, & S. E. Prussia (Eds.), *Postharvest handling: A systems approach*. New York: Academic Press.

Shewfelt, R. L., Prussia, S. E., Resurreccion, A. V. A., Hurst, W. C., & Campbell, D. T. (1987). Quality changes of vine-ripened tomatoes within the post-harvest handling system. *Journal of Food Science*, *52*, 661–664.

Shewfelt, R. L., Prussia, S. E., & Dooley, J. H. (2000). Quality of fruits and vegetables in home handling systems. In W. J. Florkowski, S. E. Prussia, & R. L. Shewfelt (Eds.), *Integrated view of fruit & vegetable quality*. Lancaster, PA: Technomic Publishing Inc.

Silitonga, P. Y., Hartoyo, S., Sinaga, B. M., & Rusastra, I. W. (2017). The influence of integrated crop management on the household food security of maize farmers in West Java Indonesia. *International Journal of Food and Agricultural Economics*, *5*, 67–77.

Singh, R. K., Gunasekaran, A., & Kumar, P. (2018). Third party logistics (3PL) selection for cold chain management; A fuzzy AHP and fuzzy TOPSIS approach. *Annals of Operations Research*, *267*, 531–553.

Smith-Spark, J. H., Katz, H. B., Wilcockson, T. D. W., & Marchant, A. P. (2018). Optimal approaches to the quality control checking of product labels. *International Journal of Industrial Ergonomics*, *68*, 118–124.

Sparks, S. A. (2013). *Postharvest handling systems for fresh fruits and vegetables in sub-Saharan Africa and potential enhancement by the Aid for Trade Initiative* (MS thesis). University of Georgia.

Sterman, J. (2020). *Management simulation games*. https://mitsloan.mit.edu/LearningEdge/simulations/Pages/Overview.aspx, Accessed 12.05.20.

Strawn, L. K., Schneider, K. R., & Danyluk, M. D. (2011). Microbial safety of tropical fruits. *Critical Reviews in Food Science and Nutrition*, *51*, 132–145.

Thorn, J. P. R. (2016). *Ecosystem services, biodiversity and human wellbeing along climatic gradients in smallholder agro-ecosystems in the Terai Plains of Nepal and northern Ghana* (D.Phil. dissertation). University of Oxford.

Thakur, S., & Kniel, K. (2018). Preharvest food safety. *Washington, ASM Press*.

Tzamalis, P. G., Panagiotakos, D. B., & Drosinos, E. H. (2016). A 'best practice score' for the assessment of food quality and safety management systems in fresh-cut produce sector. *Food Control*, *63*, 179–186.

USDA, ERS (2020). *Ag and food statistics: Tracking the essentials—Food prices and spending*, https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/food-prices-and-spending/, Accessed 04.05.20.

Valenzuela, J. L., Manzano, S., Palma, F., Carvajal, F., Garrido, D., & Jamalina, M. (2017). Oxidative stress associated with chilling injury in immature fruit: Postharvest technological and biotechnological solutions. *International Journal of Molecular Sciences*, *18*, 1467–1492.

Vasquez, A., Sherwood, N. E., Larson, N., & Story, M. (2017). Community Supported Agriculture as a dietary and health improvement strategy: A narrative review. *Journal of the Academy of Nutrition and Dietetics*, *117*, 83−94.

Vasquez-Hernandez, M. C., Parola-Contreras, I., Montoya-Gomez, L. M., Torres-Pacheco, I., Schwarz, D., & Guevara-Gonzalez, R. G. (2019). Eustressors: Chemical and physical stress factors used to enhance vegetables production. *Scientia Horticulturae*, *250*, 223−229.

Vaycheslavovich, R. R., Adilovna, K. M., & Xasanovich, R. Z. (2016). Development of approved technical means for transportation fruits and vegetables. *European Science Review*, *2016*, 175−177.

Vijayarekha, K. (2012). Machine vision application for food quality: A review. *Research Journal of Applied Sciences, Engineering and Technology*, *4*, 5453−5458.

Wang, J., Zhang, M., Gao, Z., & Adikhari, B. (2018). Smart storage technologies applied to fresh foods: A review. *Critical Reviews in Food Science and Nutrition*, *58*, 2689−2699.

Weatherspoon, D., Oehmke, J., Dembele, A., & Weatherspoon, L. (2015). Fresh vegetable demand behaviour in an urban food desert. *Urban Studies (Edinburgh, Scotland)*, *52*, 960−979.

WHO (2018). *Healthy diet*. https://www.who.int/news-room/fact-sheets/detail/healthy-diet.

Wilson, C. (2013). *Establishment of a World Food Preservation Center: Concept, need and opportunity*. http://jpht.info/index.php/jpht/article/view/17423/8939, Accessed 18.04.20.

Wilson, K., & Morren, G. E., Jr. (Eds.), (1990). *Systems approaches for improvement in agriculture and resource management*. New York: Macmillan Publishing Co.

Yamauchi, N. (2013). Quality maintenance of postharvest horticultural crops by stress treatments and approach for the elucidation of its mechanism. *Journal of the Japanese Society for Horticultural*, *82*, 1−10.

Yeni, F., Yavas, S., Alpas, H., & Soyer, Y. (2016). Most common foodborne pathogens and mycotoxins on fresh produce: A review of recent outbreaks. *Critical Reviews in Food Science and Nutrition*, *56*, 1532−1544.

Zeide, A. (2019). Grocery garbage: Food waste and the rise of supermarkets in the mid-twentieth century United States. *History of Retailing and Consumption*, *5*, 71−86.

Zhang, J. H., Cheng, D., Wang, B. B., Khan, I., & Ni, Y. H. (2017). Ethylene control technologies in extending postharvest shelf life of climacteric fruit. *Journal of Agricultural and Food Chemistry*, *65*, 7308−7319.

Zhang, B., Gu, B., Tian, G., Zhao, J., Huang, J., & Xiong, Y. (2018). Challenges and solutions of optical-based nondestructive quality inspection for robotic fruit and vegetable grading systems: A technical review. *Trends in Food Science and Technology*, *81*, 213−231.

Zoellner, C., Al-Mamun, M. A., Grohn, Y., Jackson, P., & Worobo, R. (2018). Postharvest supply chain with microbial travelers: A farm-to-retail microbial simulation and visualization framework. *Applied and Environmental Microbiology*, *84*, e00813−e00818. Available from https://doi.org/10.1128/AEM.00813-18.

Further reading

Senge, P. M. (2006). *The fifth discipline, the art & practice of the learning organization*. New York: Crown Publishing Group.

CHAPTER

7

Fresh-cut produce quality: implications for postharvest

Silvana Nicola[1], *Giacomo Cocetta*[2], *Antonio Ferrante*[2] *and Andrea Ertani*[1]

[1]Department of Agricultural, Forest and Food Sciences - DISAFA, University of Turin, Turin, Italy [2]Department of Agricultural and Environmental Sciences - Production, Landscape, Agroenergy - DiSAA, University of Milan, Milan, Italy

Abbreviations

AA	ascorbic acid
cfu	colony forming unit
CVS	computer vision systems
DHA	dehydroascorbic acid
DNA	deoxyribonucleic acid
EMA	equilibrium-modified atmosphere
EO	essential oil
EU	European Union
FS	flotation systems
GAP	good agricultural practices
GC−Ms	gas chromatography−mass spectrometry
GHP	good hygiene practices
GMP	good manufacturing practices
HACCP	hazard analysis critical control point
IY	internal yellowing
LOX	lipoxygenase
MA	modified atmosphere
MAP	modified atmosphere packaging
MDA	malondialdehyde
NIR	near infrared
PAL	phenylalanine ammonia lyase
POD	peroxidase
PPO	polyphenol oxidase
RH	relative humidity

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00007-5

ROS	reactive oxygen species
RRO_2	respiration rate for oxygen
SCS	soilless culture system
TCS	traditional culture system
TPC	total plate count
UV	ultraviolet
vis/NIR	visible−NIR
VOCs	volatile organic compounds
YMC	yeast and mold count

7.1 Introduction

In recent years, the consumer demand for fruit and vegetables decreased in Europe. However, instead of a decrease, the ready-to-eat product sector reported an increase in sales (Nicola & Fontana, 2014; Nicola, Tibaldi, & Fontana, 2009). The fresh-cut sector is increasing more rapidly than other fruit and vegetable segments, thanks to its value to the food service industry, as well as its expanding production and access to markets across the world (Jideani, Anaysi, Micheau, Udoro, & Onipe, 2017).

The International Fresh-cut Produce Association defines fresh-cut products as "fruit or vegetables that have been trimmed and/or peeled and/or cut into 100% usable product that is bagged or prepackaged to offer consumers high nutrition, convenience, and flavor while still maintaining its freshness" (Lamikanra, 2002). The fresh-cut sector exhibits innovations in product quality and safety attributes, which are usually appreciated by consumers (Condurso et al., 2020). The nutritional and sensory quality of fresh-cut products is comparable to the unprocessed product because they contain similar nutrients as the fresh products, with the additional advantage of their convenience (Artes-Hernandez, Gomez, & Artes, 2013). Fresh-cut fruit and vegetable products can be prepared with slight peeling, shredding, cutting, trimming, and sanitizing processes. After that, fresh-cut products are packaged using semipermeable films and stored under controlled temperature, to provide convenient and safe ready-to-eat products for consumers. Fresh-cut products, thus, are highly perishable, but also agronomically and technologically more susceptible to quality deterioration than whole vegetables or fruit. The processing operations eliminate any inedible parts but reduce the edible product shelf life by several weeks or months, depending on the raw material. Leafy vegetables, particularly baby leaves, are the consumers' favorite (Grahn, Benedict, Thornton, & Miles, 2015), but they are very delicate and susceptible to process manipulations. Control and innovation technology implementation needs to be pursued to optimize all the fresh-cut production and processing procedures.

A fresh-cut product is physically altered from its original state during trimming, peeling, washing, and cutting operations. However, it remains in a fresh state and is thus characterized by living tissues that undergo or are susceptible to enzymatic activity, texture decay, undesirable volatile compound production, and microbial contamination, which reduce the shelf life.

In the fresh-cut industry, shelf life is the time required by a fresh-cut product to lose quality attributes, such as freshness, firmness, texture, color, aroma, and nutritional value, below a level acceptable to the consumer. The relative importance of each quality factor varies according to the product and market. The final potential postharvest quality and shelf life of fresh produce are determined before harvesting. Processing practices, for example, packaging and storage temperature, do not improve quality; they can only slow the rate at which deterioration occurs. Practices such as washing, sorting, and sizing are services performed with the consumer in mind and generally do not improve the inherent quality (Gil, Selma, López-Gálvez, & Allende, 2009). The first and most important aspect that affects the subsequent postharvest processing and shelf life phases is the raw material quality at harvest.

Fresh produce in general, and fresh-cut produce in particular, is perishable. Once harvested, quality deterioration occurs leading to raw material losses even before the produce reaches the consumer. Finding information on the postharvest losses for fruit and vegetable crops can be a difficult task (Kitinoja & Kader, 2015). Fresh fruit and vegetable postharvest losses range from 5% to 25% in developed countries and 20% to 50% in developing countries, respectively (Sudheer & Indira, 2007). Reduction in postharvest losses of fruit and vegetables is a complementary means for increasing productivity. High levels of waste result in higher prices for the final product. Improper handling during the harvest on farms causes quality deterioration. Quality in value chains is crucial in terms of food safety, quality, and environmental impact. Low input and efficient cultural practices, postharvest technologies, and value chain management contribute to "making the difference" in an industry that wishes to be efficient and competitive. The critical points that need to be tackled in the fresh-cut sector include:

- early cold chain implementation;
- storing and shipping conditions prior to reaching the processing plant;
- logistics;
- processing inputs;
- handling in distribution.

For these reasons, innovative technologies have been developed to enhance raw material production, preserve quality, guarantee safety, prolong shelf life, and diversify the fresh-cut products available to consumers.

7.1.1 Food safety risks in the fresh-cut chains

The fresh-cut vegetable safety is related to the absence of inherent antinutritional substances, such as nitrate, alkaloids, protease inhibitors, oxalates, and cyanogens, accumulated during growth (Sinha & Khare, 2017), external microbial (see Chapter 20: Microbial Quality and Safety of Fresh and Fresh-cut Product), and chemical contamination during postharvest. The antinutritional factors negatively interfere with the metabolic processes in terms of growth and bioavailability of nutrients (see Chapter 19: Nutritional quality of fruits and vegetables, and Chapter 21: Measuring Consumer Acceptance of Vegetables). These critical factors can be controlled throughout entire chains by implementing targeted cultural techniques and observing sanitation programs. Good agricultural practices (GAPs) and good manufacturing practices (GMPs) provide recommended guidelines that guarantee a minimum safety level. The hazard analysis critical control point (HACCP), which includes good hygiene practices (GHPs), is regulated in the European Union (EU) by EU-Reg. N. 852–853–854/2004. Produce sanitation should start in the field and should encompass all growing, harvesting, handling, and processing areas and a documentation of all the procedures applied should be recorded by the producer (logbook) (see this chapter and also Chapter 13: Sorting For Defects).

The several variables related to produce harvesting, such as maturity phase, handling, transportation, and storage, may have a great impact on the quality of intact raw materials and consequently on the minimally processed products. The consumption of fresh-cut products continues to increase among some consumer segments in the EU and the United States, due to healthy lifestyle recommendations. At the same time, the rate of foodborne illness caused by the ingestion of these products remains high (Callejón et al., 2015). From 2004 to 2012, the United States and EU have reported a total of 377 and 198 outbreaks associated with fresh vegetables, sprouts, and fruits. In the United States, the number of outbreaks due to fresh produce ranged from 23 to 60 per year. There were substantial increases in 2006 (57 outbreaks), 2008 (51 outbreaks), and 2011 (60 outbreaks) (Dewey-Mattia, Manikonda, Hall, Wise, & Crowe, 2018). In the EU, the number of outbreaks varied between 10 and 42, evidencing increases in 2006 (29 outbreaks), 2009 (34 outbreaks), and 2010 (44 outbreaks) (EFSA (European Food Safety Authority), 2015). In Europe, over 400 cases of Salmonellosis occurred from baby spinach and alfalfa sprouts and 3911 cases of *Escherichia coli* from vegetable sprouts in 2011; in the United States over 2000 cases of Salmonellosis occurred from tomatoes, spinach, cantaloupe, sweet pepper, and over 500 cases of *E. coli* from leafy vegetables.

A larger volume and greater variety of fresh-cut products have become available because of the fresh-cut sector growth. Fresh fruit and vegetables normally contain high amounts of microorganisms at harvesting before processing. Soil, water, air, and insects all contribute to the microflora of vegetables, but their importance differs according to the edible part of the plant. For example, leaves are primarily exposed to water, whereas roots have more contact with the soil. The numbers and the species of microorganisms found on fresh produce, and specifically on fresh-cut products, are highly variable. Fresh produce is considered to be a possible source of foodborne outbreaks caused by a variety of pathogens such as *Hepatitis A virus*, *Campylobacter*, *Salmonella*, *E. coli*, *Staphylococcus*, *Clostridium*, *Shigella*, *Listeria*, *Cyclospora*, and *Cryptosporidium*. Specific pathogen-food combinations have emerged in recurrent outbreaks: *Salmonella* infections from melons and tomatoes, *E. coli* O157:H7 infections from leafy green vegetables, *Cyclospora* infections from raspberries, and hepatitis from green onions. According to Golberg, Kroupitski, Belausov, Pinto, and Sela (2011), *E. coli* and *Salmonella typhimurium* are able to penetrate the leaves of iceberg lettuce. The range of the contamination depends on the harvest time, weather conditions at harvesting, applied fertilizer, handling by workers during harvest, worker's hygiene conditions, sorting, and the subsequent processing, for example, the contact with cutting knives, transport belts, boxes, or water used for washing.

The difficulties involved in killing and removing microorganisms from raw materials can originate from preharvest sources, such as feces, soil, sewage and sludge, irrigation water, water used to apply fungicides, insecticides and herbicides, improper manure, dust, wild and domestic animals, and human handling (Beuchat, 2007). The control of these contamination sources can enhance the successful management of microbial safety risk in the fresh-cut industry. Four types of microbes are present on the surface of fresh-cut produce (see also Chapter 20: Microbial Quality and Safety of Fresh and Fresh-cut Product):

1. useful microbes, such as some lactic acid bacteria, which should not be removed or killed;
2. spoilage microbes, such as pectinolytic Gram-negative bacteria belonging to *Pseudomonadaceae* or *Enterobacteriaceae* and yeasts with fermentative metabolism such as *Saccharomyces* spp., found on fruit, which should be minimized during processing because they reduce shelf life;
3. human pathogens (e.g., *Clostridium botulinum*, *E. coli*, *Listeria monocytogenes*, *Salmonella* spp., *Staphylococcus aureus*) responsible for foodborne disease outbreaks;
4. commensal organisms, with no positive or harmful effect on either humans or plant and plant pathogens with no harmful effect on humans.

The aim of the fresh-cut industry is to prevent the presence of pathogens and assure that they are not introduced during the processing system. Because of their growth, internalization and infiltration behavior, sanitizer treatments are not effective and cannot assure safety; thus GAPs, GMPs, and HACCP are essential to prevent human pathogen contamination.

7.2 Cultivation management for the fresh-cut industry

7.2.1 Raw material quality for the fresh-cut industry

In vegetable crops such as leafy salads, preharvest and postharvest stresses can induce metabolism changes that enhance quality losses (Rico, Martin-Diana, Barat, & Barry-Ryan, 2007; Rouphael et al., 2012). Leafy vegetables are immediately processed after harvest within 24−48 h. Preharvest stresses such as nutrient deficiencies, particularly N-starvation, high salinity, and high-temperature exposure just before harvest can affect the quality of products during distribution chains (Lee & Kader, 2000). Low-nitrogen fertilization is often imposed to leafy vegetables such as lettuce, rocket, and spinach to avoid high leaf nitrate concentration at harvest. High salt concentration (particularly sodium) can also be a problem in greenhouses and field along the coastal areas, where there is low water quality with high electrical conductivity (EC). In the Mediterranean areas, vegetables grown under tunnels can be exposed to high temperatures (up to 40°C) during the harvest period.

Any of the preharvest stressful conditions can negatively or positively affect the quality and shelf life of the final product. The understanding of these conditions is crucial to assess the postharvest potential of fresh produce, especially those that will be further stressed by fresh cutting. The raw material going to the fresh-cut industry must be in a perfect state with regard to safety, physiology, extrinsic, and internal quality before processing. The most important prerequisites concern:

- the absence of insects, soil, metals, and weeds, which increase the length and the cost of the washing phase and jeopardize the quality;
- a low level of microbial contamination that accelerates metabolic processes that reduce the shelf life;
- the absence of pathogens that cannot be either controlled or eliminated during processing;
- a high-quality standard in terms of appearance, texture, flavor, and nutritional value.

Cultivation conditions, such as the growing systems, irrigation, climate, and fertilization, influence the quality of the raw material and can modify its physiological behavior and suitability for fresh-cut processing. The preharvest and harvest conditions that affect vegetable quality and shelf life are related to:

- genetically controlled factors (cultivar, strain);
- climatic conditions [light, temperature, relative humidity (RH), etc.];
- soil conditions (type of soil, pH, moisture, microflora, soil-borne diseases, etc.);
- culture systems (open-field cultivation, protected cultivation, soilless system, etc.);
- agricultural practices (biostimulants, fertilizers, pesticides, plant growth regulators, irrigation, etc.);
- harvesting (harvest timing and temperature, mechanical harvest, manual harvest, etc.).

The influence of genotype, growing conditions, maturity at harvest, and storage conditions are critical factors that determine the ultimate quality level in fresh produce before fresh-cut processing (Kader, 2008). Climatic conditions (temperature, light, rain, RH, and wind) and agronomic practices (planting density, tree pruning, fruit thinning, plant nutrition, cultural system, control of weeds, diseases, and pests) allow to reach high yield but can be detrimental to inherent quality of produce. It is necessary to identify the optimal cultivation practices that maximize both quality and yield avoiding nutrient and water excess, and to encourage the growers to adopt growing practices that enhance produce quality even with a reduction in yield, for providing premium quality raw materials for fresh-cut processing. Raw material variability remains a challenge: cultivars, growing conditions, climatic conditions, preprocessing handling, and storage all affect the visual quality, shelf life, flavor, compositional and textural quality.

7.2.2 Cultivars

The first step for reaching the highest quality of the product at harvest is the identification of the most suitable cultivar for the cultivation environment. Crop agronomic management combined with the environment conditions during cultivation allows the expression of the genotype potentiality. Choosing the proper cultivar is not an easy task because various parties in the fresh-cut production and distribution have often conflicting needs. Breeding programs to select cultivars that can improve the crop performance and processors (see also Chapter 9: Postharvest Quality Properties of Potential Tropical Fruits Related to their Unique Structural Characters) reduce production costs and optimize postharvest technology efficiency. In recent years, breeding programs have been focused on developing new varieties and selections especially for yield, fruit size, disease resistance, long shelf life, minimum harvest maturity, lowest storage, and shipping temperatures. All these parameters are crucial for growers, processors, buyers, and retailers but can have negative consequences on flavor quality of the product (Kader, 2008).

Growers want cultivars that are resistant to biotic and abiotic stresses, while assuring a high yield, suitability for mechanical harvesting, plant size uniformity, low waste, and uniform maturity. The absence of biotic and abiotic stresses reduces both the metabolic processes after harvest and microbial contamination at any stage. Resistance to biotic and abiotic factors allows not only the reduction of pesticide use, but also the production of unblemished raw materials. Breeders have selected *Cichorium intybus* L. (chicory) cultivars with high bolting tolerance and frost resistance without any variation in color. Cultivars with high bolting tolerance satisfy commercial and sensorial maturity requirements and lead to a reduction in the discarded material, thus lowering postharvest losses. Baby-leaf cultivars of lettuce (*Lactuca sativa* L.) have been selected because of their resistance to different *Bremia lactucae* strains, while spinach (*Spinacia oleracea* L.) cultivars have been selected because of their resistance to *Peronospora farinosa*.

Processors want cultivars with low respiration and enzymatic rates and with tolerance to stress due to mechanical operations, such as washing, sorting, cutting, and drying. Selecting varieties with low respiration rates and lowering the respiration rate by cooling after harvest are very useful tools to extend the shelf life of the fresh produce. Seefeldt, Løkke, and Edelenbos (2012) studied the effect of variety and harvest time on the respiration rate of broccoli florets (*Brassica oleracea*, Italica group) and found that the respiration rate among the tested broccoli varieties can be related to the structure of the heads and the inflorescences size. Varieties with low respiration rate for oxygen (RRO_2) had small inflorescence gathered in a compact head, while those with high RRO_2 had a large inflorescence in loose heads. In addition, the varieties with high dry matter contents had also high RRO_2 within the same species. Also preferred are cultivars tolerant of low temperatures used in value chains. For instance, head vegetables (e.g., lettuce, chicory) are preferred to baby leaves (e.g., rocket, *Eruca sativa* Mill; corn salad, *Valerianella olitoria* L.) because they are more resistant to mechanical stress and extended storability prior to processing. The latter feature improves the logistic management of the produce flow. However, the recent consumer demand for softer leaves with variation in flavor, color, and shape has encouraged the development of new lettuce types. Martínez-Sánchez et al. (2012) compared the whole-head lettuce, as the most common raw material for the fresh-cut industry, with baby-leaf and multileaf as the newest baby-sized lettuce leaves (Green Leaf, Red Leaf, and Lollo Rosso cultivars). The new baby-sized leaves both at immature and mature stages have been developed as high-quality lettuce varieties for the fresh-cut sector.

Baby-sized lettuce compared to the whole-head lettuce presents some advantages:

- greater efficiency due to the higher percentage of usable product;
- easier and faster processing because the entire leaf is harvested and processed;
- more attractive presentation in the packaging because of 3-D structure;
- minimal oxidation due to the smaller stem diameter and wounded surface.

Baby-leaf vegetables are harvested in the very young stage during development when the plant reaches 10–15 cm of height and three to five true leaves. Leaf tissues are not genetically programmed for the senescence and quality losses are due to degradation processes. Adult leafy vegetables, instead, are harvested when the leaves are at the mature stage and the harvest activates the senescence that is similar to natural senescence. Martínez-Sánchez et al. (2012) recommended the development of baby-sized lettuce varieties because of excellent sensory characteristics and nutritional quality; they meet fresh-cut-specific requirements in terms of visual quality, microbial load, and high content of phytochemicals.

Leaf shape often depends on cultivar and can facilitate cleaning and washing operations during processing. This is typical for the case of spinach. Spinach cultivars are often classified according to leaf shape, that is, smooth, savoy, or semisavoy. The smooth leaf and semisavoy types are mainly used for processing, while the savoy type is used for the fresh market. The savoy types are preferred for shipping because they are less likely to wilt or turn yellow before reaching the market. The smooth type spinach cultivars are suitable for canned, frozen, or fresh-cut produce, because the leaves are easy to clean before processing.

Enzymatic rates of different key pathways can depend on cultivars. All types of "radicchio", a chicory cultivar famous for its color and slightly bitter flavor, have a long shelf life associated with a reduced oxidation of the cutting point. The high concentrations of anthocyanins and phenols can protect the produce from reactive oxygen species (ROS) and prolong the storage and shelf life. Radicchio has longer shelf life than other salads thanks to the high anthocyanins content. Cultivar selection is of great importance in fresh-cut fruit processing, because cultivars can widely differ for flesh texture, skin color, flavor, nutritional value, susceptibility to mechanical damage, and browning potential. The commercial success of fresh-cut peach and nectarine slices [*Prunus persica* (L.) Batsch] has been limited, due to their short shelf life because of cut-surface browning and pit cavity breakdown (Gorny, Hess-Pierce, & Kader, 1999). Their shelf life can vary between 2 and 12 days at 0°C, depending on the cultivar. The selection of appropriate cultivars, along with an appropriate maturity at harvest and proper storage conditions, can be considered the most important factors that determine the shelf life of fresh-cut fruits. The shelf life of fresh-cut slices of pear cultivars (*Pyrus communis* L.) varies greatly due to their different degrees of flesh softening and surface discoloration. The shelf life of pear slices is reduced with an increased incidence of cut-surface browning. Gorny, Cifuentes, Hess-Pierce, and Kader (2000), when comparing Bartlett, Bosc, Anjou, and Red Anjou varieties, stated that Bartlett pears were the most suitable cultivars for fresh-cut processing, because they exhibited the longest postcutting shelf life of all cultivars tested.

1-Methylcyclopropene (1-MCP) is a well-known ethylene action inhibitor and its efficacy depends on the crop's ethylene sensitivity. 1-MCP can bind the ethylene receptors and prevent the physiological action of ethylene. The effectiveness of 1-MCP is cultivar-specific and influenced by the maturity of the fruit. Calderon-Lopez, Bartsch, Lee, and Watkins (2005) found that slices prepared from apple cultivars (*Malus* × *domestica* Borkh.) treated with 1-MCP had lower ethylene effect and were firmer than those of untreated fruits. Fruit firmness generally decreases with increasing core temperature, but postharvest quality decay due to storage temperature is not only species-specific but, also, cultivar-specific. This is, for instance, the case of apples. Toivonen and Hampson (2009) investigated the response of four apple cultivars (Gala, Granny Smith, Ambrosia, and Aurora Golden Gala) to fresh-cut processing at core temperature of 1°C, 5°C, 13°C, and 20°C. It was concluded that Gala apples were best processed at low core temperatures, Ambrosia could be processed at all temperatures tested, and Aurora Golden Gala produced better quality slices when fruit was stored at room temperature (20°C) before slicing. These results mark the necessity of developing new apple lines directed to their quality as fresh-cut products in addition to the potential storage quality of the intact fruit.

Nowadays, it is crucial to satisfy the consumer expectations in terms of quality. One of the main parameters considered by consumers when choosing a product is the color of the product. Consumers associate color with freshness, better flavor, and ripeness, which depend on genotype, growing conditions, harvesting stage, processing, storage and distribution conditions. In fruit, such as apples, cherries (*Prunus avium* L., *Prunus cerasus* L.), and strawberries (*Fragaria* × *ananassa* Duch.), there has been much interest in breeding fruit varieties with different color, hues, patterns, or with a total anthocyanin content. Red-skinned apples are preferred to the other colored apples.

The produce color can also be associated with the produce antioxidant composition, such as red can be due to anthocyanins or carotenoids such as lycopene. The breeding between varieties with high or low pigments can be planned for improving the nutritional composition of different leafy vegetables. Anthocyanins increase has been obtained in a new line of red escarole as a result of an interspecies crossing between red radicchio and green escarole. The red escarole had an enhanced content of anthocyanin of escarole parental, with an improved nutraceutical and sensory features (Natalini, Cocetta, Acciarri, & Ferrante, 2018).

Differences between cultivars may give rise to specific different postharvest quality aspects valuable for the fresh-cut industry. Gonzalez-Aguilar et al. (2008) assessed the physiological and biochemical changes of different fresh-cut mango (*Mangifera indica* L.) cultivars (Keitt, Kent, and Ataulfo) stored at 5°C. Ataulfo had a much greater shelf life than the other two cultivars, almost double or triple; there was also a correlation between the content of carotene and vitamin C of Ataulfo mango and its longer shelf life compared to the other cultivars. The importance of a high vitamin C content has extensively been indicated as a factor delaying tissue senescence (Bergquist, Gertsson, Nordmark, & Olsson, 2007; Lee & Kader, 2000).

Wall, Nishijima, Fitch, and Nishijima (2010) evaluated the physicochemical, nutritional, and microbial quality of fresh-cut papaya (*Carica papaya* L.) prepared from five cultivars with varying resistance to internal yellowing (IY) (Sunrise, SunUp, Rainbow, resistant; Kapoho, Laie Gold, susceptible), a disease caused by *Enterobacter cloacae*, an opportunistic pathogen. A zero-tolerance for foodborne coliforms makes resistance to IY an important criterion in breeding papaya cultivars suitable for fresh-cut food, but because the infection is restricted to the flesh surrounding the seed cavity, infected fruit cannot be sorted from good quality fruit based on external appearance. Microbial quality is fundamental to observe the food safety guidelines, and the use of IY-resistant cultivars could eliminate or reduce coliform bacteria load. While Kapoho and Laie Gold cultivars are not good candidates because of susceptibility to IY, although Laie Gold is high in vitamin and sugar contents, Rainbow is one of the IY-resistant cultivars. The latter, in addition, is better than the former for its higher content in vitamin A and sugars, and it does not develop the flesh translucency problem. The authors concluded that the processors of fresh-cut papaya products should choose the best cultivars for processing by considering not only appearance, but also texture, flavor, and nutritional content.

Raw materials for the fresh-cut industry originate a certain amount of waste after sorting and processing that could be valuable as a source of bioactive compounds. The waste amount is species and cultivar dependent. Tarazona-Díaz, Viegas, Moldao-Martins, and Aguayo (2011) tested five fresh-cut watermelon (*Citrullus lanatus* Thumb.) cultivars to determine: (1) the percentage of waste product produced during fresh-cut processing, (2) the difference among the cultivars in terms of their bioactive compounds, and (3) the composition of watermelon rind and flesh, with the possibility of reusing the rind as an additive in functional foods. The authors compared the following cultivars: (1) Fashion, seedless, dark rind; (2) Azabache, seeded, dark rind; (3) Motril, seedless, striped rind; (4) Kudam, micro-seed (open-pollinated cultivar), striped rind; (5) Boston, seedless, striped rind. Results indicated that the amount of by-product generated by processing varied from 31.27% to 40.61% of initial fresh weight depending on the cultivar. All cultivars were poor in total antioxidant content. However, the sensory panel indicated that the five cultivars would have a good acceptance in the market. "Fashion" watermelon had the highest citrulline content (an amino acid that may help regulate blood pressure) and could be used as a source for human consumption as fresh-cut watermelon or for citrulline extraction from discarded rind.

In the fresh-cut industry, tomatoes have been used whole, but recently the breeding companies have been working for obtaining cultivars that do not release juice after slicing. These cultivars can be used as fresh-cut tomatoes without increasing the microbial growth. Since the ethylene is an important plant hormone in regulating tomato senescence, breeding programs have been performed, including *never ripe* (*Nr* mutant) or nonripening (nor mutant). The use of these genotypes as background reduced the tomato ethylene sensitivity and longer shelf life, especially in fresh-cut tomatoes. These tomatoes have lower ethylene with higher membrane stability and lower electrolyte leakage. Higher membrane stability and higher tolerance to wounding are important traits in selecting cultivars for the fresh-cut tomato (Natalini, Martinez-Diaz, Ferrante, & Pardossi, 2017).

In conclusion, during the latest decade, processing technologies and distribution chains have driven the demand of cultivar selection and breeding mostly based on yield and postprocessing performance in terms of shelf life, leaving at a lower priority the consumer demand for high organoleptic quality, flavor, and nutritional values. Nevertheless, there is increasing interest to select and breed cultivars satisfying production and processing needs of growers and processors as well as satisfying nutritional and sensory characteristics requested by the consumer. Furthermore, research has been focused basically on few species that are the core of the fresh-cut industry, such as lettuce, spinach, melon, watermelon, apple, and lately on some tropical fruits. There is a need to expand investigations on genetic materials for several species that represent a niche in the fresh-cut industry but could gain popularity thanks to ameliorated performance. The constant expansion of the fresh-cut business all over the world can drive the demand for improved and new varieties or even species to be included in value chains.

7.2.3 Growing conditions and raw material quality and safety

Climatic conditions, including light and temperature, and soil type, have an important influence on the chemical composition of horticultural crops. The amount and intensity of light during the growing season have a definite influence on the amount of ascorbic acid (AA) that is formed, thus affecting the postharvest shelf life (Lee & Kader, 2000). A study on baby leaves (spinach, red chard—*Beta vulgaris* L.; pea shoots—*Pisum sativum* L.; rocket and corn salad) obtained from a grocery store throughout the season showed that total vitamin C content, that is, AA and dehydroascorbic acid (DHA), varies significantly among species, among cultivars, and over the season (Mogren, Reade, & Monaghan, 2018). Variations in the chemical composition in spinach due to the season were also found by Conte et al. (2008), who showed that the product harvested in February had a lower AA content than that of March, probably due to the lower solar light intensity occurring in February. The total vitamin C levels were very high (1494 and 1559 mg/kg f.w., respectively), most probably because of the favorable environmental growing conditions (Southern Italy).

High light intensity reduces the amounts of oxalate and nitrate in leaves (Conte et al., 2008; Proietti, Moscatello, Leccese, Colla, & Battistelli, 2004). Lower nitrate accumulation in leafy vegetables occurs when higher light intensity is available during plant growth. The nitrate reduction is catalyzed by the light-dependent nitrate reductase enzyme. Therefore higher light availability enhances the nitrate reduction and assimilation. Light and temperature also affect anthocyanin biosynthesis in several species which, in many instances, is favored by ultraviolet (UV) wavelengths and low temperatures (Kleinhenz, French, Gazula, & Scheerens, 2003; and citations therein). Sunlight is the most important external factor that regulates anthocyanin synthesis in apple skin (Takos et al., 2006).

Environmental conditions and seasonal variation influence vegetable and fruit tolerance to biotic and abiotic stresses. Seasons have direct effect on the primary and secondary metabolism of vegetables. Winter with lower light intensity and temperature reduces the plant growth and crops have longer growing cycles. However, the crop performance also depends on the nutrient availability. The baby leaf of *Corchorus olitorius* grown in floating systems in different seasons showed higher phenols and anthocyanins in spring–summer than in winter (Giro & Ferrante, 2016).

Adverse conditions that negatively stress a plant make vegetables and fruits unsuitable for processing. Conte et al. (2008) studied the effect of the seasonality on the microbiological quality at harvest of baby-leaf spinach grown in open field in a sandy clay soil in three different periods from October to January. The authors found that the growing period did not affect the total mesophilic bacterial contamination that was equal to 10^5 cfu/g for all the investigated samples. Nicola, Pignata, and Tibaldi (2018a) studied the effect of the seasonality on the microbial contamination at harvest (total plate count, TPC; yeast and mold count, YMC) of green lettuce (Green Lollo) grown in greenhouse with a continuous flotation system in three different periods (summer, fall, and winter). Even in this case the seasonality did not affect the microbial quality at harvest in terms of TPC and of YMC, leading to an average contamination of 1.7×10^3 and 4.7×10^1 cfu/g, respectively. At the end of 9 days of shelf life of the fresh-cut species results confirmed no effect due to seasonality. Rastogi et al. (2012) evaluated the effect of growing season (summer vs winter), field location (northern region—California, summer season, vs southern region—Arizona and South California, winter season), and environmental conditions on the variability of the bacterial community composition in open-field grown lettuce. The total bacterial population averaged between 10^5 and 10^6 per gram of tissue, whereas counts of culturable bacteria were, on average, one (summer season) or two (winter season) orders of magnitude lower. The bacterial core phyllosphere microbiota on lettuce was represented by *Pseudomonas*, *Bacillus*, *Massilia*, *Arthrobacter*, and *Pantoea* genus. Summer-grown lettuce showed an over-representation of *Enterobacteraceae* sequences and culturable coliforms compared to the winter-grown lettuce. In winter samples, coliforms were much lower than in summer samples, following the seasonality of *E. coli* O157:H7. The specific mechanisms that allowed a clear separation between summer and winter in terms of the bacterial community composition that characterized the lettuce that was grown in the two regions was however not clear. Seasonal differences such as RH, temperature, or irrigation practices can have a different degree or a different mechanism of action on the observed variation in bacterial community composition. Northern or southern production regions could have had, for instance, an influence per se rather than the summer or winter season on the observed variation.

After harvesting, quality deterioration can be accelerated in produce damaged by pests, fungi, bacteria, and viruses, which alter the plant metabolism and increase the risk of a second microbial contamination. Cultivation for fresh-cut processing should take place in areas far from chemical, atmospheric, or animal husbandry pollutant sources, which jeopardize the safety of the raw material.

Water influences the raw material microbial quality throughout the entire processing cycle. Water used for production and harvest operations can contaminate vegetables if the edible portions have been in direct contact with water containing pathogens harmful to humans or through water-to-soil and soil-to-product contact (Solomon, Pang, & Matthews, 2003). It is important to assure an appropriate chemical and microbial quality of the irrigation water and the water used in harvest operations. The chemical quality of water can influence plant growth. An example is salinity, which increases the susceptibility of plants to many diseases such as *Fusarium* spp. and *Verticillium* spp. wilts (Besri, 1997). The water should be periodically controlled through microbial and chemical analyses, including tests on the levels of fecal coliforms (i.e., *E. coli*) and heavy metals, whose absence is a safety indicator. However, growers may encounter difficulties in controlling water quality because it originates from sources that could become polluted. Irrigation water comes from surface and underground sources that can be contaminated by drift, run off, or leaching of water from polluted areas (Malakar, Snow, & Ray, 2019; Steele & Odumeru, 2004).

Irrigation methods (e.g., drip irrigation, overhead sprinkler, furrow, and subirrigation systems) can be chosen according to their potential to introduce or promote the growth of pathogens on produce. Water quality, irrigation, and postharvest disinfecting treatments appear to be of paramount importance in reducing the risk of *E. coli* contamination in lettuce (University of Arizona-Cooperative Extension, 2004a). Fonseca (2006) evaluated the postharvest quality and microbial population of iceberg lettuce affected by moisture at harvest. Iceberg lettuce irrigated 4 days before harvest had microbial counts over 0.4 log cfu/g higher than on lettuce irrigated 16 days before harvest. In addition, the microbial population of lettuce irrigated 4 days before harvest with overhead sprinklers was much higher than lettuce irrigated using the furrow system. Fonseca, Fallon, Sanchez, and Nolte (2011) assessed the contamination risk of *E. coli* in commercial lettuce grown under three different irrigation systems (overhead sprinkler, subsurface drip, surface furrow), investigated the survival of the pathogen once the bacterium reaches the soil, and determined its potential relationship with irrigation management. Fonseca and coauthors confirmed that the risk of *E. coli* contamination on leafy vegetables increases when sprinkle irrigation is used, and water is contaminated. Furthermore, *E. coli* survival in furrow-irrigated soil marks the importance of an early irrigation stopping for both sprinkler and furrow methods. After a 3-year survey, the researchers concluded that the highest risk of finding the pathogen in irrigation water is in warmer periods, but its survival in soil is lower in the same period.

Water influences not only the microbial quality, but also the shelf life of vegetables. Some studies suggest that in some cases "controlled" water stress during plant growth can produce beneficial effects during postharvest storage (University of Arizona-Cooperative Extension, 2004b). Moisture stress imposed on broccoli (*B. oleracea* L. var. *italica*) during maturity increased their shelf life from 2 to 3 days to as many as 13 days at 15°C. Similarly, water stress can improve the postharvest quality of carrots (*Daucus carota* L.), melons (*Cucumis melo* L.), and celery (*Apium graveolens* L.), but the positive effect of stress depends on when the plants are subjected to it.

Because water influences cell expansion and leaf water status, it might be expected that irrigation affect postharvest quality of leafy vegetables. Luna, Tudela, Martínez-Sánchez, Allende, and Gil (2013) studied the influence of both deficit and excess irrigation on respiration rate, tissue browning, and microbial quality of fresh-cut romaine lettuce, the second most important type of lettuce after iceberg. The authors tested six different irrigation regimes set according to a standard irrigation regime (Sir): −35% Sir (<221 mm), −15% Sir (221−265 mm), Sir (266−320 mm), +15% Sir (321−370 mm), +35% Sir (>430 mm), +75% Sir (>430 mm). Irrigation regime influenced significantly not only the raw material at harvest, but also the postcutting quality and the shelf life of fresh-cut romaine lettuce. The excess of irrigation increased polyphenol oxidase (PPO; EC 1.10.3.2) activity, accelerated the cut-edge browning, and the microbiological growth, while the deficit of irrigation reduced the cut-edge browning despite the accumulation of phenolic compounds. The authors concluded that phenolic compounds in romaine lettuce are not a browning limiting factor, as it was reported in iceberg lettuce in another paper (Luna et al., 2012). The highest respiration rate was observed when lettuce was cultivated under the most severe deficit (−35% Sir) or excess of irrigation (+35% Sir). As expected, the highest deficit of irrigation decreased yield in terms of fresh weight, but also with the most extreme excess of water, as it was indicated by Fonseca (2006). A similar study conducted by the same authors growing iceberg lettuce gave similar results (Luna et al., 2012). Iceberg lettuce had greater head weight with medium irrigation regime than those cultivated under deficit or excess regime. Browning at the cut edge was increased with storage time particularly when the irrigation regime was increased during plant growth. Increasing the irrigation regime had negative effect on lettuce quality as high enzymatic activities were positively correlated with browning, while irrigation deficit preserved quality and shelf life of fresh-cut iceberg lettuce.

The soil type and crop management do not only affect the nutritional quality, but also the safety of the raw material. Frequent soil chemical analyses are essential for an efficient management of the soil−water−plant system to avoid crop production losses and decrease the environmental impact. The soil texture influences the mobility and efficiency of nitrogen and mineral uptake, which in turn has an impact on the quality of the final product. Cantaloupe grown in clay soil produced better tasting fruit, in terms of sweetness and flavor, with superior fresh-cut quality, in terms of less sour taste and off-flavor, than melons grown in sandy soil (Bett-Garber, Lamikanra, Lester, Ingram, & Watson, 2005). Mylavarapu and Zinati (2009) found that the incorporation of compost improved the physical and chemical properties of sandy soils where parsley (*Petroselinum crispum* Mill.) was cultivated as well as increased parsley yields. The compost application benefited water and nutrient properties of sandy textured soils. Preharvest growth conditions and ripening stage at harvest lead to quality changes in fresh-cut fruit. Experiments performed on melon grown in two different years showed different volatiles and quality parameters. These results indicate that year-on-year climate variation has a complex effect on the physiological status of melon flesh and the retention of aroma in fresh-cut melon during storage (Spadafora et al., 2019).

The soil type and management are fundamental also for the prevention of preharvest contamination of fresh produce from pathogens, heavy metals, and pollutants. To develop strategies that minimize the risk of pathogen survival and spread within agricultural systems and food chains, it is important to understand the fate of pathogens, such as *E. coli*, in environmental substrates such as manure-amended soils and how manure-amended soils affect their survival. Franz et al. (2008) studied the effects of manure-amended soil characteristics on the survival of *E. coli* O157:H7 in 36 Dutch soils. Comparing sandy soils to loamy soils, the authors observed that the initial rate of decline of *E. coli* O157:H7 is faster in sandy soils, but that decline rate slows down more with progressing time than in loamy soils. The pathogen survival increased in soils with a history of low-quality manure application (artificial fertilizers and slurry) compared to those with high-quality manure application (farmyard manure and compost). The authors concluded that *E. coli* O157:H7 population declines faster in soil with a high carbon:nitrogen ratio and consequently a relatively low rate of nutrient release.

The pathogen contamination risk is high when growing vegetables, especially for leafy vegetables such as spinach, lettuce, rocket, which are in direct contact with the soil and are consumed raw. In general, the presence of pathogens in soil amendments can be solved using stabilizing organic residues instead of fresh organic wastes, ensuring proper composting. The use of animal slurry is rare in intensive vegetable production in Mediterranean regions, mainly due to food safety issues (Nicola, Fontana, Monaco, & Grignani, 2013). In fact, several foodborne disease outbreaks in the recent decade have discouraged many vegetable growers from manure and slurry use, most probably as a preventive action because the safety of the available slurry and manure can be limited. The survival of foodborne pathogens is a potential threat to humans, far more important than any other quality aspect. Jensen, Storm, Forslund, Baggesen, and Dalsgaard (2013) reported the transfer of *E. coli* from animal slurry fertilizer to lettuce. This occurred in a pilot study for which animal slurry was applied as fertilizer in three agricultural fields in Denmark, prior to the planting of lettuce seedlings and with *E. coli* serving as an indicator of fecal contamination and as an indicator for potential bacterial enteric pathogens. The study revealed a frequent contamination (44.9%) and levels above 2 log cfu/g in 42.4% of the contaminated samples of lettuce grown under natural conditions in slurry-amended soils. This fecal contamination indicates a potential presence of pathogens such as *Salmonella* and *Campylobacter*, which could represent a real hazard to human health. In addition, streptomycin- and ampicillin-resistant *E. coli* were found in 15% and 1.4% of the lettuce pools, respectively, which indicates a risk of transferring antimicrobial-resistant genes. Because a relatively high number of *E. coli* in lettuce was found at harvest as compared with the numbers found in the soil, it was suggested that the animal slurry fertilization was not the sole source of fecal contamination, but that the surrounding environment and wildlife played a role. In fact, wildlife intrusion followed by defecation in produce fields can readily introduce zoonotic pathogens into the produce growing and harvesting environment. In 2015, the US FDA addressed the risks from wildlife entering fields, imposing monitoring and eventually retaining from harvesting produce if visibly or likely to be contaminated with animal feces. For instance, the contamination of, for example, *E. coli* can occur from animal feces and furrow water onto adjacent heads of lettuce during foliar irrigation, as analyzed by Jeamsripong, Chase, Jay-Russell, Buchanan, and Atwill (2019).

Evidently, all the environmental conditions surrounding plant growth have to be taken into account to set the most appropriate conditions to obtain optimal raw materials at harvest. As fresh-cut produce is prepared from a raw material that is in contact with soil, microbial contamination can occur. GAPs and GHPs suggest that land used for grazing livestock is not suitable for growing vegetables and it is recommended that manure and compost are avoided as fertilizers because they can be sources of microbial and heavy metal contamination.

Inherent fruit quality attributes, such as sugar and acid content, ripening and storability, and external fruit quality attributes, such as color, shape, stage of growth, and firmness, are closely correlated with the main nutrients: nitrogen, phosphorus, potassium, calcium, and magnesium. The nutrients can be supplied to the plant through distribution on the soil surface or by fertigation. Fertigation increases the efficient use of fertilizers and nutrient availability at root level, and fertigation in particular increases the mobility of potassium and phosphorus.

In fruits, nitrogen (N) is negatively correlated with the firmness, dry matter percentage, refractometric index, soluble sugar content, and acidity. An excess of N availability causes poor fruit skin color development and increases plant susceptibility to pests and physiological disorders. In vegetables, particularly leafy vegetables, N supplied as nitrate is negatively correlated to the dry matter percentage and directly correlated to the nitrate content in the edible portion (Fontana, Nicola, Hoeberechts, Saglietti, & Piovano, 2004; Nicola, Fontana, Hoeberechts, & Saglietti, 2005). In leafy vegetables, N fertilization can be scheduled to reduce the nitrate accumulation in plant parts to reach acceptable threshold levels, which are generally below 2500 mg/kg f.w. (Nicola et al., 2015). In the EU, specific limitations are set for the nitrate content in the final product for lettuce (*L. sativa* L.), spinach (*S. oleracea* L.), and rocket (*E. sativa*, *Diplotaxis* sp., *Brassica tenuifolia*, *Sisymbrium tenuifolium*) (EU-Reg. 1258/2011, amending EU-Reg. 1881/2006 that amended EU-Reg. N. 563/2002). Nitrate accumulation in plant parts depends on species, cultivar, season, and cropping system and affect product marketability and postharvest shelf life (Fontana et al., 2004; Nicola & Fontana, 2014; Nicola, Hoeberechts, & Fontana, 2005).

Among the plant mineral nutrients, potassium (K) is the cation having the strongest effect on fruit quality attributes that determine fruit marketability, consumer preference, and the concentration of phytonutrients (Lester, Jifon, & Makus, 2010; and citations therein). K effects on fruit marketability attributes include maturity, yield, firmness, soluble solids, and sugars; on consumer preference, they include sugar content, sweetness, and texture; on phytochemical concentrations, they include AA and carotenoid concentrations. All these aspects depend on K application modes (wet, through foliar or hydroponic application, or dry, in soil), doses (applications number), and timing (plant stage, cultural season). Supplementing sufficient soil K with additional foliar K applications during cantaloupe development and maturation improves the fruit marketable quality by increasing firmness and the sugar content, and fruit nutritional quality by increasing AA, beta-carotene, and the K levels (Lester, Jifon, & Stewart, 2007).

The preharvest nutritional status of fruit, especially with respect to calcium (Ca), is an important factor that affects the potential storage life (Gąstoł & Domagała-Świątkiewicz, 2006). Fruits with a high level of Ca have a lower respiration rate and longer potential storage life than fruits containing low levels of Ca. Ca plays a key role in the retention of firmness, delaying fruit ripening and reducing physiological disorders. Many physiological disorders in fruits are associated with Ca deficiency. The most common disorders induced by Ca deficiency are the blossom-end rot in tomatoes, tip burn in lettuce, and vitrescence in melon (Ahmed, Yu-Xin, & Qi-Chang, 2020; Indeche, Yoshida, Goto, Yasuba, & Tanaka, 2020; Jean-Baptiste, Morard, & Bernadac, 1999). The easiest way to maximize the Ca level in fruit is to use a foliar spray, although in many instances the uptake and penetration of Ca into the fruit and its movement within the fruit tissues is difficult to achieve (Mengel, 2002). Preharvest Ca applications on apples improved flesh firmness at harvest, especially during stressful seasons in which fruit Ca content is suspected to be relatively low, reduced the incidence of bitter pit and lenticel blotch after cold storage (Casero, Benavides, & Recasens, 2009). The total fruit Ca increases in all seasons with Ca treatments, but this increase is not proportional to the number of applications.

Leafy vegetables used for the fresh-cut industry are grown, in general, in open-field production. Conversely, in Italy, most of them are grown under protected cultivations, increasing yields and crop cycles, allowing out-of-season production, control the abiotic stresses, and facilitate pest management (Nicola & Fontana, 2007). The produce originates from different geographic areas, according to the season. Each geographic area is characterized by different environmental conditions, cultivar availability, and agronomic practices. These factors can influence not only the quality of the raw material at harvest, but also the efficiency of postharvest technologies, such as the choice of operational temperatures and packaging systems. Fruit and vegetables are produced both in open field (Fig. 7.1) and in protected cultivations, either in macro-tunnel or in greenhouse (Fig. 7.2A and B); some baby-leaf species (e.g., rocket, corn salad, baby lettuce, spinach) or aromatic plants are produced in soilless culture such as floating systems (FS) (Fig. 7.3). Compared to the open-field system, the protected culture system offers many advantages, for example, protection from damaging

FIGURE 7.1 Head lettuce varieties grown in open field.

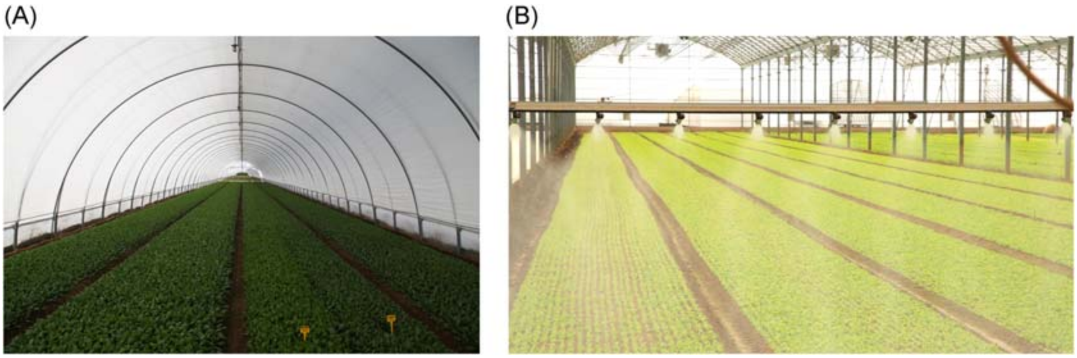


FIGURE 7.2 Baby spinach grown in macro-tunnel (A) and baby-leaf lettuce under greenhouse (B).

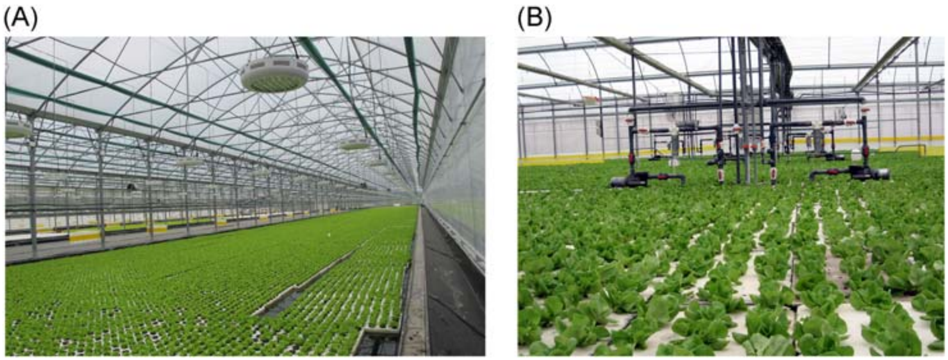


FIGURE 7.3 Soilless culture system with subirrigations: the flotation system for basil (A) and lettuce (B).

winds and other adverse weather conditions such as rain and hail, a reduction in evapotranspiration rate, an increase in photosynthesis rate, and an advance in the harvest date. The covering material of the greenhouses enhances the internal air temperature and leads to reduced air and soil temperature ranges. All these aspects affect plant health and hence raw material quality, yield, and safety. Voća et al. (2006) compared strawberry crops grown in open-field cultivation, soil-protected cultivation, and soilless-protected cultivation systems and found that the cultivation system had a great influence on the color and firmness of the strawberry fruit cv. Elsanta. Overall better fruit coloring was obtained in the protected cultivation systems, although the soilless system gave the lowest fruit firmness. The overall chemical composition of the fruit indicated that the highest quality was reached with the soil-protected cultivation.

Vegetables usually contain relatively high numbers of microorganisms at harvest because they are in contact with soil during growth (Tournas, 2005). Not all microorganisms are capable of proliferating on vegetables. Several microbial species can break the protective cover of plants and, then, grow and cause spoilage; others can enter the plant tissue through wounds and can grow and damage the vegetable. Some fungal spores can survive for some time in the soil and contaminate plants one season after another; these organisms may cause plant disease in the field, as well as spoilage during storage. In these circumstances, field treatments with fungicides and the use of resistant cultivars are necessary to avoid disease development and spoilage. The avoidance of disease development and spoilage are main factors that favor the development of the soilless culture system (SCS).

Most of the studies comparing traditional culture system (TCS) to SCS have indicated that SCS increase earliness, yield, or both (Ferrante, Incrocci, Maggini, Tognoni, & Serra, 2003; Fontana & Nicola, 2009; Fontana et al., 2004; Incrocci, Lorenzini, Malorgio, Pardossi, & Tognoni, 2001; Nicola, Fontana, et al., 2005; Nicola, Hoeberechts et al., 2005; Santamaria & Valenzano, 2001). By comparing soil and SCS for lettuce production in open field, Selma et al. (2012) showed that fresh-cut lettuce from SCS had significantly higher antioxidant content and better microbial quality than fresh-cut lettuce from soil. The protected SCS allows for higher qualitative and quantitative standardization of cultural techniques, and the reduction of both production costs and environmental impact. The system is a valid alternative to the soil cultivation system as it helps to avoid soil-borne diseases and controls mineral plant nutrition to standardize the qualitative characteristics of the final product. The use of mineral and sterile media with a low environmental impact may be an alternative to the practice of soil disinfection. When investigating a soilless system, to obtain uniform produce of high quality, it is crucial to adjust the nutrient solution, moisture, and water content of the growing medium because they are the most important aspects, apart from growing environmental conditions.

Intensive crop production systems, such as soilless culture, can increase not only yield but also quality and safety of fresh produce (Tzortzakis, Nicola, Savvas, & Voogt, 2020). Soilless cultivation generally refers to any method of growing plants without the use of soil as a rooting medium, whereas the term "hydroponics" refers to systems based on water as nutrient medium. The increased interest in the commercial application of soilless cultivation in the last decades has encouraged intensive research activity focusing on the development of new growing systems and a better understanding of the crop physiology and its impact on quality aspects.

The major advantage of soilless cultivation is the uncoupling of the plant growth from problems associated with the soil, such as soil-borne diseases, nonarable soil, soil salinity, poor physical or chemical properties, low temperature, and extensive use of agrochemicals. Water culture systems such as floating hydroponics, nutrient film technique, and aeroponics are mainly used for leafy vegetable production. All these systems can be applied with the aim of cultivating in areas with scarce availability of arable land, or even within big cities/metropolis (Kalantari, Mohd Tahir, Mahmoudi Lahijani, & Kalantari, 2017). There is an increase in the diffusion of numerous indoor farms (or vertical farms, or plant factories) in this context (Pennisi et al., 2019).

Vertical farming is a novel technology, in which plants are growing in multiple layers mounted into closed constructions nontransparent to sunlight, using LED lamps for artificial lighting and full control of all climate parameters. Vertical farms allow growers to obtain good production in small areas, also in multiple layers, with less inputs (mostly water and nutrients). There are examples of successful cultivation of various species, including leafy vegetables (Fig. 7.4), aromatic plants, microgreens, saffron, mushrooms (Fig. 7.5), strawberries, among others (Nicola et al., 2020).

FIGURE 7.4 Lettuce in a vertical farm.

FIGURE 7.5 Mushroom production in vertical and indoor system.

The soilless-protected cultivation system is highly productive and has proved to enhance product quality and the postharvest shelf life of many fresh-cut vegetables (Fontana, & Nicola, 2008, 2009; Fontana et al., 2004; Fontana, Torassa, Hoeberechts, & Nicola, 2006; Fontana, Nicola, Hoeberechts, & Saglietti, 2003; Hoeberechts, Nicola, Fontana, Saglietti, & Piovano, 2004; Luna, Martínez-Sánchez et al., 2013; Nicola, Fontana, et al., 2005; Nicola, Hoeberechts et al., 2005; Nicola, Hoeberechts, & Fontana, 2004; Nicola, Hoeberechts, Fontana, & Saglietti, 2003; Pace, Capotorto, Gonnella, Baruzzi, & Cefola, 2018; Pignata, Ertani, Casale, Piano, & Nicola, 2020).

Among the different soilless cultivation systems, the FS is a growing system that has led scientists and extension specialists to consider it as a way of producing leafy vegetables with characteristics that satisfy the requirements of entire production chains. The FS is a subirrigation system that consists of trays that float on a water bed or nutrient solution (Nicola et al., 2015; Nicola & Ertani, 2021). The system is suitable for raising vegetables with both short production cycle and high plant density; it can be considered an efficient system to produce leafy vegetables with high added value, processed as fresh-cut produce. In Italy, there is a growing expansion of the system, especially for growing all types of head lettuces, several baby leaves such as mizuna, rocket salad, lamb's lettuce, baby lettuce, and herbs such as basil. With the FS, 8–10 crops per years can be obtained (Benini, 2019; Bianchi, 2018; Fritegotto, Pennuzzi, & Cinelli, 2016). The system is generally used in greenhouse, but there are vertical farms starting to use it to produce leafy vegetables and herbs for the fresh-cut industry (Cinquemani, 2019).

The FS allows the produce quality at harvest to be improved, reduces microbial contamination, and eliminates soil and chemical residue spoilage. Normally, produce obtained from TCS can reach a total bacterial count of 10^6–10^9 cfu/g, which can be reduced by 2–3 log cfu/g after washing and sanitation practices. On purslane (*Portulaca oleracea* L.) grown in FS, the initial mesophilic load and *Enterobacteria* counts load was 2.7–3.0 and 2.1–2.2 log cfu/g, respectively, on processing day (Rodríguez-Hidalgo, Artés-Hernández, Gómez, Artés, & Fernandez, 2010). FS used to grow green lettuce, red lettuce, spinach, and rocket resulted at harvest in an average TPC of 10^3 cfu/g and YMC of 10^2; only spinach had a higher contamination of TPC (10^6 cfu/g) (Nicola et al., 2018a). In general, fresh-cut green lettuce or fresh-cut mix of green lettuce and red lettuce at the end of 9 days of shelf life at 4°C remained with the same magnitude of contamination (Pignata et al., 2020), while fresh-cut mix of green lettuce and either rocket or spinach increased of one or two logs, respectively (Pignata, 2016). The raw material obtained using FS in confined greenhouse is free of soil residue and dirt, and considering the overall very low microbial contamination, it was hypothesized, that washing is considered a critical point in the production process of the ready-to-eat vegetables. The use of floating systems allows to use softer washing procedures, such as eliminating chlorine from the water sanitation process, with less stress for the leaf tissue.

The NGS (New Growing System, NGS Almería, Spain, patent no. 2.221.636/7) technology is an innovative and versatile SCS that improves the yield and raw material quality at harvest and enhances the postharvest shelf life, by standardizing the growing system (Nicola, Pignata, Casale, Hazrati, & Ertani, 2021; Nicola & Ertani, 2021). Selma et al. (2012) assessed the microbiological quality of fresh-cut lettuce obtained by soil- and soilless-grown lettuce. Cultivation was in open field and the SCS used was the NGS. The SCS was more effective in controlling microbial contamination because soilless-grown lettuce had a lower initial microbial load and slower microbial growth during storage. At the end of intended shelf life period, the differences in microbial counts were 3 and 1.5 log units higher for lactic acid bacteria and total coliforms than in samples from soil grown lettuce. Nicola, Pignata, and Tibaldi (2018c) also found low mesophilic aerobic bacterial contamination ($<10^1$ cfu/g) and low YMC ($<10^1$ cfu/g) in strawberry "Mara de Bois" grown in substrate-based soilless growing system. After 4 days of shelf life, the fresh-cut strawberries still presented $<10^1$ cfu/g of contamination for both counts. A higher sanitary quality can be provided by the SCS as an alternative to traditional soil cultivation, because it avoids soil contaminants and achieves lower coliform counts.

7.2.4 Raw material harvest and handling

Good preharvest and harvest practices are necessary to reduce commodity damage. The quality of a raw material and the storage conditions before processing are very important to keep the quality of a vegetable. The harvest, handling, shipping, and storage before processing are very important stages where low temperatures are essential to preserve the quality of the raw material. Cold chains should start from the field to the processing industry. Low temperatures, in a range from 0°C to 10°C, depending on the species and cultivars, keep the turgor in vegetables unaltered and slow down the microbial growth. However, cultivation protocols are not yet broadly organized or optimized to handle the harvest phase with a minimization lag time before implementing cold chains.

Currently, fresh-cut vegetables shelf life is ca. 6–7 days in Italy and in many EU countries. The shelf life of fresh-cut produce in the United States exceeds 2 weeks, depending on the species. The long shelf life is achieved, apart from the limited range of species and typologies produced, due to prompt cooling and the maintenance of cold chains (see also Chapter 16: Investigating Losses Occurring During Shipment: Forensic Aspects of Cargo Claims), with temperatures generally below 4°C, after harvest during processing, shipping, and distribution, while these temperatures are rarely maintained in many European countries. In Italy, in no instance in value chains a temperature below 8°C is required nor recommended by law (DM n. 3746, June 20, 2014; DL n. 77, May 13, 2011).

The stage of maturity of fruit and vegetables destined for fresh-cut processing is a critical factor that should be carefully taken into consideration for ensuring the potential quality and shelf life of the product. The eating quality and shelf life of fresh-cut fruit products are influenced by the stage of ripeness at cutting (Gorny et al., 2000). Leafy vegetables are best tasting when harvested immature, whereas fruit vegetables and fruits are best tasting when harvested fully ripe (Kader, 2008). Maturity and ripeness stage at harvest are critical issues for fruits. Harvesting fruits before they reach optimal maturity is a common commercial practice, because of the higher prices obtained when the market availability is low at the beginning of the harvest season. Early harvesting of climacteric fruits assures that fruits are more tolerant to mechanical stresses and store longer. Conversely, harvesting at optimal maturity based on flavor would be more appropriated for the consumer. Ripe fruits increase the biosynthesis of non-volatile and volatile compounds influencing fruit flavor, or good eating quality that cannot be achieved in early harvested produce (Kader, 2008). Customer dissatisfaction with produce flavor contributes to the low consumption of fruits and vegetables (Mitcham, 2010). It is necessary to encourage the growers to harvest fruits at partially ripe to fully ripe stage by developing handling techniques to protect fruit from physical damage (Kader, 2008).

The shelf life of fresh-cut fruits is ca. 5 days because it is quite difficult for fresh-cut industry to maintain a proper ripening stage on a commercial scale. Fruit is generally harvested at "partially ripe" stage, which is an imprecise definition (Bai, Wu, Manthey, Goodner, & Baldwin, 2009) and varies within the same species according to the species and cultivar. The maturity stage of fruit for fresh-cut industry is much debated: harvesting "partially ripe" fruit means an easier management of fresh-cut processing and quality control during distribution compared to harvesting "riper" fruit, which is more flavorful and softer, but more difficult to handle for growers, processors, and retailers. For these reasons, fresh-cut apple offer has rapidly increased in recent years because apples are easier to manage compared to other fruits, such as peach, pear, or tropical fruit. Bai et al. (2009) suggested to harvest pear fruit 1 month later than the commercial practice for improving the quality of flat flavor, firm, and rough texture, and to limit the high potential for browning. Results from experiments showed that by delaying harvesting, the fruit had larger size, lower flesh firmness, lower titratable acidity, lower phenolic content, and higher volatiles. These parameters enhance the consumer acceptance, and, in fact, a panel preferred the delayed-harvest cut fruit compared to those from commercial harvest, especially in terms of visual quality, flavor, texture, and overall quality.

In the case of leafy vegetables, there is a wide range of possibilities for harvesting raw materials depending on the final destination of the produce, the requested quality attributes, and their tolerance to the postharvest handling and processing. The maturity indicators of intact leafy vegetables are size, head length, head width, firmness, and compactness; while for nonheading lettuces, the number of leaves can be used as a harvest index (Gil, Tudela, Martínez-Sánchez, & Luna, 2012; and citations therein). Size is the maturity indicator for Belgian endive, cabbage, endive, iceberg lettuce, radicchio, spinach, and Swiss chard. Furthermore, the head compactness is an important maturity indicator for cabbage and iceberg lettuce. In general, different maturity indicators can be used for harvesting lettuce for the fresh-cut industry. Head weight is the main parameter for quality evaluation of head vegetables, while for baby and mature leaves, leaf and petiole length are good maturity parameters to assure the quality of the fresh-cut product. For culinary herbs the harvest maturity can have relevance on the aromatic profile. Early harvesting, fresh-cut processing, and shelf life conditions can differently influence each compound improving or worsening the essential oil (EO) quality according to the final use by the industry (Fontana, Tibaldi, & Nicola, 2010). The aromatic profile of dill (*Anethum graveolens* L.) changed when its leaves were harvested as young leaves (38 days after sowing), at preblossoming and blossoming stage (50−70 days after sowing) or at full fruit maturity (130 days after sowing) (Tibaldi, Fontana, & Nicola, 2010).

The growth stage at harvest can influence the shelf life of the baby leaves harvested at an early growth stage due to market demand. The rate of deterioration has often been related to the metabolic processes and respiration rate, that are usually higher in younger leaves. The high respiration rate explains why it is hard to reach a commercial shelf life longer than 7 days. Young and tender baby-leaf vegetables of new varieties and species have continuously been developed for fresh-cut industry, but younger plants tend to accumulate more nitrate (Fontana & Nicola, 2008). It is then crucial to establish the harvest maturity indicators to describe the right time for harvesting raw materials with high nutritional value and optimal postharvest performance.

Harvesting directly affects the appearance and shelf life of the final product. The safety and the quality of fresh-cut produce depend not only on the cultural practices and postharvest conditioning, but also on the harvesting and handling procedures. Factors that can affect the microbial growth in the raw material include the climatic conditions which the plants are produced in, and the temperature and the air conditions at which the produce is stored after harvest. Harvesting at the higher temperature of the day causes wilting, shriveling, softness, and a high respiration rate and shortens shelf life. Zhan, Fontana, Tibaldi, and Nicola (2009) found that leaving garden cress (*Lepidium sativum* L.) harvested leaves at 28°C for 1 h, simulating summer air temperatures, negatively influenced the pigments content, which decreased over time, and caused ca. 13% loss in AA before packaging. PPO (EC 1.10.3.2) and peroxidase (POD, EC 1.11.1.17) activities were higher in garden cress leaves kept for 1 h at 28°C than leaves promptly processed. The high air temperature affects the leaf turgidity and increases the susceptibility of leafy vegetables to the physical damage during harvest-handling practices. An efficient and rapid harvest handling and storage implementation after the cultivation phase are fundamental factors that help in the quality preservation of the raw material, thus improving the processing and reducing the quality deterioration during shelf life.

Rough handling creates areas that darken, soften, and make the product vulnerable to pathogen attacks. Microbes can also readily attach to cut leafy vegetable surfaces reducing the safety and nutritional quality (see also Chapter 21: Measuring Consumer Acceptance of Vegetables). At harvest, appropriate measures should be taken to reduce or eliminate the potential risk of pathogens contamination through soil contact at the cut surface. The reduction or elimination of pathogens can be achieved by cleaning the cutters and containers, by increasing the cutting quality, for example, cutter sharpening, and by guaranteeing the hygiene of field workers.

The harvesting method, whether by hand or mechanical, and the handling can determine the variation in maturity and physical injury and, consequently, can influence the nutritional composition of vegetables. The use of good preharvest, harvest, and handling practices is necessary to reduce commodity damage. Harvesting early in the morning, before plants become warm and respiration rate increases, lowers the needed cooling and often lengthens the preprocessing storage. Placing the harvested produce quickly under shade, in opaque or dark boxes, or using white tarpaulins to reflect heat from the filled bins can cut the load temperature significantly. The often disregarded stages of value chains, the harvesting and handling, should be optimized and cool chains implemented as early as possible to maintain product quality to guarantee food safety and to reduce the amount of cooling needed afterwards (Fig. 7.6, see also Chapter 16: Investigating Losses Occurring During Shipment: Forensic Aspects of Cargo Claims).

Fresh fruit and vegetables are living tissues, and subject to continual changes after harvest. Fresh produce consumes photosynthates that were stored in the product before the harvest. The consumption rate depends on the respiratory activity of a particular commodity and its temperature. Delays between harvesting and cooling or processing can result in

FIGURE 7.6 Harvested iceberg lettuce stored in a dark, cold room (4°C) before processing.

direct losses due to water loss and microbial contamination and indirect losses, such as flavor and nutritional quality loss (see also Chapter 14: Non-destructive Evaluation: Detection of External and Internal Attributes Frequently Associated With Quality and Damage, and Chapter 16: Investigating Losses Occurring During Shipment: Forensic Aspects of Cargo Claims). The rate of product deterioration is proportional to the rate of respiration, which increases with the temperature. Shriveling and the loss of fresh and glossy appearance are the most noticeable effects of cooling delays, particularly for commodities that lose water quickly and show visible symptoms at low levels of water loss, like most leafy vegetables. A negative correlation has been found between the respiration rate and shelf life (Ninfali & Bacchiocca, 2004). Vegetables characterized by low respiratory rates, such as carrots, have a long shelf life. Preprocessing storage conditions are fundamental to preserve raw material quality; the optimal vegetable storage temperature should be observed to avoid chilling injuries, such as browning or pitting, and vegetable thermal shock due to the high-temperature gap between the field and the storage room.

7.3 Processing management for fresh-cut chains

On a physiological point of view, the fresh-cut produce is characterized by alive tissues, in which most of the metabolic processes are still active. Fresh-cut processing operations act as stressful factors by accelerating the color, texture, firmness, flavor, and nutritional value deterioration of the product and compromising its shelf life. Moreover, wounded surfaces provide favorable conditions for microbial growth. Therefore, adequate control strategies during the storage of fresh-cut produce should minimize nutritional and sensorial losses and reduce microbial growth. Proper handling, the use of effective sanitizers, adequate temperature storage, and packaging are the main ways of reducing rapid degradation of the fresh-cut produce.

7.3.1 The postharvest quality of fresh-cut produce

It was previously stated that, at harvest, quality results from the combination of genetic background, environmental conditions, and agronomic management (irrigation, fertilization, and pest control). Postharvest practices such as washing, sorting (see also Chapter 14: Non-destructive Evaluation: Detection of External and Internal Attributes Frequently Associated With Quality and Damage), sizing, cutting, blending, and packaging do not change the inner quality of the product but add value for the consumer, who is looking for convenient, healthy, and tasty food (Fig. 7.7A and B). Like any perishable product, fresh-cut fruit and vegetables are characterized by an irreversible deterioration of quality. Therefore the overall quality of these types of products cannot improve during further storage; it can only be retained. The deterioration can be retarded by optimal temperature management (Mercier, Villeneuve, Mondor, & Uysal, 2017), in combination with packaging techniques (Wilson, Stanley, Eyles, & Ross, 2019) and/or postharvest treatments, including the use of antibrowning agents, edible coating, chemical treatments, ethylene absorbers, among others (Oms-Oliu et al., 2010; Sadeghi, Lee, & Seo, 2019; Yousuf, Qadri, & Srivastava, 2018). Because consumer preferences differ among consumer segments, part

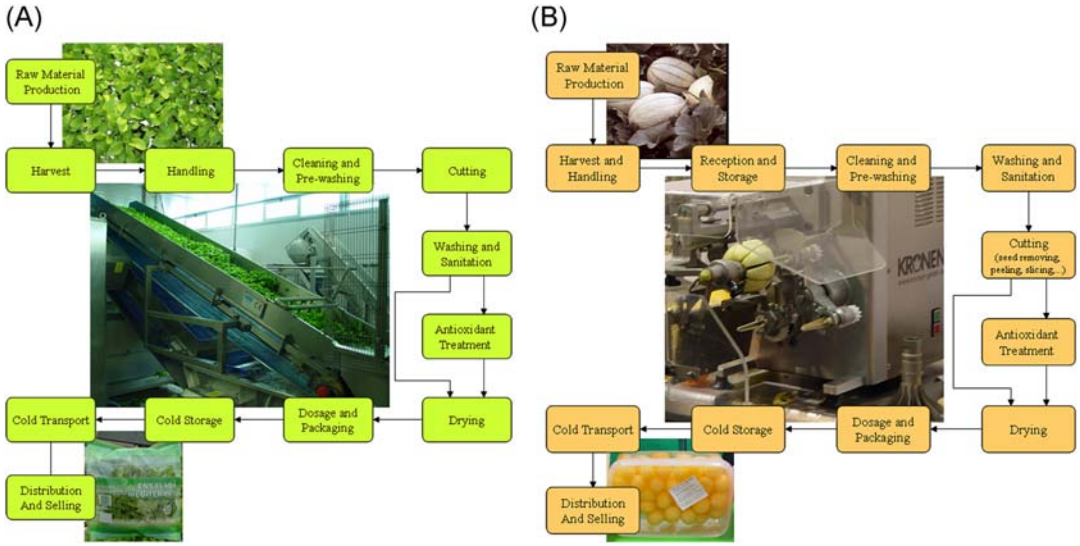


FIGURE 7.7 General diagram flows of processing operations for leafy vegetables (A) and fruit (B).

of the postharvest activity is also related to direct the appropriate product to the consumer segment appreciation. In fact, certain quality attributes can affect the price of a fresh-cut product based on how much the consumers will be willing to pay for a specific attribute (Pilone, Stasi, & Baselice, 2017). Fresh products are susceptible to deterioration between harvest and consumption. This time frame may be quite long, or very short, depending on the species, harvesting and handling methods, processing, length, and temperature of storage and distribution, market conditions, etc. The shelf life extension and the maintenance of postharvest quality, therefore, will depend on a combination of pre- and postharvest factors (Ansah, Amodio, & Colelli, 2018). The main objectives of postharvest technology concern quality and safety assurance, and loss reduction in postharvest chains.

7.3.2 Cutting

Producing fresh-cut fruit and vegetables involves substantial mechanical injury due to peeling, slicing, dicing, shredding, or chopping, depending on the product (Fig. 7.8A–D). Thus, the physiology of minimally processed fruit and vegetables is essentially the physiology of wounded tissues, which are subjected to an increase in respiration rate and ethylene production, membrane degradation leading to cellular disruption, and decompartmentalization of enzymes and substrates, and accumulation of secondary metabolites. All these biochemical reactions are responsible for changes in quality characteristics, such as texture, color, flavor, and nutritional value (Portela & Cantwell, 2001; and citations therein). The intensity of the wound's response in fresh-cut tissues can be mediated by several physical, chemical, and physiological factors. These factors include genetic background, signaling activation, stage of physiological maturity, temperature, gas composition, light, water vapor pressure, various inhibitors or elicitors, and severity of wounding (Saltveit, 2016).

FIGURE 7.8 Slicing onions (A), trimming asparagus (B), peeling carrots (C), and slicing tomatoes (D) in fresh-cut processing plants.

The severity of wounding depends on the type of cutting, cutting area size, and shape. The response of the tissue to processing wounds usually increases as the severity of the injury increases. Peeling and cutting increase the respiration rate from onefold to sevenfold, compared with the same fresh whole produce (Rivera-López, Vázquez-Ortiz, Ayala-Zavala, Sotelo-Mundo, & González-Aguilar, 2005). Del Aguila et al. (2006) measured the differences of respiration rate, ethylene production, and soluble solids between whole and shredded radish (*Raphanus sativus* L. cv. Crimson Gigante) and between shredded and sliced radish. During cold storage, the respiration rate of whole radish remained stable, while oscillations in fresh-cut radish were observed, with a generally higher respiration in shredded radish. Nine hours after processing, ethylene production was higher in the shredded and sliced radish than in the whole radish, and the shredded radish lost more soluble solids than the sliced or whole radish. The decrease in soluble solids was partially attributed to the consumption of carbohydrates during respiration related to the repair of injury, and the higher injured area of shredded radish may have caused an amplification of the response to injury.

Tibaldi, Battista, Fontana, and Nicola (2010), comparing two cutting shapes (slice vs dice) on fresh-cut processing operations of pumpkin (*Cucurbita moschata* Duchesne), packaging the fresh-cut products in three films with different permeance to O_2, and storing the packaged bags either at 4°C or 8°C, found that fresh-cut pumpkin can be stored for 9 days at 4°C if it is sliced and packaged with a film permeance above 1300 $cm^3/m^2/d/bar$ because of its lower respiration rate compared to dice-shaped pumpkin. Nicola, Tibaldi, Gaino, and Pignata (2018) repeated the same experiment on *Cucurbita maxima* Duchesne and confirmed the previous results. The larger cutting area of pumpkin dices than that of pumpkin slices accelerated the quality decay promoting anaerobic process at the end of the shelf life. Deza-Durand and Petersen (2011) investigated the effect of cutting direction on aroma compounds and respiration rates in fresh-cut iceberg lettuce. During fresh-cut processing operations, lettuce was cut either longitudinally or transversally to the midrib and then stored either at 6°C or 10°C for 4 days after having placed the fresh-cut lettuce in jars sealed with punctured films. The results showed that cutting the lettuce transversally to the midrib caused more severe damage to the tissue than cutting longitudinally, based on the increase in the levels of volatile organic compounds (VOCs) produced through the lipoxygenase (LOX) pathway responsible of off-odor development. Deza-Durand and Petersen (2011) hypothesized that, because LOX is a stress-related enzyme, the higher damage in lettuce cut in the transverse direction might indicate a greater disruption of membranes. Higher respiration rate of lettuce was observed for transverse cutting at the beginning of the storage period in comparison with longitudinal cutting but decreased sharply after 1 day of storage. The respiration rate was not as good an indicator of stress as cutting direction because it was mainly affected by storage temperature.

Cutting operations, in combination with other factors, can determine important changes in the product flavor, by altering the production of different VOCs. The combined effect of cut size, storage time, temperature, and growing season has been studied in fresh-cut melon (*Cucumis melo* L.) (Spadafora et al., 2019). Results showed that VOCs accumulation, quality indexes as well the expression of genes, and transcription factors related to VOCs biosynthesis and to quality were first affected by season, and then by postharvest conditions.

Cutting and shredding should be performed with the sharpest possible knives or blades made from stainless steel (Allende, Tomás-Barberán, & Gil, 2006). Saltveit (1997) considered that very sharp cutting tools could limit the number of injured cells. Portela and Cantwell (2001) evaluated the consequences of blade sharpness and thereby the degree of wounding on the appearance and physiology of fresh-cut cantaloupe. Pieces prepared using a sharp borer maintained marketable visual quality for at least 6 days, while those prepared using a blunt borer were unacceptable at 6 days, due to surface translucency and color changes. Borer sharpness did not affect the changes in decay, firmness, sugar content, or aroma, while blunt-cut pieces had increased ethanol concentrations, off-odor, and electrolyte leakage compared to sharp-cut pieces.

Cutting technique quality can influence microbial growth and the bacterial cross-contamination. O'Beirne, Gleeson, Auty, and Jordan (2014) observed that the use of sharp machine blades during the preparation of fresh-cut packed carrots reduced the depth of contamination by *E. coli* O157:H7. Gleeson and O'Beirne (2005) evaluated the effects of different slicing methods on the subsequent growth and survival of *E. coli*, *Listeria innocua*, and background microflora during storage at 8°C on modified atmosphere (MA) packaged vegetables (sliced carrot, and sliced iceberg and butterhead lettuce). In general, the slicing method had no significant effect on the initial inoculation levels. *L. innocua* grew better and *E. coli* survived better on vegetables sliced with blades that caused the most damage to cut surfaces. Slicing manually with a blunt knife or with machine blades gave consistently higher *E. coli* and *L. innocua* counts during storage than slicing manually with a razor blade. The effects of hand tearing were similar to slicing with a razor blade. The slicing method also affected the growth of the total background microflora; razor-sliced vegetables tended to have lower counts than other treatments. Product respiration was also affected by the slicing method; the use of a razor blade resulted in lower respiration rates.

Different solutions have been tested to prevent the acceleration of decay due to peeling, cutting, or slicing, for example, the "immersion therapy" that consists of cutting a fruit while it is submerged in water. The cutting of a submerged fruit controls turgor pressure, due to the formation of a water barrier that prevents movement of fruit fluids, while the product is being cut (Allende et al., 2006). Additionally, the watery environment helps to flush potentially damaging enzymes away from plant tissues. Another technique is the cutting operation performed under UV-C radiation. Lamikanra, Kueneman, Ukuku, and Bett-Garber (2005) observed that postcut application of UV-improved shelf life of cut cantaloupe, while cutting fruit under UV-C radiation further improved product quality. More specifically, the study found that UV-C radiation during processing reduced rancidity and improved firmness retention in the stored fruit. The UV-C radiation also reduced spoilage microorganisms such as mesophilic and lactic acid bacteria. The positive effect of UV light in combination with wounding has been also observed in a study made on carrot (Surjadinata, Jacobo-Velázquez, & Cisneros-Zevallos, 2017). Different cut sizes have been combined with UV-A, UV-B, and UV-C light. The combined effect of wounding and UV increased the phenolic content, the antioxidant capacity, and the phenylalanine ammonia lyase (PAL; EC 4.3.1.5) activity. UV-C was more efficient and rapid than others. Moreover, the highest phenolics accumulation was observed in the case of shredded carrots, compared to less severely cut ones.

A novel approach to wounding physiology includes the potential benefits deriving from cutting/slicing and the consequent enhancement of health-related properties of fresh-cut produce. It has been largely shown that wounding activates a cascade of responses at cellular level, which involves bioactive molecules, including phenolic compounds, and glucosinolates, among others. Thus, in certain species, the cutting action can be considered a tool for enhancing the accumulation of bioactive substances. This approach has been successfully applied to carrot (Surjadinata & Cisneros-Zevallos, 2012), potato (Torres-Contreras, Nair, Cisneros-Zevallos, & Jacobo-Velázquez, 2014), and broccoli (Villarreal-García, Nair, Cisneros-Zevallos, & Jacobo-Velázquez, 2016). However, it is important to notice that the positive effect of cutting on fruit and vegetables is particularly relevant in certain species and tissues (Reyes, Villarreal, & Cisneros-Zevallos, 2007). Also, in the case of perishable molecules such as AA, the cutting action is often accelerating the degradation process that leads to a rapid loss of nutritional value. In fresh-cut baby spinach, cutting determined a rapid loss of AA, especially at 20°C, while at 4°C, the effect was less evident, and AA degradation was slower (Cocetta, Baldassarre, Spinardi, & Ferrante, 2014).

Finally, the "water-jet cutting" method that is successfully used for, for example, meat, poultry, and vegetables (McGlynn, Bellmer, & Reilly, 2003), can also be used in the fresh-cut industry. This is a "noncontact" cutting method (Allende et al., 2006) that slices fresh fruit and vegetables utilizing a high-pressure fluid jet that minimizes bruising in the cut pieces and tissue damage in the vicinity of the cut surface. This method reduces the excessive tissue damage caused by compression and tearing the piece along the cut surfaces. It has been found that in fruit and vegetables sliced with a high-pressure fluid jet, the cell tissue damage is minimized, so that when the fruit or vegetable is subsequently eaten, it provides essentially the same sensory qualities, odor, texture, and taste as the freshly harvested fruit or vegetable. This type of slicing, together with proper storage conditions, allows produce shelf life to be prolonged in comparison to other conventional cutting methods, such as regular kitchen paring knives, commercial rotary blade cutters, razor sharp, or thin blade knives. The vegetables particularly adapted to being cut by this method are fresh root vegetables, leafy vegetables, and fruit, and vegetables with firm tissues.

The efficiency of this cutting method depends on the orifice size, water pressure, and standoff distance, which must be tuned according to the inherent characteristics of the species and cultivar (Bansal & Walker, 1999). McGlynn et al. (2003) assessed the effect of water-jet cutting on the shelf life of cut watermelon (*Citrullus lanatus* cv. Sangria). A comparison of pieces cut with a water jet with those cut with a knife showed that the former were firmer than the latter after 7 and 10 days of storage, and this difference was presumed to be due to weight loss. The experiment showed that water-jet-cut watermelon pieces tended to lose less moisture during storage than knife-cut pieces. The decrease in weight losses due to the loss of liquid during storage could have a significant impact on the consumer perception of freshness and texture and could influence microbial control strategies. The effect of ultrahigh-pressure water-jet cutting was tested in the production of fresh-cut iceberg lettuce (*L. sativa* L.) and endive (*Cichorium endivia* L.) in comparison to conventional blade cutting (Hägele et al., 2016). The authors found that the application of water-jet cutting was suitable for a "compact" species as iceberg lettuce as well as for a "loose" one as endive. Both species showed good results in terms of stress reactions, physiological status, microbiological, and visual quality. The authors identified optimal water pressure and orifice size, to be used for this kind of products. It is also important to consider that compared to blades, water-cut systems require less maintenance and can reduce the risk of cross-contamination.

Recently, ultrasonic cutting has been proposed as novel method for the preparation of fresh-cut red delicious and golden delicious apples (Yildiz, Palma, & Feng, 2019). The results showed that ultrasound affected PPO activity and pH, avoiding visual alteration such as browning. Moreover, apples cut with ultrasound showed a smoother surface, as evidenced by sensory evaluation, and microscope analyses.

7.3.3 Washing, sanitation systems, and processing aids

During processing, pre- and postcutting washing operations of produce are crucial to make the product ready-to-eat. The produce must be clean, free of soil residue, insects, metals, and weeds, and safe. The raw material should be carefully cleaned before processing because fresh-cut produce is prepared from materials grown mostly in contact with soil and without any strong antimicrobial treatments, such as pasteurization or sterilization. Even healthy-looking products from the field can harbor large populations of pathogens, particularly during warm weather. Only products obtained in protected cultivation and in soilless conditions, without any overhead irrigation throughout the production, have been proven to lead to low microbial contamination at harvest (Nicola et al., 2018a; 2018c).

Washing raw materials before cutting (fruit and vegetables) and during fresh-cut processing (leafy vegetables) is the most effective way of minimizing the risk of the presence of pathogens and of any residue left on the produce from harvest and handling conditions (Fig. 7.9A–C). When fruit and vegetables are exposed to contaminated water, they often become infected and subsequently decay during shipping and handling; thus the quality of water used must be as high as possible. Pathogens present on freshly harvested products accumulate in recirculated water-handling systems and greatly reduce sanitation efficiency. Fresh-cut produce is highly susceptible to microbial contamination, because microbial cross-contamination can occur through shredders and slicers and the inner tissues can be exposed to microbial attachment and growth after cutting. Many postharvest

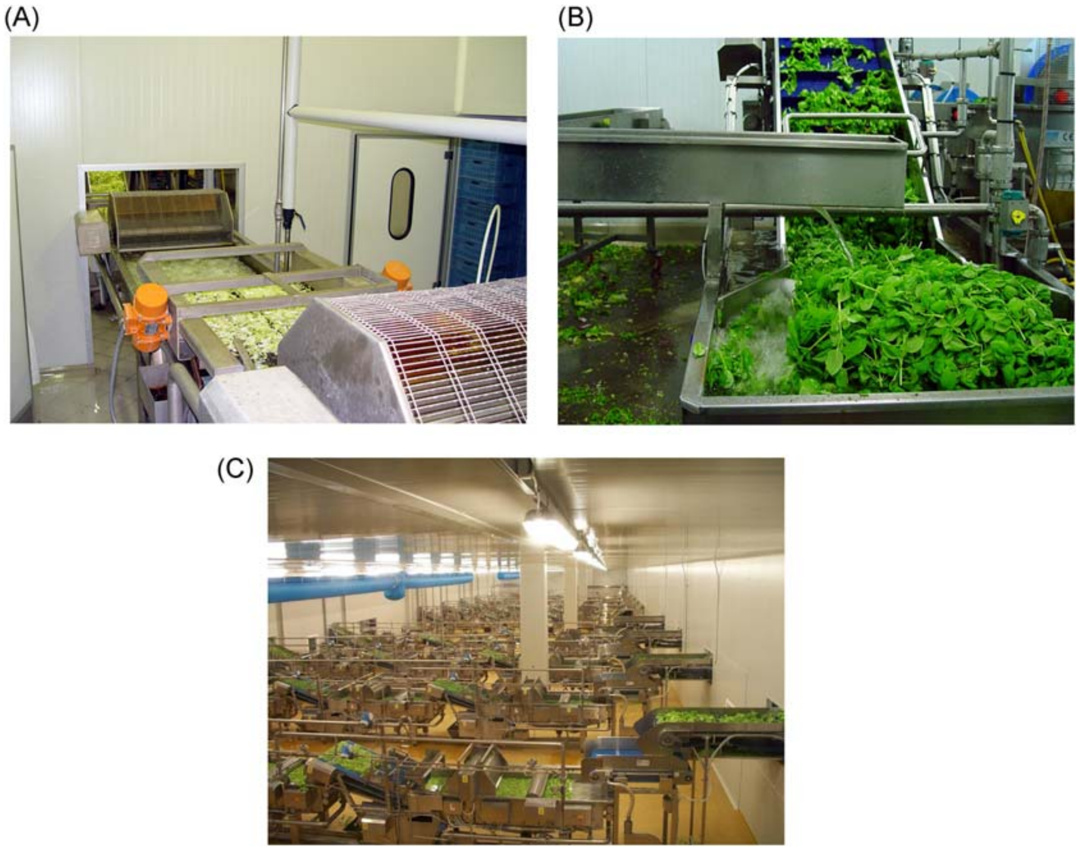


FIGURE 7.9 Washing of fresh-cut lettuce (A) and basil (B) in processing plants. View of a processing plant (C).

decay problems result from the ineffective sanitizing of dump tanks, flumes, and hydrocoolers. Moreover, the operations should be conducted at a low temperature to reduce microbial growth. A delay between prewashing and subsequent operations without product refrigeration can allow microbial growth and a subsequent shortening of the shelf life.

The effectiveness of washing to remove soil impurities and microbial contaminations is related to numerous factors, such as raw material spoilage, the duration of the washing treatment, the washing water temperature, the method of washing (dipping, rinsing, or dipping/blowing), the type and concentration of the sanitizer, the type of the sanitation method (chemical or physical treatment), and the type of fresh-cut fruit or vegetable.

Chlorine is the most widely used disinfection product in the fresh-cut industry. However, an excessive amount of chlorine or chlorine-based sanitizing products (hyperchlorination), often used to guarantee an optimal sanitization, can cause toxicity problems related to chlorine harmful sub-products deriving from the reaction between chlorine and the organic matter present in the washing water (Banach, Sampers, Van Haute, & der Fels-Klerx, 2015). Consequently, alternatives to chlorine-based sanitizers are needed.

At the moment, alternative disinfection agents used and tested for water and produce sanitation are ozone, organic acids, hydrogen peroxide, alcohols, and phosphoric acid, while the physical methods used and tested are UV-light radiation, high-pressure, high-intensity electric field pulses, radio frequency, ionizing radiation, ultrasounds, and hot water treatments, including the combinations of some of them for synergistic effects (Allende et al., 2006; and citations therein; Seymour, Burfoot, Smith, Cox, & Lockwood, 2002; Alexopoulos et al., 2013; Artés, Gómez, Aguayo, Escalona, & Artés-Hernández, 2009; Beirão-Da-Costa, Moura-Guedes, Ferreira-Pinto, Empis, & Moldão-Martins, 2012; Birmpa, Sfika, & Vantarakis, 2013; Gil et al., 2009; Gómez-López, Gil, Allende, Vanhee, & Selma, 2015; Gopal, Coventry, Wan, Roginski, & Ajlouni, 2010; Gutiérrez, Chaves, & Rodríguez, 2017; Kim et al., 2013; Kim, Fonseca, Kubota, & Choi, 2007; Lopez-Galvez, Ragaert, Palermo, Eriksson, & Devlieghere, 2013; Nou & Luo, 2010; Ramos-Villarroel, Aron-Maftei, Martín-Belloso, & Soliva-Fortuny, 2014; Wulfkuehler, Gras, & Carle, 2013).

In the last decades, EOs have also been studied as natural disinfectants or antimicrobial agents (Roller & Seedhar, 2002; and citations therein; Scollard, Francis, & O'Beirne, 2013; Yuan, Teo, & Yuk, 2019). In a review written by Ayala-Zavala, González-Aguilar, and Del Toro-Sánchez (2009) on using the antimicrobial and aromatic attributes of EOs to enhance safety and aroma appeal of fresh-cut fruits and vegetables, the antimicrobial effect of thymol, eugenol, menthol, and other compounds against pathogens and suggested that possible combinations of fresh-cuts are extensively reported. However, the high risk of transference of off-odors from the EOs to the commodities raises the needs for further sensorial investigations; the positive or negative sensorial impact of EO on fresh-cut produce should be additionally considered. Scollard et al. (2013) examined the antilisterial effectiveness of selected EOs and shredded herbs (thyme, oregano, and rosemary) on a range of MA packaged fresh-cut vegetables (lettuce, carrot disks, cabbage, and dry coleslaw mix). The authors found that the antilisterial effects were in the following order: thyme EO > oregano EO > rosemary herb. The antimicrobial effects of EOs varied depending on which EO was used and the type of fresh-cut vegetable involved. Both antilisterial and general antibacterial effects were observed for thyme and oregano EOs. Thyme EO was found to be the most effective treatment against *Listeria*. Oregano EO was also found to have strong antilisterial effects, but not as strong as those of thyme EO. Rosemary EO showed no antilisterial effects except in the presence of shredded cabbage, and these effects were considerably smaller than those of the other EOs. By contrast, strong antilisterial effects were evident from rosemary herb, but only after stomaching, indicating that the herb is only effective when it is completely macerated with the vegetable sample in the stomacher. Furthermore, the efficacy of the treatments varied according to the vegetable tested.

There are several techniques available for the isolation of the EO from a selected herb and can be more or less complex and result in a different composition of the EO. These techniques include supercritical fluid extraction, ultrasound-assisted extraction and microwave-assisted extraction, among others. Comparison between the extraction methods has indicated a comparable profile of volatile secondary metabolites in the EOs obtained from mint species (Orio et al., 2012) and other *Lamiaceae* species (Binello et al., 2014).

The use of ozone reduces the amount of wastewater, lowers the refrigeration costs of chilled water due to the less frequent flume water changing, and it can be combined with chlorine, the use of which can be reduced by 25% leaving less residual odor on the product (Strickland, Sopher, Rice, & Battles, 2010). The main systems for ozone application include the gaseous phase storage or ozonated dips. Several studies demonstrated that gaseous ozone is generally more effective than in aqueous solutions (Ramos, Miller, Brandão, Teixeira, & Silva, 2013). The use of ozonated water has been suggested as an interesting alternative to chlorine due to its efficacy at low concentrations (0.2−5 ppm) and short contact times (from 15 s to few minutes). Alexopoulos et al. (2013) tested the effectiveness of ozonated water (0.5 mg/L) dipping on fresh-cut lettuce and bell pepper. The study showed that treatments were most effective when vegetables were continuously exposed to ozone, as the microbial load was progressively decreased. Moreover, the best results found in bell pepper compared to lettuce were attributed to the smoother and more uniform surface of the fruit. However, the efficacy of ozonated water depends on ozone solubility, which increases as the water temperature decreases and is influenced by organic content and pH of the water (Artés et al., 2009; Ölmez & Kretzschmar, 2009).

Organic acids (e.g., lactic, citric, acetic, peracetic, or tartaric acid) dipping have a much more residual antimicrobial effect than ozone and chlorine treatments on the microflora of lettuce during storage (Akbas & Ölmez, 2007). The antimicrobial action of organic acids depends on several factors, such as a reduction in pH, the ratio of the undissociated fraction of the acid, chain length, cell physiology, and metabolism. Martín-Diana et al. (2005) compared calcium lactate with chlorine as a washing treatment for fresh-cut lettuce and carrots. Calcium lactate was not significantly different from chlorine treatment in terms of maintaining color and texture during the entire storage period. Furthermore, carotenoid levels were higher in calcium lactate-treated carrots than chlorine-treated samples after 10 days of storage at 4°C. Ultimately, the mesophilic, psychotropic, and lactic bacteria counts were not significantly different for the calcium lactate and chlorine treatments for either vegetable. Thus calcium lactate appears to be a suitable washing treatment, which has no posttreatment bleaching effect on fresh-cut lettuce and does not cause the appearance of whiteness on the surface of sliced carrots.

Recently, the peracetic acid (PAA) was successfully employed on a laboratory and on industrial scale as water disinfection agent in fresh-cut lettuce production (Banach et al., 2020). The results showed that PAA (ca. 75 mg/L) determined a 5-log reduction of *E. coli* in the water. The number of evidences supporting the efficacy of PAA is growing and its effects, in comparison to sodium hypochlorite, have also been shown at a molecular level (Daddiego et al., 2018). Moreover, PAA has been successfully applied in combination to ultrasound (Silveira et al., 2018) and this treatment reduced *Salmonella enterica typhimurium* counts to undetectable levels, thus indicating a potential application of these combined treatment on a large industrial scale.

Investigating potential alternatives to chlorine-based disinfection of fresh-cut products is a very active field and several promising treatments, or combinations of them, have been found to be effective. However, a sure and conclusive disinfection system able to remove dirt, weeds, pesticide residues, and pathogens, while, at the same time, not negatively affecting the intrinsic, and extrinsic quality of the product has yet to be found.

When planning the concentration of chlorine to be used, one should consider its reaction to organic matter. When the chlorinated solution comes in contact with a cut produce, the sanitizer will react with the organic matter (such as vegetable tissue, cellular juices, soil particles, microbes) and the available (free) chlorine will be depleted. The difference between total chlorine and available chlorine depends on the amount of organic matter and inorganic compounds that react with the free chlorine (FC) during washing. The smaller the amount of organic cellular compounds released by cutting the produce, the smaller the difference between the total and available chlorine. Consequently, the proper concentration of chlorine to be used during sanitation should also be considered according to the type of produce, cut size, and type (e.g., slice, shred, whole leaf). To guarantee the optimal sanitizing effect and prevent cross-contaminations, the level of FC must be maintained constant. With this aim, Abnavi, Alradaan, Munther, Kothapalli, and Srinivasan (2019) have proposed a lab-scale model for the optimization of FC control in sanitizing water. This method has been tested for different lettuce types (romaine, iceberg, green leaf, and red leaf), carrots, and green cabbage and it was based on the changes in the chemical oxygen demand evolution.

The chlorine concentrations and washing times vary to a great extent from a processor to another, and these differences are mainly related to the different operational temperatures and the resulting bleaching effects that are tolerated by the consumers in any given market. Chlorine lethal effect increases with temperature and its effect on microbial removal occurs when the water is warmer than the produce (Beuchat, 2007; Hernandez-Brenes, 2002). According to Beuchat (2007), the lethal effect of chlorine occurs within the first few seconds of treatment, and the population of microorganisms decreases as the concentration of chlorine increases to about 300 μg/mL, above which its effectiveness is not proportional to the increased concentration. Treatments with 50−200 μg/mL chlorine and a washing time of 1−2 min can reduce the number of microorganisms by 1−2 log cfu/g in some instances but can at the same time be completely ineffective in others (Hernandez-Brenes, 2002; Roller & Seedhar, 2002). Usually, in the Mediterranean regions, the chlorine concentration used is between 30 and 50 μg/mL, in combination with an operational water temperature around 12°C. Several studies have demonstrated that chlorine rinses can decrease the bacterial load from <1 to 3.15 log cfu/g, and its efficacy depends on inoculation method, chlorine concentration, contact time, and microorganism type (Ramos et al., 2013).

Raw materials are generally washed in cold water, because low temperatures slow down plant respiration, transpiration, and microbial activity. Water temperatures range between

4°C and 12°C, although washing hot raw materials (e.g., summer in the Mediterranean) with colder water could cause the vegetable tissues to absorb any chemical contaminants present in water (Hernandez-Brenes, 2002; and citations therein). Maintaining the water temperature 5°C above the internal temperature of the produce can prevent this effect. One precaution could be an initial air-cooling step before washing to minimize the temperature gap between the produce and the water temperature.

After washing, with or without a chemical sanitizer, a sanitation physical method or a dipping treatment could occur on whole or cut or peeled produce. Several studies have investigated the effect of dipping treatments on quality and safety of fresh-cut fruit and vegetables. Dipping operations are processing aids used for chemical and physical treatments and postcutting application of additives. Heat treatments are becoming very popular in the fresh-cut industry. These treatments help in preventing of enzymatic browning, responsible of color, flavor, and texture changes as well as of nutritional losses and, at the same time, heat can inhibit microorganism growth. Heat treatments can be applied in the form of hot water, hot vapor, hot air, or hot water rinse brushing (Sivakumar & Fallik, 2013). Several studies have investigated the application of heat treatments by dipping for quality retention and safety control to replace the use of chemical treatments. In general, this treatment is particularly indicated for fresh-cut fruits, florets, and roots, including fresh-cut carrot (Alegria et al., 2012), melon (Aguayo, Escalona, & Artés, 2008), broccoli florets (Moreira, Ponce, Ansorena, & Roura, 2011; Moreira, Roura, & Ponce, 2011), potatoes (Tsouvaltzis, Deltsidis, & Brecht, 2011), mangoes (Djioua et al., 2010), peaches (Koukounaras, Diamantidis, & Sfakiotakis, 2008; Steiner et al., 2006), kiwifruits (Beirão-da-Costa et al., 2008), and apples (Kabelitz, Schmidt, Herppich, & Hassenberg, 2019). In general, temperatures used for hot water dips on different fresh-cut products can range from 40°C to 60°C, while dipping duration ranges from few seconds to many minutes (up to 70 min). The selection of appropriate treatment conditions (temperature × duration) is a crucial factor in determining the overall quality of the horticultural product at the end of treatment and during shelf life. These conditions depend on the plant organ (leaf, fruit, root, etc.), maturity stage, fruit size, cultivar, growing conditions, and on timing of application as pre- or postcutting treatment.

Dipping treatments could also consist of using a solution containing antibrowning compounds, such as AA or a calcium salt with an organic acid, antimicrobial agents, or edible coatings to extend the postcutting shelf life of fruit and vegetables. Treatments with citric acid (CA) were found effective in maintaining the nutritional value of minimally processed lamb's lettuce (*V. olitoria*). Data showed that the washing treatment with CA allowed maintaining a higher concentration of AA and leaf functionality, as measured non-destructively by chlorophyll *a* fluorescence assay (Cocetta, Francini, Trivellini, & Ferrante, 2016).

Edible coatings based on different chemical constituents can be an effective strategy to prolong the shelf life and improve the quality of fresh-cut fruits (Maringgal, Hashim, Tawakkal, & Mohamed, 2019; and citations therein). Edible coatings have been applied to many fresh-cut products, including papaya (Batista et al., 2020), carrots (Vargas, Chiralt, Albors, & González-Martínez, 2009), pears (Oms-Oliu, Soliva-Fortuny, & Martín-Belloso, 2008; Xiao, Luo, Luo, & Wang,2011; Xiao, Zhu, Luo, Song, & Deng, 2010), bananas (Bico, Raposo, Morais, & RMSC Morais, 2009), apples (Freitas, Cortez-Vega, Pizato, Prentice-Hernández, & Borges, 2013; Rojas-Graü, Tapia, Rodríguez, Carmona, & Martin-Belloso, 2007), melons (Poverenov et al., 2014), mangoes (Robles-Sánchez, Rojas-Graü, Odriozola-Serrano, González-Aguilar, & Martin-Belloso, 2013), and persimmons (Sanchis et al., 2016). The coating supplies a selective barrier to moisture transfer, gas exchange, or oxidation processes, which slows ripening, reduces weight loss, inhibits browning, and helps to preserve fresh aroma and flavor. One of the most important advantages of using the edible coating is that several active ingredients can be incorporated into the polymer matrix and consumed with the food (Rojas-Graü, Soliva-Fortuny, & Martín-Belloso, 2009). Edible coatings are also used as carriers of active ingredients, such as antibrowning (AA), antimicrobial (organic acids, fatty acids esters, polypeptides, plant EOs), and texture enhancer (calcium chloride, calcium lactate, calcium gluconate) compounds, as well as flavors and nutraceuticals (vitamins, minerals, fatty acids), to improve quality, safety, and nutritional value of fresh-cut fruits. Among the edible coatings, alginate, chitosan (CH), gellan, and pectin are the most common coating materials used in the fresh-cut fruit industry.

CH is a natural, non-toxic, biodegradable polymer with antimicrobial activity and film-forming capacity. The functional properties of CH films can be enhanced by combining them with other hydrocolloids, controlled atmosphere, or chemical dipping. Xiao et al. (2010) investigated the effects of pure oxygen pretreatment and CH coating containing 0.03% rosemary extracts on the quality of fresh-cut Huangguan pears. The authors found that the combination of pure oxygen pretreatment prior to slicing and CH coating plus rosemary extract may be a potential method to maintain the fresh-cut fruit quality and to reduce browning, softening, and decay, which are the main problems in fresh-cut pears during storage. Xiao et al. (2011) evaluated the effects of sodium chlorite dip treatment and CH coatings on the quality of fresh-cut d'Anjou pears. The edible coatings were prepared from CH and its water-soluble derivative carboxymethyl CH. The authors found that the combination of sodium chlorite with carboxymethyl CH had beneficial effects in reducing the cut-surface discoloration and in inactivating *E. coli* O157:H7. So far, the effectiveness of various dipping operations has been demonstrated exclusively on fruits. However, recently the application of an edible coating has been tested on a particularly perishable vegetable, artichoke (*Cynara scolymus* L.) (El-Mogy, Parmar, Ali, Abdel-Aziz, & Abdeldaym, 2020). The authors showed that the postharvest application of a *Cordia myxa* (Cg) gum-based coating supplemented with $CaCl_2$ was effective in delaying browning and extending the shelf life of artichoke bottoms during refrigerated storage. After dipping, the products are drained and dried by air, then packaged.

7.3.4 Drying systems

Moisture control is one of the most important factors for maintaining the stability of fresh-cut products. After washing, the excess water should be removed from the fresh-cut product before packaging to prevent rapid microbial development and enzymatic processes that would lead to product quality deterioration. Various methods can be used to remove water excess, including centrifugation, vibrating surfaces, air blasts, or blotting. Water remaining on the product is a critical issue.

The duration and speed of centrifugation need to be adjusted for each product (Fig. 7.10). Minimal centrifugation can leave residual water on the produce surface, thus

FIGURE 7.10 Iceberg lettuce after drying centrifugation.

favoring microbial growth, while excessive centrifugation can result in cellular damage and cause cellular leakage. Fresh-cut products are often left with too much moisture, which causes their rapid deterioration. Pirovani, Güemes, and Piagentini (2003) evaluated the effect of speed (from 0 to 1080 rpm) and operation duration (from 1 to 9 min) of spin drying on the excess water remaining on washed, fresh-cut spinach as well as the microbial growth and sensory deterioration during storage of fresh-cut packaged spinach. The combination of the centrifugation speed and operation duration affected the water removal. According to their results, it is necessary to reach higher centrifugal speeds than 600−700 rpm and a duration longer than 4 min to obtain an optimal drying level of spinach (i.e., 0.1%−0.3% of water excess).

Luo and Tao (2003) used imaging technology to determine the tissue damage of fresh-cut iceberg lettuce and baby spinach during a centrifuge-drying process. Large differences in damage were found for fresh-cut iceberg lettuce between the two centrifuge-drying speeds of 150 and 750 rpm. Furthermore, a significant difference was found at 750 rpm depending on the location of the samples in the centrifuge-drying basket; the tissues of samples located near the side of the drying basket were more damaged than those located at the top, in the center, or at the bottom. For baby spinach, the damage due to the centrifugal force was similar to the results for iceberg lettuce, the samples at the bottom of the basket in addition to those near the side of the basket suffered from severe tissue damage. The damage to the spinach tissues was possibly influenced by both the centrifuge speed and the weight of the product in the drying basket.

Drying tunnels with continuous airflows are also used, especially for more delicate vegetables (Donati, 2003). The critical points when using air-drying tunnels are the optimal adjustment of the air temperature to avoid possible raw material fading, the thermal shock between air temperature flow and raw material temperature, and the residual water on the raw material, all of which are factors that could reduce shelf life quality. Some companies have recently introduced cool-drying tunnels, which are very efficient, but require an additional cost.

FIGURE 7.11 Packages for fresh-cut produce.

7.3.5 Packaging

Packaging is the final step in the fresh-cut production pipeline. A proper packaging, in combination with an accurate temperature management, can significantly extend the shelf life and provide the consumer with high quality and safe produce (Fig. 7.11). The most studied packaging method is modified atmosphere packaging (MAP). Low O_2 concentrations (1%−5%) reduce the respiration rate, chlorophyll degradation, and ethylene biosynthesis, while high CO_2 concentrations (5%−10%) reduce the respiration rate and slow plant metabolism. The main aim of packaging is to create an atmosphere able to slow down the produce metabolic activities, while maintaining the minimal O_2 concentration and the maximum tolerated CO_2 concentration. In this way, both fermentation and metabolic disorders are avoided (Jacxsens, 2002). On the other hand, Rojas-Graü, Oms-Oliu, Soliva-Fortuny, and Martín-Belloso (2009) reported that the use of elevated O_2 relative pressures (70 kPa O_2) can be proposed as an alternative to low O_2 atmospheres to inhibit the growth of naturally occurring microorganisms, prevent undesired anoxic respiration processes, and preserve the fresh-like quality of fresh-cut produce. According to several authors, high O_2 concentration can generate ROS that would, in turn, damage microbial cells and reduce microbial growth. However, there is still limited information about the effects of high O_2 concentrations on the antioxidant content of fresh-cut produce.

A MA is generated by the respiration of fresh-cut produce (passive MAP) or attained by a gas flushing (active MAP) (Artés, 2000a, 2000b; Bolin & Huxsoll, 1991; Kader, 2002a;

King, Magnuson, Török, & Goodman, 1991). The passive MAP is applied to fresh-cut vegetables sealed within bags of semipermeable films, harnessing the naturally occurring respiration of the living vegetable tissues to modify the atmospheric conditions (Thomas & O'Beirne, 2000). One of the most important factors of this technique is the gas permeability of the selected film that must allow an adequate O_2 and CO_2 exchange between the product and the atmosphere to establish the desired gas composition inside the bag. Due to perishability and the short commercial life of freshly processed produce, the MA is often actively established either by flushing with the desired atmosphere or by creating a slight vacuum and replacing the package atmosphere with the desired gas mixture (Artés, 2000a; Kader, 2002a).

The choice of a packaging film depends on the permeability of the film to the O_2 and CO_2 that must be adapted to the respiration rate of the produce. If the permeability for O_2 and CO_2 is perfectly matched to the respiration rate of the produce, an ideal equilibrium-modified atmosphere (EMA) can be established inside the package. The EMA depends on many factors: the product respiration rate, respiring surface area, storage temperature, packaging film permeability and equipment, RH, filling weight, package volume, film surface area, degree and kind of illumination of the display in the retail store, as well as the initial microbial load (Artés & Martínez, 1996; Day, 2000; Jacxsens, Devlieghere, & Debevere, 1999; Kader, 2002a, 2002b; Nicola, Fontana, Tibaldi, & Zhan, 2010).

The dynamic variation of internal gases composition is the result of the multiple interactions involving the product, the inner atmosphere of the package, and the external environment. Nowadays, modeling is an efficient tool that can be used for the design and the optimization of a tailor-made MAP system (Belay, Caleb, & Opara, 2016 and references therein).

MAP systems alone are not effective in avoiding tissue browning, decay processes, and microbial growth. The polymeric films used in MAP have some limitations because of their structure and permeation properties. They may cause the water loss, which results in softening, translucency or weight loss, or, on the contrary, can increase the formation of water condensates that would promote microbial growth. For these reasons, in recent years, research has been focused on increasing the effectiveness of MAP by combining it with other sanitation technologies, such as ozonation and UV light, or with dipping operations, such as the application of edible coating added of antibrowning and antimicrobial agents (Chauhan, Raju, Ravi, Singh, & Bawa, 2011; Krasnova, Dukalska, Seglina, Misina, & Kārlina, 2013; Rojas-Graü, Oms-Oliu et al., 2009). In a review, Rojas-Graü, Soliva-Fortuny et al. (2009) extensively report the scientific works of the last years on the use of innovative atmospheres and edible coatings for maintaining freshness and safety of fresh-cut fruit and vegetables. Also, the packaging can be successfully combined with active components that can enhance its effectiveness with improved properties such as antifog agents, ethylene and gas absorbers, or various patches or sachets that would release active molecules within the package, following a controlled kinetic (Gaikwad, Singh, & Singh Negi, 2020; Wilson et al., 2019). However, in certain cases the presence of such additional features within the package would influence the consumers perception and the commercial success of the product, as reported by Wilson, Harte, and Almenar (2018) in the case of cantaloupe melon.

Packaged fruit and vegetables are usually exposed to different surrounding temperatures during shipping from the processing plant to the consumer, storage, and display at retail; MAP is not a substitute for a proper cold chain management, but it can help to extend the shelf life. A change in the environmental temperature creates a specific problem in EMA establishment because the respiration rate is influenced more by temperature changes than film permeability to O_2 and CO_2 (Jacxsens, Devlieghere, & Debevere, 2002).

7.3.6 Temperatures, cold chain, and light

To delay quality losses and to reduce the proliferation of spoilage microorganisms, fresh and fresh-cut produce temperature should be maintained at 7°C−8°C. However, temperature abuse can be a common issue. Therefore, an important step in cold chain management is to monitor the cold chain by recording the temperature of fresh produce throughout entire value chains (see also Chapter 16: Investigating Losses Occurring During Shipment: Forensic Aspects of Cargo Claims). Moreover, the implementation of temperature monitoring within an adequate HACCP program is crucial. Often, the research experiments in this field are conducted at a laboratory scale, under controlled conditions, and in some cases, this is a limitation for the further application on a larger/real commercial scale. There are, however, some results from investigations conducted in realistic circumstances encountered in the food industry. The possibility to set up experimental trials under real conditions is facilitated by the use of innovative, portable, and non-destructive tools, which can allow the evaluation of product physiological status under various conditions, from the field to the final consumer. Rediers, Claes, Peeters, and Willems (2009) used time−temperature data loggers to follow endive temperature from the on-farm refrigerators to the on-processor storage to the distributor company and to restaurants up to the act of consumption. All these steps were at air temperature setting of 4°C. In the production facility the processing water was at 4°C and the facility was at 8°C. The researchers found that in the on-farm refrigerators, where heads were stored in Euro Pool System crates piled up on pallets, the endive was cooled more rapidly at the top of the pallet than in the middle or in the bottom (2.5 h extra to reach 8°C for the heads in the middle of the pallet and 3.5 h extra for those in the bottom of the pallet). In addition, regardless of the refrigeration temperature, endive required 3 h of cooling on a warm day (temperature range 14°C−35°C), while only 2 h on a moderate day (temperature range 5°C−19°C). During transport the endive temperature was 16°C and, once stored in the processing facility, it took from 5:00 p.m. to 4:00 a.m. to reach the temperature of 4°C. At that point, endive was kept at 4°C during processing and during the transport to the distribution company, while during the final transport to the three restaurants, temperature rose 2°C−4°C and kept fluctuating in the restaurant refrigerators because proximity to ovens and of more often opening of the door than that of industry refrigerators. In conclusion, it seems that the real critical points when fresh-cut produce rises its temperature were during transport, from farm to the processor, from the distributor company to restaurant delivery, and during storage in restaurants. The levels of all indicator microorganisms and pathogens were confined within the limits prescribed by EU-Reg. EC 2073/2005. Thus the critical issue is not food safety, while major factors appear to be cooling costs, product quality, and product waste due to temperature abuse.

Novel approaches based on modeling can be applied in the fresh-cut industry for the estimation of the product shelf life in a real context. Tsironi et al. (2017) have developed a model that can be successfully applied for the estimation of fresh-cut salads (*L. sativa* and *E. sativa*) shelf life, based on temperature monitoring along the cold chain.

Fresh-cut packaged products need to be stored at low temperatures with 95% RH to reduce transpiration, water loss and to slow the respiration rate, enzymatic processes, and microbial activity. The storage temperature required by fresh-cut products needs to be adjusted not only according to their metabolic and microbial activities, but also according to genetic factors and to the specific processing techniques applied.

Several authors have studied the effects of storage temperature and time on quality and microbial growth. Lamikanra and Watson (2003) evaluated the effects of storage time and temperature (4°C or 15°C) on esterase activity in fresh-cut cantaloupe. The enzymatic activity, after 24 h in storage, was reduced by 40% and 10% in fruit stored at 4°C and 15°C, respectively. Pectin methyl esterase activity in cut fruit also decreased by about 25% at both temperatures after 24 h but greatly increased after 72 h in fruit stored at 15°C. Fontana and Nicola (2008) studied the effect of storage temperature (4°C, 8°C, or 16°C) on the freshness of fresh-cut garden cress stored from 7 to 10 days. The fresh weight loss increased linearly with increasing temperature, reaching a maximum value of 1.9% at 16°C after 8 days of storage. An optimal temperature was defined as 4°C to guarantee microbial and sensory quality. In some cases, after harvest, product can be temporarily stored under suboptimal conditions before further processing. Ukuku and Sapers (2007) investigated on the effects of a waiting period at room temperature (ca. 22°C) before refrigerating fresh-cut watermelon, cantaloupe, and honeydew pieces contaminated with *Salmonella*. The *Salmonella* populations in the fresh-cut watermelon and honeydew pieces declined by 1 log cfu/g when stored immediately at 5°C for 12 days, while the populations in the fresh-cut cantaloupe did not show any significant changes. The *Salmonella* populations in the fresh-cut melons stored immediately at 10°C for 12 days increased significantly from 10^2 to 10^3 cfu/g in the watermelon, $10^{1.9}$ to 10^3 cfu/g in the honeydew, and 10^2 to $10^{3.6}$ cfu/g in the cantaloupe pieces. Keeping freshly prepared, contaminated fresh-cut melon pieces at 22°C for 3 h or more prior to refrigerated storage could increase the chances of *Salmonella* growth, especially if the fresh-cut melons were subsequently stored at an improper temperature.

Storage temperature is of paramount importance for controlling the evolution of the microbial growth and for maintaining the overall quality of fresh-cut products. Knowledge on temperature oscillations of fresh-cut product along the cold chain is necessary to determine the influence of the temperature on the loss of quality and shelf life. Fresh-cut products are classified as refrigerated products, whose storage temperature must be kept at a maximum of 7°C with a tolerance of up to 10°C in the warmest conditions (Jacxsens et al., 2002).

In many European countries, a specific regulation concerning temperature control for fresh-cut products is lackinig. Italy is the first and sole EU country that introduced a national law specifically for the fresh-cut industry (D.L. May 13, 2011, n. 77), which went into effect in 2014 (D.M. June 20, 2014, n. 3746). It requires, among other things, that the storage temperature in distribution chains should not be above 8°C. Optimal temperature conditions should be clearly indicated on the package label for domestic refrigeration storage as well. The maximum temperature allowed during processing is 14°C, being 8°C the maximum temperature allowed for storing the raw material and the packed bags after processing.

Considering the application of the HACCP system to the fresh-cut industry sector, the time/temperature conditions at harvest and during postharvest handling are essential critical control points that should be constantly monitored. Recently, the issue of time and temperature abuse in the food industry has been revised (Ndraha, Hsiao, Vlajic, Yang, & Lin, 2018). The air temperature during sorting and preparation must be lower than 12°C, while during washing, cutting, and packaging, the air temperature should be maintained at between 4°C and 6°C (see also Chapter 14: Non-destructive Evaluation: Detection of External and Internal Attributes Frequently Associated With Quality and Damage). Temperature ranges (≥10°C) can be found in a fresh-cut product cold chain during shipping and unloading at the supermarket, storage and display at retail, and in domestic refrigerators (see also Chapter 16: Investigating Losses Occurring During Shipment: Forensic Aspects of Cargo Claims). During transport in refrigerated vehicles, the main problem is to maintain the cold chain as the door may be opened and closed frequently and the doors may be left open for variable periods of time, while orders are prepared and delivered. A rapid increase in product temperature can occur on transfer from temperature-controlled vehicles to ambient conditions during unloading at the distributor. The control of temperature performance and display units in supermarkets is rather poor, and the temperature of the fresh-cut product depends on its location on the chilled display shelf. The temperature distribution in the display environment is critical. The temperature is usually not optimal (8°C−10°C) and may accelerate fermentation inside packages and reduce both the shelf life and the packaging effectiveness (Emond, 2007). Finally, improper cold chain management continues in home refrigerators. Temperature abuse, such as storage at ambient temperature and improper cooling, has been identified as the main cause of microbial and quality deterioration. Nunes, Emond, Rauth, Dea, and Chau (2009) investigated the temperatures registered inside local distribution trucks or in retailer displays and the effects on improper temperature management on the produce quality. The study evaluated the segment of distribution chains that includes the time the produce arrives from distribution center to the store is displayed at the store, and then stored under home conditions. A wide variation of the temperature measured inside the retail displays was registered depending on the store and the displays, from −1.2°C to 19.2°C in refrigerated displays and from 7.6°C to 27.7°C in nonrefrigerated displays. The major cause of produce waste was the improper temperature management (55%), while the expired date and mechanical damage counted for 45%. Thus, fruit and vegetables are often kept under improper storage conditions, resulting in produce with poor quality and shorter shelf life and in waste increase at retail and consumer levels (see also Chapter 16: Investigating Losses Occurring During Shipment: Forensic Aspects of Cargo Claims).

In recent years, research has paid attention to the light conditions during shelf life to simulate the retail display conditions, especially in leafy vegetables and greens, such as garden cress, broccoli, cauliflower, Swiss chard leaves, lettuce, celery, and spinach (Kasim & Kasim, 2012; Olarte, Sanz, Echávarri, & Ayala, 2009; Zhan et al., 2009; Zhan et al., 2013a; Zhan, Hu, Li, & Pang, 2012; Zhan et al., 2013b; Zhan, Li, Hu, Pang, & Fan, 2012; Zhan, Hu, Pang, Li, & Shao, 2014; Zhan, Li et al., 2020). Although the display of vegetables in stores is mostly done in light conditions, several studies recommend low light intensity conditions or darkness to delay the leaf yellowing of vegetables in retail markets. Light conditions favor the chlorophyll degradation causing the leaf yellowing, which is one of the most important factors determining the fresh-like appearance of the product and, thus, the consumer purchase. Despite this, some studies have been reported in which continuous light-stored leaves of fresh-cut products retained more chlorophyll than dark-stored leaves (Noichinda, Bodhipadma, Mahamontri, Narongruk, & Ketsa, 2007; Zhan et al., 2013a, 2013b, 2020; Zhan, Hu, Li, & Pang, 2012). Zhan et al., 2013b found that light-stored leaves of fresh-cut romaine lettuce preserved more chlorophyll *a* during 7 days of storage at 4°C than dark-stored leaves. Light delayed the decline of soluble sugar and total soluble solid content and concurrently increased the DHA and dry matter content in comparison to storing leaves in dark environment. Studies conducted by Zhan, Hu et al. (2012) highlighted that light exposure accelerates fresh weight loss during storage; this occurred in broccoli, Romaine lettuce (Zhan et al., 2013b; Zhan, Li, Hu, Pang, & Fan, 2012), celery (Zhan et al., 2013a), and spinach (Zhan, Li et al., 2020; Zhang et al., 2020), confirming similar results in the literature (in Chinese kale, Noichinda et al., 2007; in Romaine lettuce, Martínez-Sánchez, Tudela, Luna, Allende, & Gil, 2011). A general tendency was that light conditions preserve or increase the amount of AA compared to dark conditions (Zhan et al., 2013a; Zhan, Hu, Pang, Li, & Shao, 2014; Zhan, Hu, Li, & Pang, 2012; Zhan, Li, Hu, Pang, & Fan, 2012), as well as an inhibition of PPO and POD and a decrease of browning (Zhan, Li et al., 2012; Zhan et al., 2013b). Continuous light irradiation (30 μmol/m^2/s) on spinach for 7 days of storage induced an increase in total phenolic compounds by activating PAL and inhibiting PPO and POD compared to darkness (Zhan, Li et al., 2020; Zhang et al., 2020). Total antioxidant capacity increased with light irradiation too, due to high total phenolic compounds and phenolic acids. Light conditions can affect not only the physiological response of fresh-cut produce, but also the packaging performance in preserving the sensorial attributes (Olarte et al., 2009).

The recent advances in the development and use of LED-based illumination systems have led to innovative application in agriculture. LED is a cost-effective technology and it allows a fine-tuning and a precise selection of specific wavelengths to be applied during cultivation. Also, the potentiality of LED light as a tool for maintaining the postharvest quality of fresh-cut products has been investigated in recent years. For example, the application of LED light at around 405 nm was proven to be effective in inactivate *Salmonella* spp. on fresh-cut papaya (Kim, Bang, & Yuk, 2017), while 460 nm LEDs acted against *Salmonella* spp. on fresh-cut pineapple slices (Ghate et al., 2017).

Further and detailed studies need to be conducted on the effect of different light sources, intensities, and spectral composition on physiological responses of fresh-cut fruit and vegetables and on the nutritional quality. Ultimately, the effect of light should be checked in relation to temperature changes during storage, when open display cabinets are still used. In fact, incandescent and halogen bulbs can increase the ambient temperature, while fluorescent light and LED light does not. In-bag product temperature is expected to be higher than out-bag temperature due to the greenhouse effect, to the reduced evaporative cooling and trapped warm air if the light is used in open display cabinet (Fig. 7.12). Lastly, the possible effects of continuous or alternating lighting should be checked against store opening hours, that is, the fluctuation of light/dark conditions has not yet been investigated.

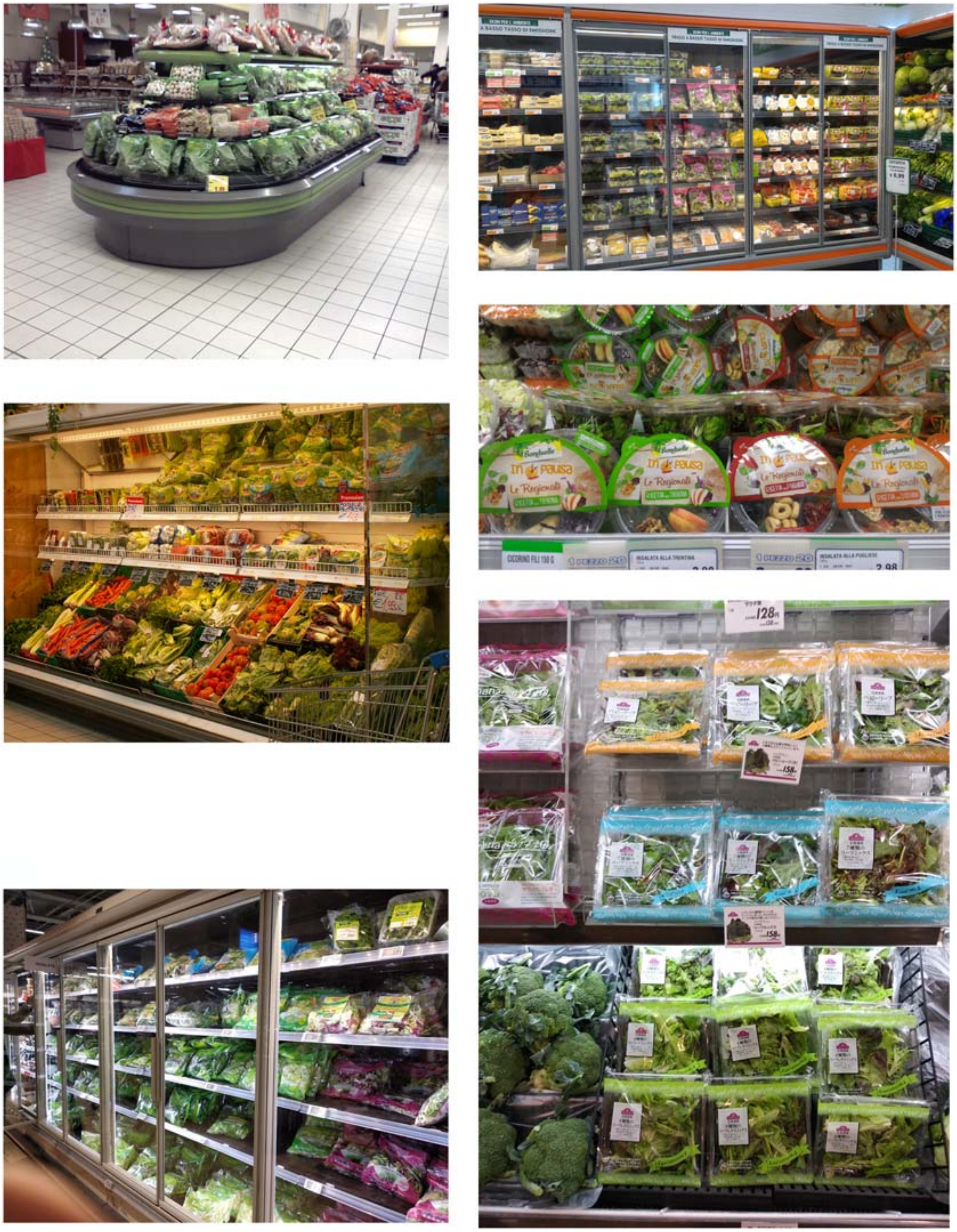


FIGURE 7.12 Display cabinets in different supermarkets.

7.4 Quality measurements

The quality of fresh-cut products comprises appearance, nutritional value, texture, as well as flavor and safety, which determine their value to the consumers. Fresh-cut produce satisfies consumer demand for convenient, healthy food rich in vitamins, minerals, and dietary fiber. The postharvest quality of fresh-cut produce depends on several preharvest and genetic factors. Contrary to the traditionally processed foods, fresh-cut products contain living tissues that sustain injury during processing. It is known that the vegetables that are stressed in the preharvest period will invariably have reduced postharvest quality. Fresh-cut produce deteriorates faster than corresponding intact produce, due to the damage caused by minimal processing, which accelerates several physiological mechanisms that lead to a reduction in produce quality and shelf life. Understanding the components of fresh-cut produce quality involves the use of destructive and non-destructive measurements.

7.4.1 Destructive measurements

Enzymatic browning negatively affects the quality of the fresh-cut fruit and vegetable produce. Several fruits and vegetables, such as apples, pears, peaches, potatoes, and lettuce, are susceptible to enzymatic browning during storage. Enzymatic browning involves phenolic compounds, oxygen, and PPOs (Marszałek et al., 2018; Putnik et al., 2017). Enzymatic browning of fresh-cut products can cause a considerable economic loss, especially if browning happens early in the shelf life. PPO enzyme has also some beneficial effects in plants defense pathway, as well as it also improves the flavor in many food products (Panadare & Rathod, 2018). PPO activity depends on the pH. Generally, the optimal pH of PPO ranges between 4.0 and 8.0 (Taranto et al., 2017). Temperature is an additional important factor significantly influencing the catalytic activity of the PPO. The optimal PPO temperature range varies for different plant sources: 25°C–35°C in lettuce, 25°C–45°C in olive, and 50°C in cucumber (Taranto et al., 2017). In light of this, the control of browning from harvesting to consumption is important in reducing losses and preserving the economic value of fruit and vegetables.

Several researches have shown that not all vegetables are suitable as fresh-cut product (Ahvenainen, 1996). Allende, Aguayo, and Artes (2004) evidenced that fresh-cut lettuce from "Lollo Rossa" had less browning than from "Salinas" cultivars. Cantos, Espin, and Tomas-Barberan (2001) observed differences on the browning of fresh-cut product in six lettuce cultivars.

The quality decline of fresh-cut products causes the production of ROS and consequent lipid peroxidation of membrane. Malondialdehyde (MDA) is widely used as a marker enzyme of oxidative lipid peroxidation caused by stress conditions. Traditional method to detect MDA concentration in plants is thiobarbituric acid reactive substances test. Recently, high performance liquid chromatography and hyperspectral imaging were also employed to detect MDA in plant tissues (Kong, Liu, Zhang, Zhang, & Feng, 2016). ROS or intermediates are produced by the incomplete reduction of oxygen that creates superoxide ($\bullet O_2^-$), hydrogen peroxide (H_2O_2), hydroxyl radical (OH^-), singlet oxygen, and lipid hydroperoxides. ROS cause a stimulation of several enzymes, such as superoxide dismutase, catalase, and glutathione POD, as well as the activity of free radical scavengers, such as β-carotene, AA, α-tocopherol, glutathione, and phenolics (Waszczak, Carmody, & Kangasjärvi, 2018). The quantification of these compounds can be a useful parameter to evaluate the quality of fresh-cut produce.

Altered phenolic metabolism is thought to be involved in lettuce tissue browning. The first step in the phenylpropanoid pathway is the conversion of L-phenylalanine to *trans*-cinnamic acid by the enzyme PAL (EC 4.3.1.5). Following reactions produce several metabolites such as 5-caffeoylquinic acid, 3,5-dicaffeoylquinic acid, caffeoyltartaric acid, and dicaffeoyltartaric acid that have been related to browning in cut lettuce. Increased PAL activity has been associated with a decrease in the shelf life and overall visual quality of minimally processed lettuce (López-Gálvez, Saltveit, & Cantwell, 1996). The correlation between phenolic concentration in the plant and antioxidant activity is known. The Folin–Ciocalteu assay is used to determine the total phenol content while flavonoids are an estimate, according to the aluminum chloride calorimetric method. The antioxidant activity is measured by 1,1-diphenyl-2-picrylhydrazyl radical scavenging, ferrous ion chelating, and the inhibition of β-carotene bleaching tests (Benabdallah, Rahmoune, Boumendjel, Aissi, & Messaoud, 2016).

Fruit texture can be evaluated by empirical methods such as penetrometer that is strictly related to cortex firmness assessment (Harker, Gunson, & Jaeger, 2003). Several complex apparatuses have been proposed for the texture evaluation. Among them a wide variety of techniques are available, such as mechanical measurements (Harker, White, Gunson, Hallett, & Nihal De Silva, 2006), sound recording during chewing (Ioannides et al., 2007), and the detection of vibration generated by sample fracturing (Taniwaki & Sakurai, 2008). The combined and simultaneous analysis of both texture components (mechanical and acoustic) can be used as an efficient approach, enabling a complete and exhaustive texture characterization (Costa et al., 2011; Zdunek, Konopacka, & Jesionkowska, 2010).

Nucleic acid–based systems for the detection of genomic deoxyribonucleic acid (DNA) are an efficient technique to evaluate the microbiological quality of fresh-cut produce. This system permits a quick and highly sensitive identification when the microorganisms affect the quality of fresh-cut produce (Feng et al., 2016) using polymerase chain reaction for extraction and quantification of bacteria DNA. Enzyme-linked immunosorbent assay is also a suitable technique that uses the antigen–antibody interaction for assays of pathogenic bacteria such as *L. monocytogenes*, *Salmonella*, *E. coli*, and *Campylobacter* (Priyanka, Patil, & Dwarakanath, 2016).

7.4.2 Non-destructive measurements

Non-destructive tests in fresh and processed foods are critical for monitoring and controlling product quality (see also Chapter 15: Cooling Fresh Produce). Appearance is the first factor influencing consumers' choice in the phase of purchase, followed by aroma, taste, and texture. Aroma is the complex of volatile compounds of a fruit or vegetable product, whereas flavor comprises both aroma and taste. Nutritional value is an important quality constituent that is impossible to see, taste, or feel. There are some relations between textural attributes, especially juiciness and flavor, and between the color and nutritional compounds of fruits and vegetables. Appearance feature can objectively or subjectively be measured, by means of specific tools or the human eye, respectively. Color charts or guides may be utilized as references for visual evaluation, but the results may be affected by human error and environmental conditions. Several authors have proposed the use of color charts and rating scales to assess the general appearance of fresh-cut produce (Kader & Cantwell, 2006). The color may also be measured instrumentally, on the basis of light reflected off or transmitted through the commodity. The CIE L*a*b* color scale is the most frequently used for color references (Commission Internationale de l'Eclairage). This method is based on L*, a*, and b* parameters and their indirect measurements (hue and chroma). L* indicates lightness, a* is the red/green coordinate, and b* is the yellow/blue coordinate. Deltas for L* (ΔL*), a* (Δa*), and b* (Δb*) may be positive (+) or negatively (−). The Delta E (ΔE*), however, is always positive. L*a*b* color space was modeled after a color-opponent theory stating that two colors cannot be red and green at the same time or yellow and blue at the same time.

Among the non-invasive and highly sensitive tools for evaluating plant stress and leaves functionality, chlorophyll *a* fluorescence measurement is the most important method. In vegetables, the retention of green color, related to chlorophyll content, is a commonly used parameter to assess the general quality and freshness (Cefola & Pace, 2015; Limantara, Dettling, Indrawati, Indriatmoko, & Brotosudarmo, 2015). The color defines the appearance of the vegetables and influences the consumer choice. Loss of color is caused to the degradation of the pigments such as chlorophyll and carotenoids. In cucumber, chlorophyll *a* fluorescence was used to evaluate the optimal storage temperature and in iceberg lettuce, for the evaluation of storage potential. Chlorophylls are extremely susceptible to degradation throughout processing, resulting in color change from brilliant green to olive, due to the presence of brown compounds, such as pheophytin and pheophorbide. Several authors reported that chlorophyll breakdown is due to the activity of POD, LOX, and chlorophyll oxidase enzymes. To preserve chlorophyll in vegetables during processing, several practices have been studied. For example, the applications of alkaline pH in blanching water (Koca, Karadeniz, & Burdurlu, 2006), high-temperature short time processing (Schwartz & Lorenzo, 1991), edible coatings (Moreira et al., 2011; Moreira, Ponce, Ansorena, & Roura et al., 2011), and modified atmospheric packaging (Aguayo, Jansasithorn, & Kader, 2006). Additional non-destructive methods to estimate chlorophyll content involves the use of commercially chlorophyll-meters such as Minolta SPAD 502 (Minolta Camera Co., Osaka, Japan) and the Leaf+ (FT Green LLC.—Wilmington, United States). These instruments measure total chlorophyll content by stapling the leaf area with a probe and by measuring light transmission. However, the data are influenced by the chosen positions on leaf area (Yuan et al., 2016) and consequently the chlorophyll evaluation is influenced by the operator (Cavallo, Cefola, Pace, Logrieco, & Attolico, 2017).

The growing interest of near infrared (NIR) spectroscopy in postharvest technology is indicated by the significant number of publications and the use of commercial NIR systems for grading products on different fruit and vegetables (Nicolai et al., 2007), such as chicory hybrids (Francois et al., 2008) and asparagus (Sánchez, Pérez-Marín, Flores-Rojasa, Guerrero, & Garrido-Varo, 2009). The optical analyses in the region of NIR and visible–NIR (vis/NIR) play an important role in studying the freshness decay of minimally processed vegetables in the postpackaging phase and along distribution chains (Guidetti, Beghi, & Giovenzana, 2012). These techniques permit to obtain information about the functional groups by using the interaction between light and sample. For example, NIR and vis/NIR have been used to evaluate apple fruit quality attributes (Zude, Herold, Roger, Bellon-Maurel, & Landahl, 2006), chlorophyll content (Zude-Sasse, Truppel, & Herold, 2002), phytonutrients (Merzlyak, Solovchenko, & Gitelson, 2003), and firmness (Mehinagic, Royer, Symoneaux, Bertrand, & Jourjon, 2004) in several produce, such as chicory (Francois et al., 2008), asparagus (Sánchez et al., 2009), apples (Peirs, Lammertyn, Ooms, & Nicolaï, 2001), mandarins (Antonucci et al., 2011), pears (Paz, Sánchez, Pérez-Marín, Guerrero, & Garrido-Varo, 2009), mangoes (Schmilovitch, Mizrach, Hoffman, Egozi, & Fuchs, 2000), and kiwifruits (McGlone, Jordan, Seelye, & Martinsen, 2002). In a recent paper (Zhan, Li et al., 2020; Zhang et al., 2020), the authors proposed the use of visible and NIR full transmittance hyperspectral imaging to evaluate the soluble solids content in oranges. Citrus quality comprises external factors (size, color, shape, and surface defects) and internal factors (sugar, acidity, and firmness). Soluble solids content and total acidity are main quality attributes (Magwaza et al., 2012). The results of this research showed that visible and NIR full transmittance hyperspectral imaging may provide useful information for the evaluation of internal quality attributes.

Cavallo, Cefola, Pace, Logrieco, & Attolico, 2018 studied a non-destructive method of image analysis by computer vision systems (CVS) for assessing the quality of fresh-cut lettuce packaged and unpackaged. The results of this research demonstrated that this system could be used to monitor the quality level of fresh-cut lettuce regardless of packaging at all the critical checkpoints along value chains. CVS do not necessitate sample preparation and can be used as an alternative to chemical and physical analyses on unpackaged crops (Amodio, Cabezas-Serrano, Peri, & Colelli, 2011; Pace, Cavallo, Cefola, Colella, & Attolico, 2015). In recent years, several researchers have studied the volatile and semi volatile compounds in plants, such as VOCs (esters, alcohols, aldehydes, hydrocarbons, ketones, terpenes, sesquiterpene, phenols, acids), and secondary metabolites using gas chromatography–mass spectrometry (GC–Ms) (Spadafora et al., 2015; Spadafora, Amaro et al., 2016; Spadafora, Paramithiotise et al., 2016). These compounds are present in very low concentrations in plants but play an important role in plant–plant competition, in cooperative coevolution and plant's defense against stress (Brilli, Loreto, & Baccelli, 2019). The analysis of VOCs in food samples can be difficult due to the high number of compounds. In some detection systems, this can lead to the saturation of the most abundant compounds, making their quantification difficult, as well as the masking of lower concentration components that have a similar structure. Therefore, for an evaluation of the organoleptic quality, it is important to connect the VOC concentrations to the sensory panels.

In a paper of Ceccarelli et al. (2020) the authors explored the effect of fruit processing and storage on the volatilome of three cultivars of fresh-cut nectarine. VOCs were measured daily in both intact and processed fruit, using proton transfer reaction–time of flight–mass spectrometry and solid-phase microextraction–GC–Ms. The results of this study allowed the detection of a biomarker enabling the prediction of the product shelf life based on the release of flavors and off-flavors. Spadafora et al. (2019) studied the metabolites and gene expression of fresh-cut melon over 14 days of storage. The results shown that 99 VOCs were detected due to differences between melon seasons, cut size, storage temperatures, and storage time, thus confirming their positive use as markers for changes during postharvest.

7.5 Product innovation

The fresh-cut industry is oriented to optimize the processing lines lowering quality losses, but it is also interested in product innovation. Consumer is interested to novelty and products rich in bioactive compounds that have beneficial effects on human health (see also Chapter 19: Nutritional Value of fruits and vegetables, and Chapter 21: Measuring Consumer Acceptance of Vegetables). The baby-leaf sector is interested to evaluate new crop species that can satisfy the consumer's needs and that have tolerance traits against biotic and abiotic stresses.

In the recent years, some African native species have been tested in Europe as new baby leaves and with potential use as fresh-cut leafy vegetables. Crop cultivation experiments have been performed on different genotypes of jute (*C. olitorius* L.) that is commonly used as dry vegetables in Africa (Giro & Ferrante, 2018a). This species has high adaptability to the different environments and is rich in sugars with values up to 50 mg/g FW. Cultivation trials have been performed in floating systems with yield ranging from 0.8 to 2.4 kg/m^2. The nutritional quality is similar to other baby-leaf vegetables and influenced by nutrient solution concentration and growing season (Giro & Ferrante, 2016). Postharvest trials demonstrated that the quality of fresh-cut jute is retained for 10 days of storage, suggesting the potential use as innovative product in the fresh-cut industry (Giro & Ferrante, 2018b).

Among the *Brassiceae* family, the *Sisymbrium officinale* (L.) Scop. (synonym *Erisymum officinale*), also known as hedge mustard, has been evaluated as baby-leaf vegetables (Guarise, Borgonovo, Bassoli, & Ferrante, 2019). The hedge mustard is particularly suitable for the fresh-cut industry since it is rich in bioactive molecules and antioxidant compounds (Borgonovo et al., 2019). The taste is similar to wild and cultivated rocket.

The herbs sector is also increasing its interest in fresh-cut products. Experiments in fresh-cut mint leaves have been conducted, studying four mint species (Nicola, Pignata, & Tibaldi, 2018b). *Mentha* × *piperita* L. var. *officinalis* forma *rubescens* Camus, *M. spicata* L. var. *rubra*, *M. spicata* L. var. *viridis* (syn. *M. viridis* Auct.), and *Calamintha nepeta* (L.) Savi were tested packaged in different film permeances to O_2, and their shelf life was assessed after 8 days at 4°C. The mint leaves of all varieties were still well preserved after 1 week, thanks to medium-to-high permeability of the film chosen for the bags, which limited the fresh weight loss. Introducing new varieties in the fresh-cut industry require thus specific studies not only on the quality of the product but also on the best preservation film during shelf life.

The fresh-cut industries are also oriented to the identification of new species or improved cultivars in terms of tolerance against cut operations and improved in the nutritional quality. In terms of product innovation, the fresh-cut industry has been exploring the opportunity to provide mixed products containing edible flowers. These could improve both the visual appearance and the nutritional composition (Zhao et al., 2019).

Biostimulants have been widely adopted during the cultivation of vegetables or fruit destined to fresh-cut industries. Since many of these innovative agronomic tools activate the primary and secondary metabolism, their application can be rationally planned before harvesting for to improve the quality of the product and extend the shelf life. It has been reported that biostimulants can induce different antioxidant compounds that are not only useful for plant growth and defense, but also for the contribution that they can provide to the fresh-cut products (Cocetta & Ferrante, 2020).

7.6 Future considerations

The preharvest and postharvest issues described in this chapter highlight the research efforts that are being made to test and implement innovations to increase fresh-cut sector competitiveness in terms of safety and quality. A continuous exchange between scientists and the fresh-cut industry is necessary to guarantee the success of the fresh-cut system. It is advisable that new experiments would be conducted in real-world situations after having been tested in simulated conditions, that is, in laboratories or controlled cell rooms, to verify the studies under realistic situations. In addition, there is still little connection between preharvest and postharvest conditions in the mind of researchers (see also Chapter 20: Mitigating Contamination of Fresh and Fresh-Cut Produce): much postharvest research is conducted on product obtained from a grocery store without information on preharvest conditions of the raw material.

The fresh-cut sector has progressed tremendously around the world in the last decade, especially in the fruit sector and, particularly, in tropical and exotic fruit. This development is in-line with the general trend occurring in fresh produce. Thus the critical issues in the fresh-cut management are similar to those in the fresh produce management. The success of fresh-cut fruit and vegetables is visible in many emerging economies even though statistics are unavailable. In the coming decade, it is expected that the importance of the sector will increase even more, with most likely increase in the importance of safety rather than quality. Nevertheless, assessing fresh-cut produce quality remains of great importance because consumers are expecting more flavor and taste, especially from such high price products as fresh-cut products. Despite the 5 years of economic slowdown around the world that has hit some countries more severely than others, the demand for fresh-cut products keeps rising. The offer of new species and varieties expands the offer of fresh-cut items. There are promising innovations both at the farm production level and at postharvest processing level: cultivation techniques are becoming standardized, environmentally friendly, conserve water, reduce waste, and emphasize the inherent and organoleptic quality of the raw material. Therefore, research should focus on the implementation of innovative tools and processing aids in postharvest processing able to preserve the freshness and organoleptic quality obtained in the field.

Lastly, the sector is facing a striking challenge in the coming years: "waste footprint" (see also Chapter 2: Systems Approaches for Postharvest Handling). Food waste is at the top of the issues when it comes to the food sector's current sustainability agenda and fresh-cut products are among the most targeted products for waste production (Burrows, 2013). In fact, latest data in the United Kingdom indicate that 68% of salad grown for fresh-cut salad bags is wasted. If it is true that tackling the issue of waste reduction starts from breeding and ends in homes, it is also true that solutions should be found either by reducing the discharge of "not compliant" raw materials along chains or by making better use of it, such as recycling or reusing waste for other purposes, for example, composting or the extraction of the bioactive compounds it contains.

The fresh-cut industry and distribution chains must guarantee the product to the consumer. Therefore it is important to identify new quality evaluation tools that allow the control of quality at any step of distribution chains. The shelf life of fresh-cut products is limited and fast-response non-destructive tools must be developed for evaluating the nutritional and sanitary quality.

References

Abnavi, M. D., Alradaan, A., Munther, D., Kothapalli, C. R., & Srinivasan, P. (2019). Modeling of free chlorine consumption and *Escherichia coli* O157: H7 cross-contamination during fresh-cut produce wash cycles. *Journal of Food Science*, *84*(10), 2736–2744.

Aguayo, E., Escalona, V. H., & Artés, F. (2008). Effect of hot water treatment and various calcium salts on quality of fresh-cut 'Amarillo' melon. *Postharvest Biology and Technology*, *47*, 397–406.

Aguayo, E., Jansasithorn, R., & Kader, A. A. (2006). Combined effects of 1-methylcyclopropene, calcium chloride dip and/or atmospheric modification on quality changes in fresh-cut strawberries. *Postharvest Biology and Technology*, *40*, 269–278.

Ahmed, H. A., Yu-Xin, T., & Qi-Chang, Y. (2020). Lettuce plant growth and tip burn occurrence as affected by airflow using a multi-fan system in a plant factory with artificial light. *Journal of Thermal Biology*, *88*, 102496.

Ahvenainen, R. (1996). New approaches in improving the shelf life of minimally processed fruit and vegetables. *Trends in Food Science and Technology*, *7*, 179–187.

Akbas, M. Y., & Ölmez, H. (2007). Effectiveness of organic acid, ozonated water and chlorine dippings on microbial reduction and storage quality of fresh-cut iceberg lettuce. *Journal of the Science of Food and Agriculture*, *87*, 2609–2616.

Alegria, C., Pinheiro, J., Duthoit, M., Goncalves, E. M., Moldão-Martins, M., & Abreu, M. (2012). Fresh-cut carrot (cv. Nantes) quality as affected by abiotic stress (heat shock and UV-C irradiation) pre-treatments. *LWT – Food Science and Technology*, *48*, 197–203.

Alexopoulos, A., Plessas, S., Ceciu, S., Lazar, V., Mantzourani, I., Voidarou, C., ... Bezirtzoglou, E. (2013). Evaluation of ozone efficacy on the reduction of microbial population of fresh cut lettuce (*Lactuca sativa*) and green bell pepper (*Capsicum annuum*). *Food Control*, *30*(2), 491–496.

Allende, A., Aguayo, E., & Artes, F. (2004). Microbial and sensory quality of commercial fresh processed red lettuce throughout the production chain and shelf life. *International Journal of Food Microbiology*, *91*, 109–117.

Allende, A., Tomás-Barberán, F. A., & Gil, M. I. (2006). Minimal processing for healthy traditional foods. *Trends in Food Science and Technology*, *17*, 513–519.

Amodio, M. L., Cabezas-Serrano, A. B., Peri, G., & Colelli, G. (2011). Post-cutting quality changes of fresh-cut artichokes treated with different anti-browning agents as evaluated by image analysis. *Postharvest Biology and Technology*, *62*, 213–220.

Ansah, F. A., Amodio, M. L., & Colelli, G. (2018). Quality of fresh-cut products as affected by harvest and postharvest operations. *Journal of the Science of Food and Agriculture*, *98*(10), 3614–3626.

Antonucci, F., Pallottino, F., Paglia, G., Palma, A., D'Aquino, S., & Menesatti, P. (2011). Non-destructive estimation of mandarin maturity status through portable VIS-NIR spectrophotometer. *Food and Bioprocess Technology*, *4*, 809–813.

Artés, F. (2000a). Conservación de los productos vegetales en atmósfera modificada. In M. Lamúa (Ed.), *Aplicación del frío a los alimentos* (pp. 105–125). Madrid: AMV-Mundi Prensa.

Artés, F. (2000b). Productos vegetales procesados en fresco. In M. Lamúa (Ed.), *Aplicación del frío a los alimentos* (pp. 127−141). Madrid: AMV-Mundi Prensa.

Artés, F., Gómez, P., Aguayo, E., Escalona, V., & Artés-Hernández, F. (2009). Sustainable sanitation techniques for keeping quality and safety of fresh-cut plant commodities. *Postharvest Biology and Technology*, *51*, 287−296.

Artes-Hernandez, P., Gomez, P. A., & Artes, F. (2013). Unit processing operations in the fresh-cut horticultural products industry: Quality and safety preservation. In G. P. P. Lima, & F. Vianello (Eds.), *Food quality, safety and technology* (pp. 35−52). Vienna: Springer-Verlag.

Artés, F., & Martínez, J. A. (1996). Influence of packaging treatments on the keeping quality of 'Salinas' lettuce. *Lebensmittel-Wissenschaft Technologie*, *29*, 664−668.

Ayala-Zavala, J. F., González-Aguilar, G. A., & Del Toro-Sánchez, L. (2009). Enhancing safety and aroma appealing of fresh-cut fruits and vegetables using the antimicrobial and aromatic power of essential oils. *Journal of Food Science*, *74*(7), R84−R91.

Bai, J., Wu, P., Manthey, J., Goodner, K., & Baldwin, E. (2009). Effect of harvest maturity on quality of fresh-cut pear salad. *Postharvest Biology and Technology*, *51*(2), 250−256.

Banach, J. L., Sampers, I., Van Haute, S., & der Fels-Klerx, V. (2015). Effect of disinfectants on preventing the cross-contamination of pathogens in fresh produce washing water. *International Journal of Environmental Research and Public Health*, *12*(8), 8658−8677.

Banach, J. L., van Bokhorst-van de Veen, H., van Overbeek, L. S., van der Zouwen, P. S., Zwietering, M. H., & van der Fels-Klerx, H. J. (2020). Effectiveness of a peracetic acid solution on *Escherichia coli* reduction during fresh-cut lettuce processing at the laboratory and industrial scales. *International Journal of Food Microbiology*, *321*, 108537.

Bansal, R. K., & Walker, J. T. (1999). A study of high pressure water jets for cutting chicken breast meat. *Journal of Food Process Engineering*, *22*, 307−318.

Batista, D. D. V. S., Reis, R. C., Almeida, J. M., Rezende, B., Bragança, C. A. D., & da Silva, F. (2020). Edible coatings in post-harvest papaya: Impact on physical−chemical and sensory characteristics. *Journal of Food Science and Technology*, *57*(1), 274−281.

Beirão-Da-Costa, S., Moura-Guedes, M. C., Ferreira-Pinto, M. M., Empis, J., & Moldão-Martins, M. (2012). Alternative sanitizing methods to ensure safety and quality of fresh-cut kiwifruit. *Journal of Food Processing and Preservation*, *38*(1). Available from https://doi.org/10.1111/j.1745-4549.2012.00730.x.

Beirão-da-Costa, S., Steiner, A., Correia, L., Leitão, E., Empis, J., & Moldão-Martins, M. (2008). Influence of moderate heat pre-treatments on physical and chemical characteristics of kiwifruit slices. *European Food Research and Technology*, *226*, 641−651.

Belay, Z. A., Caleb, O. J., & Opara, U. L. (2016). Modelling approaches for designing and evaluating the performance of modified atmosphere packaging (MAP) systems for fresh produce: A review. *Food Packaging and Shelf Life*, *10*, 1−15.

Benabdallah, A., Rahmoune, C., Boumendjel, M., Aissi, O., & Messaoud, C. (2016). Total phenolic content and antioxidant activity of six wild *Mentha* species (*Lamiaceae*) from northeast of Algeria. *Asian Pacific Journal of Tropical Biomedicine*, *6*, 760−766.

Benini, C. (2019). Insalate Ninfa: la coltivazione in floating system più estesa d'Europa. *FruitBookMagazine*. Available from https://www.fruitbookmagazine.it/insalate-ninfa-coltivazione-floating-system-piu-grande-europa/, [14 August 2020].

Bergquist, S. A. M., Gertsson, U. E., Nordmark, L. Y. G., & Olsson, M. E. (2007). Ascorbic acid, carotenoids, and visual quality of baby spinach as affected by shade netting and postharvest storage. *Journal of Agricultural and Food Chemistry*, *55*, 8444−8451.

Besri, M. (1997). Alternatives to methyl bromide for preplant protected cultivation of vegetables in the Mediterranean developing countries. In: *Proceeding of annual international research conference on 'Methyl bromide alternatives and emissions reductions'*, November 3−5, 1997, San Diego, CA, USA. mbao.org/1997airc/015besri.pdf Visited 12.02.13.

Bett-Garber, K. L., Lamikanra, O., Lester, G. E., Ingram, D. A., & Watson, M. A. (2005). Influence of soil type and storage conditions on sensory qualities of fresh-cut Cantaloupe (*Cucumis melo*). *Journal of Science and Food Agriculture*, *85*, 825−830.

Beuchat, L. R. (2007). Managing food safety risks in the fresh-cut industry. *Acta Horticulturae*, *746*, 103−114. Available from https://doi.org/10.17660/ActaHortic.2007.746.12.

Bianchi, D. (2018). Floating sistem, quando l'esperienza paga. *ItaliaFruit News*. Available from http://www.italiafruit.net/DettaglioNews/45850/packaging-e-tecnologie/floating-sistem-quando-lesperienza-paga, [14 August 2020].

Bico, S. L. S., Raposo, M. F. J., Morais., & RMSC Morais, A. M. B. (2009). Combined effects of chemical dip and/or carrageenan coating and/or controlled atmosphere on quality of fresh-cut banana. *Food Control*, *20*, 508–514.

Binello, A., Orio, L., Pignata, G., Nicola, S., Chemat, F., & Cravotto, G. (2014). Effect of microwaves on the in situ hydrodistillation of four different *Lamiaceae*. *Comptes Rendus Chimie*, *17*(3), 181–186. Available from https://doi.org/10.1016/j.crci.2013.11.007.

Birmpa, A., Sfika, V., & Vantarakis, A. (2013). Ultraviolet light and ultrasound as non-thermal treatments for the inactivation of microorganisms in fresh ready-to-eat foods. *International Journal of Food Microbiology*, *167*(1), 96–102.

Bolin, H. R., & Huxsoll, C. C. (1991). Control of minimally processed carrot *(Daucus carota)* surface discoloration caused by abrasion peeling. *Journal of Food Science*, *56*, 416–418.

Borgonovo, G., Zimbaldi, N., Guarise, M., De Nisi, P., De Petrocellis, L., Schiano Moriello, A., & Bassoli, A. (2019). Isothiocyanates and glucosinolates from *Sisymbrium officinale* (L.) Scop. ("the Singers' Plant"): Isolation and in vitro assays on the somatosensory and pain receptor trpa1 channel. *Molecules (Basel, Switzerland)*, *24*(5), 949.

Brilli, F., Loreto, F., & Baccelli, I. (2019). Exploiting plant volatile organic compounds (VOCs) in agriculture to improve sustainable defence strategies and productivity of crops. *Frontiers in Plant Science*, *10*, 264.

Burrows, D. (2013). The great waste debate. *Fresh Produce Journal*. Available from http://www.fruitnet.com/fpj/article/159758/the-great-waste-debate.

Calderon-Lopez, B., Bartsch, J. A., Lee, C. Y., & Watkins, C. B. (2005). Cultivar effects on quality of fresh cut apple slices from 1-methylcyclopropene (1-MCP)-treated apple fruit. *Journal of Food Science*, *70*(3), S221–S227.

Callejón, M. R., Rodríguez-Naranjo, M. I., Ubeda, C., Hornedo-Ortega, R., Garcia-Parrilla, M. C., & Troncoso, A. M. (2015). Reported foodborne outbreaks due to fresh produce in the United States and European Union. *Trends and Causes Foodborne Pathogens and Disease*, *12*, 1. Available from https://doi.org/10.1089/fpd.2014.1821.

Cantos, E., Espin, J. C., & Tomas-Barberan, F. A. (2001). Effect of wounding on phenolic enzymes in six minimally processed lettuce cultivars upon storage. *Journal of Agricultural Food Chemistry*, *49*, 322–330.

Casero, T., Benavides, A. L., & Recasens, I. (2009). Interrelation between fruit mineral content and pre-harvest calcium treatments on 'Golden Smoothee' apple quality. *Journal of Plant Nutrition*, *33*(1), 27–37.

Cavallo, D. P., Cefola, M., Pace, B., Logrieco, A. F., & Attolico, G. (2017). Contactless and nondestructive chlorophyll content prediction by random forest regression: A case study on fresh-cut rocket leaves. *Computers and Electronics in Agriculture*, *140*, 303–310.

Cavallo, D. P., Cefola, M., Pace, B., Logrieco, A. F., & Attolico, G. (2018). Non-destructive automatic quality evaluation of fresh-cut iceberg lettuce through packaging material. *Journal of Food Engineering*, *223*, 46–52.

Ceccarelli, A., Farneti, B., Khomenko, I., Cellini, A., Donati, I., Aprea, E., . . . Spinelli, F. (2020). Nectarine volatilome response to fresh-cutting and storage. *Postharvest Biology and Technology*, *159*, 111020.

Cefola, M., & Pace, B. (2015). Application of oxalic acid to preserve the overall quality of rocket and baby spinach leaves during storage: Oxalic acid postharvest treatment. *Journal of Food Processing and Preservation*, *39*, 1–10.

Chauhan, O. P., Raju, P. S., Ravi, N., Singh, A., & Bawa, A. S. (2011). Effectiveness of ozone in combination with controlled atmosphere on quality characteristics including lignification of carrot sticks. *Journal of Food Engineering*, *102*, 43–48.

Cinquemani, T. (2019). Aprirà a Milano la fattoria verticale più grande d'Europa. *Agronotizie – ImagelineNetwork*. Available from https://agronotizie.imagelinenetwork.com/agricoltura-economia-politica/2019/05/30/aprira-a-milano-la-fattoria-verticale-piu-grande-d-europa/63200, [14 August 2020].

Cocetta, G., Baldassarre, V., Spinardi, A., & Ferrante, A. (2014). Effect of cutting on ascorbic acid oxidation and recycling in fresh-cut baby spinach (*Spinacia oleracea* L.) leaves. *Postharvest Biology and Technology*, *88*, 8–16.

Cocetta, G., & Ferrante, A. (2020). *Nutritional and nutraceutical value of vegetable crops as affected by biostimulants application*. *eLS*. Chichester: John Wiley & Sons, Ltd. Available from http://doi.org/10.1002/9780470015902.a0028906.

Cocetta, G., Francini, A., Trivellini, A., & Ferrante, A. (2016). Effect of washing treatments on chlorophyll a fluorescence and vitamin C content in minimality processed lamb's lettuce during storage. *Agrochimica*, *60*(1), 1–14.

Condurso, C., Cincotta, F., Tripodi, G., Merlino, M., Giarratana, F., & Verzera, A. (2020). A new approach for the shelf-life definition of minimally processed carrots. *Postharvest Biology and Technology*, *163*, 111138.

Conte, A., Conversa, G., Scrocco, C., Brescia, I., Laverse, J., Elia, A., & Del Nobile, M. A. (2008). Influence of growing periods on the quality of baby spinach leaves at harvest and during storage as minimally processed produce. *Postharvest Biology and Technology*, *50*(3), 190−196.

Costa, F., Cappellin, L., Longhi, S., Guerra, W., Magnano, P., Porro, D., Soukoulis, C., Salvi, S., Velasco, R., Biasioli, F., . . . Gasperi, F. (2011). Assessment of apple (*Malus* x *domestica* Borkh.) fruit texture by a combined acoustic-mechanical profiling strategy. *Postharvest Biology and Technology*, *6*, 21−28.

Daddiego, L., Bianco, L., Capodicasa, C., Carbone, F., Dalmastri, C., Daroda, L., . . . Bevivino, A. (2018). Omics approaches on fresh-cut lettuce reveal global molecular responses to sodium hypochlorite and peracetic acid treatment. *Journal of the Science of Food and Agriculture*, *98*(2), 737−750.

Day, B. (2000). Novel MAP for freshly prepared fruit and vegetable products. *Postharvest News and Information*, *11*, 27−31.

Del Aguila, J. S., Fumi Sasaki, F., Sichmann Heiffig, L., Ortega, E. M. M., Jacomino, A. P., & Kluge, R. A. (2006). Fresh-cut radish using different cut types and storage temperatures. *Postharvest Biology and Technology*, *40*, 149−154.

Dewey-Mattia, D., Manikonda, K., Hall, A. J., Wise, M. E., & Crowe, S. J. (2018). Surveillance for foodborne disease outbreaks − United States, 2009−2015. *MMWR Surveillance Summaries*, *67*(10), 1−11.

Deza-Durand, K. M., & Petersen, M. A. (2011). The effect of cutting direction on aroma compounds and respiration rate of fresh-cut iceberg lettuce (*Lactuca sativa* L.). *Postharvest Biology and Technology*, *61*, 83−90.

Djioua, T., Charles, F., Freire, M., Filgueiras, H., Ducamp-Collin, M. N., & Sallanon, H. (2010). Combined effects of postharvest heat treatment and chitosan coating on quality of fresh-cut mangoes (*Mangifera indica* L.). *International Journal of Food Science and Technology*, *45*, 849−855.

Donati, V. (2003). Solo se si mantiene la catena del freddo. *Colture Protette*, *8*, 39−43.

EFSA (European Food Safety Authority). (2015). The European Union summary report on trends and sources of zoonoses, zoonotic agents and food-borne outbreaks in 2013. *European Food Safety Authority Journal*, *13*(3991), 162.

El-Mogy, M. M., Parmar, A., Ali, M. R., Abdel-Aziz, M. E., & Abdeldaym, E. A. (2020). Improving postharvest storage of fresh artichoke bottoms by an edible coating of *Cordia myxa* gum. *Postharvest Biology and Technology*, *163*, 111143.

Emond, J.P. (2007). Modified atmosphere packaging: Plastic film technology and selection. In: *Proceeding of European short course on 'Quality and safety of fresh-cut produce'*, March 12−14, 2007, Bari, Italy.

Feng, K., Hu, W., Jiang, A., Sarengaowa., Xu, Y., Zou, Y., . . . Wang, X. (2016). A dual filtration-based multiplex PCR method for simultaneous detection of viable *Escherichia coli* O157:H7, *Listeria monocytogenes*, and *Staphylococcus aureus* on fresh-cut Cantaloupe. *PLoS One*, *11*, e0166874.

Ferrante, A., Incrocci, L., Maggini, R., Tognoni, F., & Serra, G. (2003). Preharvest and postharvest strategies for reducing nitrate content in rocket (*Eruca sativa*). *Acta Horticultuae*, *628*, 153−159.

Fonseca, J. M. (2006). Postharvest quality and microbial population of head lettuce as affected by moisture at harvest. *Journal of Food Science*, *71*(2), M45−M49.

Fonseca, J. M., Fallon, S. D., Sanchez, C. A., & Nolte, K. D. (2011). *Escherichia coli* survival in lettuce fields following its introduction through different irrigation systems. *Journal of Applied Microbiology*, *110*, 893−902.

Fontana, E., & Nicola, S. (2008). Producing garden cress (*Lepidium sativum* L.) for the fresh-cut chain using a soilless culture system. *The Journal of Horticultural Science and Biotechnology*, *83*(1), 23−32.

Fontana, E., & Nicola, S. (2009). Traditional and soilless culture systems to produce corn salad (*Valerianella olitoria* L.) and rocket (*Eruca sativa* Mill.) with low nitrate content. *Journal of Food, Agriculture, and Environment*, *7*(2), 405−410.

Fontana, E., Nicola, S., Hoeberechts, J., & Saglietti, D. (2003). Soilless culture systems produce ready-to-eat corn salad (*Valerianella olitoria* L.) of high quality. *Acta Horticultura*, *604*, 505−509.

Fontana, E., Nicola, S., Hoeberechts, J., Saglietti, D., & Piovano, G. (2004). Managing traditional and soilless culture system to produce corn salad (*Valerianella olitoria*) with low nitrate content and lasting postharvest shelf life. *Acta Horticulturae*, *659*, 763−768.

Fontana, E., Tibaldi, G., & Nicola, S. (2010). Effect of the nutrient solution and shelf-life conditions on the essential oil profile of minimally processed dill (*Anethum graveolens* L.) grown in a soilless culture system. *Acta Horticulturae*, *877*, 135−141.

Fontana, E., Torassa, C., Hoeberechts, J., & Nicola, S. (2006). Il crescione per la IV gamma: Aspetti di coltivazione fuori suolo e post-raccolta. *Italus Hortus*, *13*(5), 151−154.

Francois, I. M., Wins, H., Buysens, S., Godts, C., Van Pee, E., Nicolai, B., & De Proft, M. (2008). Predicting sensory attributes of different chicory hybrids using physical-chemical measurements and visible/near infrared spectroscopy. *Postharvest Biology and Technology*, *49*, 366–373.

Franz, E., Semenov, A. V., Termorshuizen, A. J., De Vos, O. J., Bokhorst, J. G., & Van Bruggen, A. H. C. (2008). Manure-amended soil characteristics affecting the survival of *E. coli* O157:H7 in 36 Dutch soils. *Environmental Microbiology*, *10*(2), 313–327.

Freitas, I. R., Cortez-Vega, W. R., Pizato, S., Prentice-Hernández, C., & Borges, C. D. (2013). Xanthan gum as a carrier of preservative agents and calcium chloride applied on fresh-cut apple. *Journal of Food Safety*, *33*, 229–238.

Fritegotto, S., Pennuzzi, L., & Cinelli, A. (2016). Floating system: Esperienza aziendale. *L'informatore Agrario*, *25*, 32–35. Available from https://www.agronova.it/web/wp-content/uploads/1-Luglio-2016_Floating-system.pdf, [14 August 2020].

Gaikwad, K. K., Singh, S., & Singh Negi, Y. (2020). Ethylene scavengers for active packaging of fresh food produce. *Environmental Chemistry Letters*, *18*, 269–284. Available from https://doi.org/10.1007/s10311-019-00938-1.

Gąstoł, M., & Domagała-Świątkiewicz, I. (2006). Effect of foliar sprays on potassium, magnesium and calcium distribution in fruits of the pear. *Journal of Fruit and Ornamental Plant Research*, *14*(2), 169–176.

Ghate, V., Kumar, A., Kim, M. J., Bang, W. S., Zhou, W., & Yuk, H. G. (2017). Effect of 460 nm light emitting diode illumination on survival of *Salmonella* spp. on fresh-cut pineapples at different irradiances and temperatures. *Journal of Food Engineering*, *196*, 130–138.

Gil, M. I., Selma, M. V., López-Gálvez, F., & Allende, A. (2009). Fresh-cut product sanitation and wash water disinfection: Problems and solutions. *International Journal of Food Microbiology*, *134*, 37–45.

Gil, M. I., Tudela, J. A., Martínez-Sánchez, A., & Luna, M. C. (2012). Harvest maturity indicators of leafy vegetables. *Stewart Postharvest Review*, *1*, 2.

Giro, A., & Ferrante, A. (2016). Yield and quality of *Corchorus olitorius* baby leaf grown in a floating system. *Journal of Horticulture Science and Biotechnology*, *91*(6), 603–610.

Giro, A., & Ferrante, A. (2018a). Eco-physiological responses and biochemical characterization of different accessions of *Corchorus olitorius* (L.). *Folia Horticulturae*, *30*(2), 333–346.

Giro, A., & Ferrante, A. (2018b). Postharvest physiology of *Corchorus olitorius* baby leaf growing with different nutrient solutions. *The Journal of Horticultural Science and Biotechnology*, *93*(4), 400–408.

Gleeson, E., & O'Beirne, D. (2005). Effects of process severity on survival and growth of *Escherichia coli* and *Listeria innocua* on minimally processed vegetables. *Food Control*, *16*, 677–685.

Golberg, D., Kroupitski, Y., Belausov, E., Pinto, R., & Sela, S. (2011). *Salmonella Typhimurium* internalization is variable in leafy vegetables and fresh herbs. *International Journal of Food and Microbiology*, *145*, 250–257.

Gómez-López, V. M., Gil, M. I., Allende, A., Vanhee, B., & Selma, M. V. (2015). Water reconditioning by high power ultrasound combined with residual chemical sanitizers to inactivate foodborne pathogens associated with fresh-cut products. *Food Control*, *53*, 29–34.

Gonzalez-Aguilar, G. A., Celis, J., Sotelo-Mundo, R. R., De La Rosa, L. A., Rodrigo-Garcia, J., & Alvarez-Parrilla, E. (2008). Physiological and biochemical changes of different fresh-cut mango cultivars stored at 5°C. *International Journal of Food Science and Technology*, *43*(1), 91–101.

Gopal, A., Coventry, J., Wan, J., Roginski, H., & Ajlouni, S. (2010). Alternative disinfection techniques to extend the shelf life of minimally processed iceberg lettuce. *Food Microbiology*, *27*, 210–219.

Gorny, J. R., Cifuentes, R. A., Hess-Pierce, B., & Kader, A. A. (2000). Quality changes in fresh-cut pear slices as affected by cultivar, ripeness stage, fruit size, and storage regime. *Journal of Food Science*, *65*(3), 541–544.

Gorny, J. R., Hess-Pierce, B., & Kader, A. A. (1999). Quality changes in fresh-cut peach and nectarine slices as affected by cultivar, storage atmosphere and chemical treatments. *Journal of Food Science*, *64*(3), 429–432.

Grahn, C. M., Benedict, C., Thornton, T., & Miles, C. (2015). Production of baby-leaf salad greens in the spring and fall seasons of Northwest Washington. *HortScience: A Publication of the American Society for Horticultural Science*, *50*, 1467–1471.

Guarise, M., Borgonovo, G., Bassoli, A., & Ferrante, A. (2019). Evaluation of two wild populations of Hedge Mustard (*Sisymbrium officinale* (L.) Scop.) as a potential leafy vegetable. *Horticulturae*, *5*(1), 13.

Guidetti, R., Beghi, R., & Giovenzana, V. (2012). *'Chemometrics in food technology, chemometrics in practical applications. Kurt Varmuza*. IntechOpen. Available from https://www.intechopen.com/books/chemometrics-in-practical-applications/chemometrics-in-food-technology.

Gutiérrez, D. R., Chaves, A. R., & Rodríguez, S. D. C. (2017). Use of UV-C and gaseous ozone as sanitizing agents for keeping the quality of fresh-cut rocket (*Eruca sativa* mill). *Journal of Food Processing and Preservation*, *41*(3), e12968.

Hägele, F., Nübling, S., Schweiggert, R. M., Nolte, L., Weiss, A., Schmidt, H., & Carle, R. (2016). Comparison of ultra-high-pressure water jet and conventional rotating blade cutting for the production of fresh-cut iceberg (*Lactuca sativa* L.) and endive (*Cichorium endivia* L.). *European Food Research and Technology*, *242*, 2071–2081. Available from https://doi.org/10.1007/s00217-016-2704-2.

Harker, F. R., Gunson, F. A., & Jaeger, S. R. (2003). The case for fruit quality: An interpretative review of consumer attitudes, and preferences for apples. *Postharvest Biology and Technology*, *28*, 333–347.

Harker, F. R., White, A., Gunson, F. A., Hallett, I. C., & Nihal De Silva, H. (2006). Instrumental measurement of apple texture: A comparison of the single-edge notched bend test and the penetrometer. *Postharvest Biology and Technology*, *39*, 185–192.

Hernandez-Brenes, C. (2002). *Good manufacturing practices for handling, packing, storage and transportation of fresh produce. Improving the safety and quality of fresh fruits and vegetables: A training manual for trainers* (pp. 1–34). College Park, MD: Joint Institute for Food Safety and Applied Nutrition, University of Maryland, Chapt. 3.

Hoeberechts, J., Nicola, S., Fontana, E., Saglietti, D., & Piovano, G. (2004). Medium, cultivar and plant density influenced production and postharvest shelf life of *Raphanus sativus* grown in a soilless culture system. *Acta Horticulturae*, *659*, 791–798.

Incrocci, L., Lorenzini, O., Malorgio, F., Pardossi, A., & Tognoni, F. (2001). Valutazione quanti-qualitativa della produzione di rucola (*Eruca vesicaria* L. Cav.) e basilico (*Ocimum basilicum* L.) ottenuta in suolo e floating system utilizzando acque irrigue con differenti contenuti di NaCl. *Italus Hortus*, *8*(6), 92–97.

Indeche, A. K., Yoshida, Y., Goto, T., Yasuba, K. I., & Tanaka, Y. (2020). Effect of defoliation on blossom-end rot incidence and calcium transport into fruit of tomato cultivars under moderate water stress. *The Horticulture Journal*, *89*(1), 22–29. Available from https://doi.org/10.2503/hortj.UTD-079, 2020.

Ioannides, Y., Howarth, M. S., Raithatha, C., Defernez, M., Kemsley, E. K., & Smith, A. C. (2007). Texture analysis of red delicious fruit: Towards multiple measurements on individual fruit. *Food Quality Preference*, *18*, 825–833.

Jacxsens, L. (2002). Chapt. 1: Literature review. In: *Influence of preservation parameters on the quality of fresh-cut vegetables* (Doctoral dissertation; pp. 1–69). Gent: Universiteit Gent.

Jacxsens, L., Devlieghere, F., & Debevere, J. (2002). Predictive modelling for packaging design: Equilibrium modified atmosphere package of fresh-cut vegetables subjected to a simulated distribution chain. *International Journal of Food Microbiology*, *73*, 331–341.

Jacxsens, L., Devlieghere, F., & Debevere, J. (1999). Validation of a systematic approach to design equilibrium modified atmosphere packages for fresh-cut produce. *Lebensmittel-Wissenschaft + Technologie*, *32*, 425–432.

Jeamsripong, S., Chase, J. A., Jay-Russell, M. T., Buchanan, R. L., & Atwill, E. R. (2019). Experimental in-field transfer and survival of *Escherichia coli* from animal feces to Romaine lettuce in Salinas Valley, California. *Microorganisms*, *7*, 408.

Jean-Baptiste, I., Morard, P., & Bernadac, A. (1999). Effects of temporary calcium deficiency on the incidence of a nutritional disorder in melon. *Acta Horticulturae*, *481*, 417–424. Available from https://doi.org/10.17660/ActaHortic.1999.481.49.

Jensen, A. N., Storm, C., Forslund, A., Baggesen, D. L., & Dalsgaard, A. (2013). *Escherichia coli* contamination of lettuce grown in soils amended with animal slurry. *Journal of Food Protection*, *76*(7), 1137–1144.

Jideani, A. I. O., Anaysi, T. A., Micheau, G. R. A., Udoro, E. O., & Onipe, O. O. (2017). *Processing and preservation of fresh-cut fruit and vegetable products*. *Postharvest handling Ibrahim Kahramanoglu*. Intech Open. Available from http://doi.org/10.5772/intechopen.69763.

Kabelitz, T., Schmidt, B., Herppich, W. B., & Hassenberg, K. (2019). Effects of hot water dipping on apple heat transfer and post-harvest fruit quality. *Lebensmittel-Wissenschaft & Technologie*, *108*, 416–420.

Kader, A. A. (2002a). Postharvest biology and technology: An overview. In A. A. Kader (Ed.), *Postharvest technology of horticultural crops* (3rd ed., pp. 39–47). Oakland, CA: University of California, Division of Agriculture and Natural Resources, Publ. 3311.

Kader, A. A. (2002b). Quality and safety factors: Definition and evaluation for fresh horticultural crops. In A. A. Kader (Ed.), *Postharvest technology of horticultural crops* (3rd ed., pp. 279–286). Oakland, CA: University of California, Division of Agriculture and Natural Resources, Publ. 3311.

Kader, A. A. (2008). Perspective flavor quality of fruits and vegetables. *Journal of the Science of Food and Agriculture*, *88*, 1863–1868.

Kader, A. A., & Cantwell, M. I. (2006). *Produce quality rating scales and color charts*. *Postharvest technology research and information center* (p. 97) University of California.

Kalantari, F., Mohd Tahir, O., Mahmoudi Lahijani, A., & Kalantari, S. (2017). A review of vertical farming technology: A guide for implementation of building integrated agriculture in cities. *Advanced Engineering Forum*, *24*, 76–91.

Kasim, M. U., & Kasim, R. (2012). Color changes of fresh-cut Swiss chard leaves stored at different light intensity. *American Journal of Food Technology*, *7*(1), 13–21.

Kim, H. J., Fonseca, J. M., Kubota, C., & Choi, J. H. (2007). Effect of hydrogen peroxide on quality of fresh-cut tomato. *Journal of Food Science*, *7*, S463–S467.

Kim, M. J., Bang, W. S., & Yuk, H. G. (2017). 405 ± 5 nm light emitting diode illumination causes photodynamic inactivation of *Salmonella* spp. on fresh-cut papaya without deterioration. *Food Microbiology*, *62*, 124–132.

Kim, Y. H., Jeong, S. G., Back, K. H., Park, K. H., Chung, M. S., & Kang, D. H. (2013). Effect of various conditions on inactivation of *Escherichia coli* O157:H7, *Salmonella* typhimurium, and *Listeria monocytogenes* in fresh-cut lettuce using ultraviolet radiation. *International Journal of Food Microbiology*, *166*, 349–355.

King, A. D., Jr., Magnuson, J. A., Török, T., & Goodman, N. (1991). Microbial flora and storage quality of partially processed lettuce. *Journal of Food Science*, *56*(2), 459–461.

Kitinoja, L., & Kader, A. (2015). Measuring postharvest losses in fruits and vegetables in developing countries. In: *Report number: White paper no. 15-02* (pp. 1–15). The Postharvest Education Foundation.

Kleinhenz, M. D., French, D. G., Gazula, A., & Scheerens, J. C. (2003). Variety, shading, and growth stage effects on pigment concentrations in lettuce grown under contrasting temperature regimes. *Horttechnology*, *13*(4), 677–683.

Koca, N., Karadeniz, F., & Burdurlu, H. S. (2006). Effect of pH on chlorophyll degradation and colour loss in blanched green peas. *Food Chemistry*, *100*, 609–615.

Kong, W. W., Liu, F., Zhang, C., Zhang, J., & Feng, H. L. (2016). Non-destructive determination of malondialdehyde (MDA) distribution in oilseed rape leaves by laboratory scale NIR hyperspectral imaging. *Scientific Reports*, *6*, 35393.

Koukounaras, A., Diamantidis, G., & Sfakiotakis, E. (2008). The effect of heat treatment on quality retention of fresh-cut peach. *Postharvest Biology Technology*, *48*, 30–36.

Krasnova, I., Dukalska, L., Seglina, D., Misina, I., & Kārlina, D. (2013). Influence of anti-browning inhibitors and biodegradable packaging on the quality of fresh-cut pears. *Proceedings of the Latvian Academy of Sciences Section B*, *67*(2, 683), 167–173.

Lamikanra, O. (2002). *Fresh-cut fruits and vegetables: Science, technology, and market* (pp. 1–469). CRC Press. (Routledge Taylor & Fracis Group. ISBN 9781587160301).

Lamikanra, O., Kueneman, D., Ukuku, D., & Bett-Garber, K. L. (2005). Effect of processing under ultraviolet light on the shelf life of fresh-cut Cantaloupe melon. *Journal of Food Science*, *70*(9), C534–C539.

Lamikanra, O., & Watson, M. A. (2003). Temperature and storage duration effects on esterase activity in fresh-cut Cantaloupe melon. *Journal of Food Science*, *68*(3), 790, 703.

Lee, S. K., & Kader, A. A. (2000). Preharvest and postharvest factors influencing vitamin C content of horticultural crops. *Postharvest Biology and Technology*, *20*, 207–220.

Lester, G. E., Jifon, J. L., & Makus, D. J. (2010). Impact of potassium nutrition on postharvest fruit quality: Melon (*Cucumis melo* L.) case study. *Plant and Soil*, *335*, 117–131.

Lester, G. E., Jifon, J. L., & Stewart, W. M. (2007). Foliar potassium improves Cantaloupe marketable and nutritional quality. *Better Crops*, *91*, 24–25.

Limantara, L., Dettling, M. B., Indrawati, R., Indriatmoko., & Brotosudarmo, T. H. P. (2015). Analysis on the chlorophyll content of commercial green leafy vegetables. *Proceedings of the Chemical Society*, *4*, 225–231.

Lopez-Galvez, F., Ragaert, P., Palermo, L. A., Eriksson, M., & Devlieghere, F. (2013). Effect of new sanitizing formulations on quality of fresh-cut iceberg lettuce. *Postharvest Biology Technology*, *85*, 102–108.

López-Gálvez, G., Saltveit, M., & Cantwell, M. (1996). Wound-induced phenylalanine ammonia lyase activity: Factors affecting its induction and correlation with the quality of minimally processed lettuces. *Postharvest Biology Technology*, *9*, 223–233.

Luna, M. C., Martínez-Sánchez, A., Selma, M. V., Tudela, J. A., Baixauli, C., & Gil, M. I. (2013). Influence of nutrient solutions in an open-field soilless system on the quality characteristics and shelf life of fresh-cut red and green lettuces (*Lactuca sativa* L.) in different seasons. *Journal of the Science and Food Agriculture*, *93*, 415–421.

Luna, M. C., Tudela, J. A., Martínez-Sánchez, A., Allende, A., & Gil, M. I. (2013). Optimizing water management to control respiration rate and reduce browning and microbial load of fresh-cut romaine lettuce. *Postharvest Biology Technology*, *80*, 9–17.

Luna, M. C., Tudela, J. A., Martínez-Sánchez, A., Allende, A., Marín, A., & Gil, M. I. (2012). Long-term deficit and excess of irrigation influences quality and browning related enzymes and phenolic metabolism of fresh-cut iceberg lettuce (*Lactuca sativa* L.). *Postharvest Biology Technology*, *73*, 37–45.

Luo, Y., & Tao, Y. (2003). Determining tissue damage of fresh-cut vegetables using imaging technology. *Acta Horticulturae*, *628*, 97–102.

Magwaza, L. S., Opara, U. L., Nieuwoudt, H., Cronje, P. J. R., Saeys, W., & Nicolai, B. (2012). NIR spectroscopy applications for internal and external quality analysis of citrus fruit-a review. *Food Bioprocess Technology*, *5*, 425–444.

Malakar, A., Snow, D. D., & Ray, C. (2019). Irrigation water quality – A contemporary perspective. *Water*, *11*(7), 1482. Available from https://doi.org/10.3390/w11071482.

Maringgal, B., Hashim, N., Tawakkal, I. S. M. A., & Mohamed, M. T. M. (2019). Recent advance in edible coating and its effect on fresh/fresh-cut fruits quality. *Trends in Food Science & Technology*, *96*, 253–267. Available from https://doi.org/10.1016/j.tifs.2019.12.024.

Marszałek, K., Szczepańska, J., Woźniak, L., Skapska, S., Barba, F. J., Brnčić, M., & Brnčić, S. R. (2018). The preservation of fruit and vegetable products under high pressure processing. *Encyclopedia of Food Security and Sustainability*, 481–492.

Martín-Diana, A. B., Rico, D., Barry-Ryan, C., Frías, J. M., Mulcahy, J., & Henehan, G. T. M. (2005). Comparison of calcium lactate with chlorine as a washing treatment for fresh-cut lettuce and carrots: Quality and nutritional parameters. *Journal of Science and Food Agriculture*, *85*, 2260–2268.

Martínez-Sánchez, A., Luna, M. C., Selma, M. V., Tudela, J. A., Abad, J., & Gil, M. I. (2012). Baby-leaf and multileaf of green and red lettuce are suitable raw materials for the fresh-cut industry. *Postharvest Biology Technology*, *63*, 1–10.

Martínez-Sánchez, A., Tudela, J. A., Luna, M. C., Allende, A., & Gil, M. I. (2011). Low oxygen levels and light exposure affect quality of fresh-cut Romaine lettuce. *Postharvest Biology Technology*, *59*, 34–42.

McGlone, V. A., Jordan, R. B., Seelye, R., & Martinsen, P. J. (2002). Comparing density and NIR methods for measurement of Kiwifruit dry matter and soluble solids content. *Postharvest Biology Technology*, *26*, 191–198.

McGlynn, W. G., Bellmer, D. D., & Reilly, S. S. (2003). Effect of precut sanitizing dip and water jet cutting on quality and shelf life of fresh-cut watermelon. *Journal of Food Quality*, *26*(6), 489–498.

Mehinagic, E., Royer, G., Symoneaux, R., Bertrand, D., & Jourjon, F. (2004). Prediction of the sensory quality of apple by physical measurements. *Postharvest Biology Technology*, *34*, 257–269.

Mengel, K. (2002). Alternative or complementary role of foliar supply in mineral nutrition. *Acta Horticulturae*, *594*, 33–47. Available from https://doi.org/10.17660/ActaHortic.2002.594.1.

Mercier, S., Villeneuve, S., Mondor, M., & Uysal, I. (2017). Time–temperature management along the food cold chain: A review of recent developments. *Comprehensive Reviews in Food Science and Food Safety*, *16*(4), 647–667.

Merzlyak, M. N., Solovchenko, A., & Gitelson, A. (2003). Reflectance spectral features and non-destructive estimation of chlorophyll, carotenoid and anthocyanin. Content in apple fruit. *Postharvest Biology Technology*, *27*, 197–211.

Mitcham, E. J. (2010). Focus on consumers to increase sales. *American Western Fruit Grower June*, *2010*, 28.

Mogren, L., Reade, J., & Monaghan, J. (2018). 'Assessment of the vitamin C content in selected baby leafy species over the season. *Acta Horticulturae*, *1209*, 27–34. Available from https://doi.org/10.17660/ActaHortic.2018.1209.4.

Moreira, M. R., Ponce, A., Ansorena, R., & Roura, S. I. (2011). Effectiveness of edible coatings combined with mild heat shocks on microbial spoilage and sensory quality of fresh cut broccoli (*Brassica oleracea* L.). *Journal of Food Science*, *76*(6), M367–M374.

Moreira, M. R., Roura, S. I., & Ponce, A. (2011). Effectiveness of chitosan edible coatings to improve microbiological and sensory quality of fresh cut broccoli. *Food Science and Technology*, *44*, 2335–2341.

Mylavarapu, R. S., & Zinati, G. M. (2009). Improvement of soil properties using compost for optimum parsley production in sandy soils. *Scientia Horticulturae-Amsterdam*, *120*, 426–430.

Natalini, A., Cocetta, G., Acciarri, N., & Ferrante, A. (2018). Physiological and biochemical characterization of a red escarole obtained from an interspecies crossing. *Agronomy*, *8*(4), 50.

Natalini, A., Martinez-Diaz, V., Ferrante, A., & Pardossi, A. (2017). Ethylene sensitivity regulates the wounding response in wild type and never ripe tomatoes. *Journal of Horticultural Science and Biotechnology*, *92*(6), 591–597.

Ndraha, N., Hsiao, H. I., Vlajic, J., Yang, M. F., & Lin, H. T. V. (2018). Time-temperature abuse in the food cold chain: Review of issues, challenges, and recommendations. *Food Control*, *89*, 12–21.

Nicola, S., Egea-Gilabert, C., Niñirola, D., Conesa, E., Pignata, G., Fontana, E., & Fernández, J. A. (2015). Nitrogen and aeration levels of the nutrient solution in soilless cultivation systems as important growing conditions affecting inherent quality of baby leaf vegetables: A review. *Acta Horticulturae*, *1099*, 167–177. Available from https://doi.org/10.17660/ActaHortic.2015.1099.17.

Nicola, S., & Ertani, A. (2021). The Floating Growing System and New Growing System® to grow leafy vegetables and herbs. *Acta Horticulturae*, *1321*, 251–258. Available from https://doi.org/10.17660/ActaHortic.2021.1321.33.

Nicola, S., & Fontana, E. (2007). Cultivation management on the farm influences postharvest quality and safety. *Acta Horticulturae*, *746*, 273–280. Available from https://doi.org/10.17660/ActaHortic.2007.746.30.

Nicola, S., & Fontana, E. (2014). Fresh-cut produce quality: Implications for a systems approach', (Chapter 9). In W. J. Florkowski, R. Shewfelt, B. Breuckner, & S. E. Prussia (Eds.), *Postharvest handling: A systems approach* (3rd ed., pp. 217–273). San Diego, CA: Academic Press/Elsevier, DOI: 10.1016/B978-0-12-408137-6.00009-0. ISBN: 978-0-12-408137-6. pp. 564 + xxii pp. pp. 624.

Nicola, S., Fontana, E., Hoeberechts, J., & Saglietti, D. (2005). *Raphanus sativus* production in soilless or traditional culture systems and postharvest packaging. *Acta Horticulturae, 682*, 1303–1310.

Nicola, S., Fontana, E., Monaco, S., & Grignani, C. (2013). The application of the nitrates directive to vegetable crops: Tools and strategies from NEV2013 for an integrated fertilization management. In K. D'Haene, B. Vandecasteele, R. De Vis, S. Crappé, D. Callens, E. Mechant, G. Hofman, & S. De Neve (Eds.), *NUTRIHORT: Nutrient management, innovative techniques and nutrient legislation in intensive horticulture for an improved water quality* (pp. 388), September 16–18, 2013, Ghent, Belgium. Proceedings: 2–8. ISBN: 978-9040303463.

Nicola, S., Fontana, E., Tibaldi, G., & Zhan, L. (2010). Qualitative and physiological response of minimally processed rocket (*Eruca sativa* Mill.) to package filling amount and shelf-life temperature. *Acta Horticulturae*, *877*, 611–618.

Nicola, S., Hoeberechts, J., & Fontana, E. (2004). Rocket (*Eruca sativa* Mill.) and corn salad (*Valerianella olitoria* L.): Production and shelf life of two leafy vegetables grown in a soilless culture system. *Acta Horticulturae*, *633*, 509–516.

Nicola, S., Hoeberechts, J., & Fontana, E. (2005). Comparison between traditional and soilless culture systems to produce rocket (*Eruca sativa*) with low nitrate content. *Acta Horticulturae*, *697*, 549–555.

Nicola, S., Hoeberechts, J., Fontana, E., & Saglietti, D. (2003). Cultural technique influences on post-harvest quality of rocket (*Eruca sativa* Mill.). *Acta Horticulturae*, *604*, 685–690.

Nicola, S., Pignata, G., & Tibaldi, G. (2018a). The floating growing system can assure a low microbial contamination of baby leaf vegetables at harvest. *Acta Horticulturae*, *1209*, 57–64. Available from https://doi.org/10.17660/ActaHortic.2018.1209.9.

Nicola, S., Pignata, G., & Tibaldi, G. (2018b). Potentiality of mint leaves as a ready-to-use product: Postharvest evaluation. *Acta Horticulturae*, *1209*, 109–113. Available from https://doi.org/10.17660/ActaHortic.2018.1209.16.

Nicola, S., Pignata, G., & Tibaldi, G. (2018c). Fresh-cut chain for soilless grown 'Mara de Bois' strawberries: The cutting process reduces the shelf-life of the produce. *Acta Horticulturae*, *1209*, 129–134. Available from https://doi.org/10.17660/ActaHortic.2018.1209.19.

Nicola, S., Pignata, G., Casale, M., Hazrati, S., & Ertani, A. (2021). Setting up a lab-scale pilot plant to study the new growing system (NGS®) for leafy vegetable and culinary herb growth. *Horticulturae*, *7*, 90. Available from https://doi.org/10.3390/horticulturae7050090.

Nicola, S., Pignata, G., Ferrante, A., Bulgari, R., Cocetta, G., & Ertani, A. (2020). Water use efficiency in greenhouse systems and its application in horticulture. *AgroLife Scientific Journal*, *9*(1), 248–262, ISSN 2285-5718.

Nicola, S., Tibaldi, G., & Fontana, E. (2009). Fresh-cut produce quality: Implications for a systems approach. In W. Florkowski, R. Shewfelt, B. Brueckner, & S. Prussia (Eds.), *Postharvest handling: A systems approach* (pp. 247–282). San Diego, CA: Elsevier B.V.

Nicola, S., Tibaldi, G., Gaino, W., & Pignata, G. (2018). Cutting shape, film and storage temperature affect the shelf-life of fresh-cut pumpkin. *Acta Horticulturae*, *1209*, 399–408. Available from https://doi.org/10.17660/ActaHortic.2018.1209.59.

Nicolai, B. M., Beullens, K., Bobelyn, E., Peirs, A., Saeys, W., Theron, K. I., & Lammertyna, J. (2007). Nondestructive measurement of fruit and vegetable quality by means of NIR spectroscopy: A review. *Postharvest Biology and Technology*, *46*, 99–118.

Ninfali, P., & Bacchiocca, M. (2004). Parameters for the detection of post-harvest quality in fresh or transformed horticultural crops. *Journal of Food and Agricultural Environment*, *2*(1), 122–127.

Noichinda, S., Bodhipadma, K., Mahamontri, C., Narongruk, T., & Ketsa, S. (2007). Light during storage prevents loss of ascorbic acid, and increase glucose and fructose levels in Chinese kale (*Brassica oleracea* var. alboglabra). *Postharvest Biology and Technology*, *44*, 312–315.

Nou, X., & Luo, Y. (2010). Whole-leaf wash improves chlorine efficacy for microbial reduction and prevents pathogen cross-contamination during fresh-cut lettuce processing. *Journal of Food Science*, *75*(5), M283–M290.

Nunes, M. C. N., Emond, J. P., Rauth, M., Dea, S., & Chau, K. V. (2009). Environmental conditions encountered during typical consumer retail display affect fruit and vegetable quality and waste. *Postharvest Biology and Technology*, *51*, 232–241.

O'Beirne, D., Gleeson, E., Auty, M., & Jordan, K. (2014). Effects of processing and storage variables on penetration and survival of *Escherichia coli* O157: H7 in fresh-cut packaged carrots. *Food Control*, *40*, 71–77.

Olarte, C., Sanz, S., Echávarri, J. F., & Ayala, F. (2009). Effect of plastic permeability and exposure to light during storage on the quality of minimally processed broccoli and cauliflower. *Lebensmittel-Wissenschaft & Technologie*, *42*, 402–411.

Ölmez, H., & Kretzschmar, U. (2009). Potential alternative disinfection methods for organic fresh-cut industry for minimizing water consumption and environmental impact. *Lebensmittel-Wissenschaft & Technologie*, *42*, 686–693.

Oms-Oliu, G., Rojas-Graü, M. A., González, L. A., Varela, P., Soliva-Fortuny, R., Hernando, M. I. H., . . . Martín-Belloso, O. (2008). Recent approaches using chemical treatments to preserve quality of fresh-cut fruit: A review. *Postharvest Biology and Technology*, *57*(3), 139–148.

Oms-Oliu, G., Soliva-Fortuny, R., & Martín-Belloso, O. (2008). Edible coatings with antibrowning agents to maintain sensory quality and antioxidant properties of fresh-cut pears. *Postharvest Biology and Technology*, *50*, 87–94.

Orio, L., Cravotto, G., Binello, A., Pignata, G., Nicola, S., & Chemat, F. (2012). Hydrodistillation and in situ microwave-generated hydrodistillation of fresh and dried mint leaves: A comparison study. *Journal of Science and Food Agriculture*, *92*(15), 3085–3090.

Pace, B., Capotorto, I., Gonnella, M., Baruzzi, F., & Cefola, M. (2018). Influence of soil and soilless agricultural growing system on postharvest quality of three ready-to-use multi-leaf lettuce cultivars. *Advances in Horticultural Science*, *32*(3), 353–362.

Pace, B., Cavallo, D. P., Cefola, M., Colella, R., & Attolico, G. (2015). Adaptive self-configuring computer vision system for quality evaluation of fresh-cut radicchio. *Innovative Food Science and Emerging Technologies*, *32*, 200–207.

Panadare, D., & Rathod, V. (2018). Extraction and purification of polyphenol oxidase: A review. *Biocatalysis and Agricultural Biotechnology*, *14*, 431–437.

Paz, P., Sánchez, M. T., Pérez-Marín, D., Guerrero, J. E., & Garrido-Varo, A. (2009). Instantaneous quantitative and qualitative assessment of pear quality using near infrared spectroscopy. *Computers and Electronics in Agriculture*, *69*, 24–32.

Peirs, A., Lammertyn, J., Ooms, K., & Nicolaï, B. M. (2001). Prediction of the optimal picking date of different apple cultivars by means of VIS/NIR-spectroscopy. *Postharvest Biology and Technology*, *21*, 189–199.

Pennisi, G., Blasioli, S., Cellini, A., Maia, L., Crepaldi, A., Braschi, I., Spinelli, F., Nicola, S., Fernandez, J., Stanghellini, S., Marcelis, L. F. M., Orsini, F., & Gianquinto, G. (2019). Unravelling the role of red: Blue LED lights on resource use efficiency and nutritional properties of indoor grown sweet basil. *Frontiers in Plant Science*, *10*(March 2019), Article 305. Available from https://doi.org/10.3389/fpls.2019.00305.

Pignata, G. (2016). *Innovation and technology in pre and postharvest of fresh produce with high added value* (Ph.D. dissertation; pp. 350). University of Turin. ISBN: 978-88-99108-06-9.

Pignata, G., Ertani, A., Casale, M., Piano, S., & Nicola, S. (2020). Mixing fresh-cut baby green and red leaf lettuce from soilless cultivation preserves phytochemical content and safety. *Agricultural and Food Science*, *29*(1), 55–65. Available from https://doi.org/10.23986/afsci.88904.

Pilone, V., Stasi, A., & Baselice, A. (2017). Quality preferences and pricing of fresh-cut salads in Italy: New evidence from market data. *British Food Journal*, *119*, 1473–1486.

Pirovani, M. E., Güemes, D. R., & Piagentini, A. M. (2003). Fresh-cut spinach quality as influenced by spin drying parameters. *Journal Food Quality*, *26*(3), 231–242.

Portela, S. I., & Cantwell, M. I. (2001). Cutting blade sharpness affects appearence and other quality attributes of fresh-cut cantaloupe melon. *Journal of Food Science*, *66*, 1265–1270.

Poverenov, E., Danino, S., Horev, B., Granit, R., Vinokur, Y., & Rodov, V. (2014). Layer-by-Layer electrostatic deposition of edible coating on fresh-cut melon model: Anticipated and unexpected effects of alginate–chitosan combination. *Food and Bioprocess Technology*, *7*, 1424–1432. Available from https://doi.org/10.1007/s11947-013-1134-4.

Priyanka, B., Patil, R. K., & Dwarakanath, S. (2016). A review on detection methods used for foodborne pathogens. *Indian Journal of Medical Research*, *144*, 327–338.

Proietti, S., Moscatello, S., Leccese, A., Colla, G., & Battistelli, A. (2004). The effect of growing spinach (*Spinacia oleracea* L.) at two light intensities on the amounts of oxalate, ascorbate and nitrate in their leaves. *Journal of Horticultural Science and Biotechnology*, *79*(4), 606–609.

Putnik, P., Kovačević, D. B., Jambrak, A. R., Barba, F. J., Cravotto, G., Binello, A., Lorenzo, J. M., & Shpigelman, A. (2017). Innovative "green" and novel strategies for the extraction of bioactive added value compounds from citrus wastes: A review. *Molecules (Basel, Switzerland)*, *22*, 680.

Ramos, B., Miller, F. A., Brandão, T. R. S., Teixeira, P., & Silva, C. L. M. (2013). Fresh fruits and vegetables – An overview on applied methodologies to improve its quality and safety. *Innovative Food Sciences and Emerging Technologies*, *20*, 1–15. Available from https://doi.org/10.1016/j.ifset.2013.07.002.

Ramos-Villarroel, A., Aron-Maftei, N., Martín-Belloso, O., & Soliva-Fortuny, R. (2014). Bacterial inactivation and quality changes of fresh-cut avocados as affected by intense light pulses of specific spectra. *International Journal of Food Science and Technology*, *49*(1), 128–136. Available from https://doi.org/10.1111/ijfs.12284.

Rastogi, G., Sbodio, A., Tech, J. J., Suslow, T. V., Coaker, G. L., & Leveau, J. H. J. (2012). Leaf microbiota in an agroecosystem: Spatiotemporal variation in bacterial community composition on field-grown lettuce. *The ISME Journal*, *6*, 1812–1822.

Rediers, H., Claes, M., Peeters, L., & Willems, K. (2009). Evaluation of the cold chain of fresh-cut endive from farmer to plate. *Postharvest Biology and Technology*, *51*, 257–262.

Reyes, L. F., Villarreal, J. E., & Cisneros-Zevallos, L. (2007). The increase in antioxidant capacity after wounding depends on the type of fruit or vegetable tissue. *Food Chemistry*, *101*(3), 1254–1262.

Rico, D., Martin-Diana, A. B., Barat, J. M., & Barry-Ryan, C. (2007). Extending and measuring the quality of fresh-cut fruit and vegetables: A review. *Trends in Food Science and Technology*, *18*, 373–386.

Rivera-López, J., Vázquez-Ortiz, F. A., Ayala-Zavala, F., Sotelo-Mundo, R. R., & González-Aguilar, G. A. (2005). Cutting shape and storage temperature affect overall quality of fresh-cut papaya cv. 'Maradol'. *Journal of Food Science*, *70*(7), S482–S489.

Robles-Sánchez, R. M., Rojas-Graü, M. A., Odriozola-Serrano, I., González-Aguilar, G., & Martin-Belloso, O. (2013). Influence of alginate-based edible coating as carrier of antibrowning agents on bioactive compounds and antioxidant activity in fresh-cut Kent mangoes. *Lebensmittel-Wissenschaft & Technologie*, *50*, 240–246.

Rodríguez-Hidalgo, S., Artés-Hernández, F., Gómez, P., Artés, F., & Fernandez, J. A. (2010). Quality changes on minimally processed purslane baby leaves growth under floating trays system. *Acta Horticulturae*, *877*, 641–648.

Rojas-Graü, M. A., Oms-Oliu, G., Soliva-Fortuny, R., & Martín-Belloso, O. (2009). The use of packaging techniques to maintain freshness in fresh-cut fruits and vegetables: A review. *The International Journal of Food Science Technology*, *44*, 875–889.

Rojas-Graü, M. A., Soliva-Fortuny, R., & Martín-Belloso, O. (2009). Edible coatings to incorporate active ingredients to fresh cut fruits: A review. *Trends in Food Science and Technology*, *20*, 438–447.

Rojas-Graü, M. A., Tapia, M. S., Rodríguez, F. J., Carmona, A. J., & Martin-Belloso, O. (2007). Alginate and gellan-based edible coatings as carriers of antibrowning agents applied on fresh-cut Fuji apples. *Food Hydrocolloid*, *21*, 118–127.

Roller, S., & Seedhar, P. (2002). Carvacrol and cinnamic acid inhibit microbial growth in fresh-cut melon and kiwifruit at 4°C and 8°C. *Letters in Applied Microbiology*, *35*(5), 390–394.

Rouphael, Y., Cardarelli, M., Bassal, A., Leonardi, C., Giuffrida, F., & Colla, G. (2012). Vegetable quality as affected by genetic, agronomic and environmental factors. *Journal of Food, Agriculture and Environment*, *10*, 680–688.

Sadeghi, K., Lee, Y., & Seo, J. (2019). Ethylene scavenging systems in packaging of fresh produce: A review. *Food Reviews International*, 1–22.

Saltveit, M. E. (1997). Physical and physiological changes in minimally processed fruits and vegetables. In F. A. Tomás-Barberán, & R. J. Robins (Eds.), *Phytochemistry of fruit and vegetables* (pp. 205–220). New York: Oxford University Press.

Saltveit, M. E. (2016). The three responses of plant tissue to wounding. *Acta Horticulturae*, *1141*, 13–20. Available from https://doi.org/10.17660/ActaHortic.2016.1141.2.

Sánchez, M. T., Pérez-Marín, D., Flores-Rojasa, K., Guerrero, J. E., & Garrido-Varo, A. (2009). Use of near-infrared reflectance spectroscopy for shelf-life discrimination of green asparagus stored in a cool room under controlled atmosphere. *Talanta*, *78*, 530–536.

Sanchis, E., Gonzalez, S., Ghidelli, C., Sheth, C. C., Mateos, M., Palou, L., & Pérez-Gago, M. B. (2016). Browning inhibition and microbial control in fresh-cut persimmon (*Diospyros kaki* Thunb. cv. Rojo Brillante) by apple pectin-based edible coatings. *Postharvest Biology and Technology*, *112*, 186–193.

Santamaria, P., & Valenzano, V. (2001). La qualità degli ortaggi allevati senza suolo. *Italus Hortus*, *8*(6), 31–38.

Schmilovitch, Z., Mizrach, A., Hoffman, A., Egozi, H., & Fuchs, Y. (2000). Determination of mango physiological indices by near-infrared spectrometry. *Postharvest Biology and Technology*, *19*, 245–252.

Schwartz, S. J., & Lorenzo, T. V. (1991). Chlorophyll stability during continuous aseptic processing and storage. *Journal of Food Science*, *56*, 1059–1062.

Scollard, J., Francis, G. A., & O'Beirne, D. (2013). Some conventional and latent anti-listerial effects of essential oils, herbs, carrot and cabbage in fresh-cut vegetable systems. *Postharvest Biology and Technology*, *77*, 87–93.

Seefeldt, H. F., Løkke, M. M., & Edelenbos, M. (2012). Effect of variety and harvest time on respiration rate of broccoli florets and wild rocket salad using a novel O_2 sensor. *Postharvest Biology and Technology*, *69*, 7–14.

Selma, M. V., Luna, M. C., Martínez-Sánchez, A., Tudela, J. A., Beltrán, D., Baixauli, C., & Gil, M. I. (2012). Sensory quality, bioactive constituents and microbiological quality of green and red fresh-cut lettuces (*Lactuca sativa* L.) are influenced by soil and soilless agricultural production systems. *Postharvest Biology and Technology*, *63*, 16–24.

Seymour, I. J., Burfoot, D., Smith, R. L., Cox, L. A., & Lockwood, A. (2002). Ultrasound decontamination of minimally processed fruits and vegetables. *International Journal of Food Science Technology*, *37*, 547–557.

Silveira, L. O., do Rosário, D. K. A., Giori, A. C. G., Oliveira, S. B. S., da Silva Mutz, Y., Marques, C. S., Coelho, J. M., & Bernardes, P. C. (2018). Combination of peracetic acid and ultrasound reduces Salmonella typhimurium on fresh lettuce (*Lactuca sativa* L. var. crispa). *Journal of Food Science and Technology*, *55*, 1535–1540. Available from https://doi.org/10.1007/s13197-018-3071-8.

Sinha, K., & Khare, V. (2017). Review on: Antinutritional factors in vegetable crops. *The Pharma Innovation*, *6*, 353–358.

Sivakumar, D., & Fallik, E. (2013). Influence of heat treatments on quality retention of fresh and fresh-cut produce. *Food Reviews International*, *29*(3), 294–320.

Solomon, E. B., Pang, H. J., & Matthews, K. R. (2003). Persistence of *Escherichia coli* O157:H7 on lettuce plants following spray irrigation with contaminated water. *Journal of Food Protection*, *66*(12), 2198–2202.

Spadafora, N. D., Amaro, A. L., Perira, M. J., Muller, C. T., Pintado, M., & Rogers, H. J. (2016). Multi-trait analysis of post-harvest storage in rocket salad (*Diplotaxis tenuifolia*) links sensoriales, volatile and nutritional data. *Food Chemistry*, *211*, 114–123.

Spadafora, N. D., Cocetta, G., Cavaiuolo, M., Bulgari, R., Dhorajiwala, R., Ferrante, A., . . . Müller, C. T. (2019). A complex interaction between pre-harvest and post-harvest factors determines fresh-cut melon quality and aroma. *Scientific Reports*, *9*, 2745.

Spadafora, N. D., Machado, I., Müller, C. T., Pintado, M., Bates, M., & Rogers, H. J. (2015). Physiological, metabolite and volatile analysis of cut size in melon during postharvest storage. *Acta Horticulturae*, *1071*, 787–793.

Spadafora, N. D., Paramithiotis, S., Drosinos, E. H., Cammarisano, L., Rogers, H. J., & Müller, C. T. (2016). Detection of *Listeria monocytogenes* in cut melon fruit using analysis of volatile organic compounds. *Food Microbiology*, *54*, 52–59.

Steele, M., & Odumeru, J. (2004). Irrigation water as source of foodborne pathogens on fruit and vegetables. *Journal of Food Protection*, *67*(12), 2839–2849.

Steiner, A., Abreu, M., Correia, L., Beirão-da-Costa, S., Leitão, E., Beirão-da-Costa, M. L., . . . Moldão-Martins, M. (2006). Metabolic response to combined mild heat pre-treatments and modified atmosphere packaging on fresh-cut peach. *European Food Research and Technology*, *222*, 217–222.

Strickland, W., Sopher, C. D., Rice, R. G., & Battles, G. T. (2010). Six years of ozone processing of fresh cut salad mixes. *Ozone: Science & Engineering*, *32*(1), 66–70.

Sudheer, K. P., & Indira, V. (2007). *Post-harvest technology of horticultural crops* (p. 291) New Delhi: New India Publishing.

Surjadinata, B. B., & Cisneros-Zevallos, L. (2012). 'Biosynthesis of phenolic antioxidants in carrot tissue increases with wounding intensity. *Food Chemistry*, *134*(2), 615–624.

Surjadinata, B. B., Jacobo-Velázquez, D. A., & Cisneros-Zevallos, L. (2017). UVA, UVB and UVC light enhances the biosynthesis of phenolic antioxidants in fresh-cut carrot through a synergistic effect with wounding. *Molecules (Basel, Switzerland)*, *22*(4), 668.

Takos, A. M., Jaffé, F. W., Jacob, S. R., Bogs, J., Robinson, S. P., & Walker, A. R. (2006). Light-induced expression of a *MYB* gene regulates anthocyanin biosynthesis in red apples. *Plant Physiology*, *142*(3), 1216–1232.

Taniwaki, M., & Sakurai, N. (2008). Texture measurement of cabbages using an acoustical vibration method. *Postharvest Biology and Technology*, *50*, 176–181.

Taranto, F., Pasqualone, A., Mangini, G., Tripodi, P., Miazzi, M. M., Pavan, S., & Montemurro, C. (2017). Polyphenol oxidases in crops: Biochemical, physiological and genetic aspects. *International Journal of Molecular Sciences*, *18*, 377.

Tarazona-Díaz, M. P., Viegas, J., Moldao-Martins, M., & Aguayo, E. (2011). Bioactive compounds from flesh and by-product of fresh-cut watermelon cultivars. *Journal of the Science of Food and Agriculture*, *91*, 805–812.

Thomas, C., & O'Beirne, D. (2000). Evolution of the impact of short-term temperature abuse on the microbiology and shelf life of a model ready-to-use vegetable combination product. *International Journal of Food Microbiology*, *59*, 47–57.

Tibaldi, G., Battista, G., Fontana, E., & Nicola, S. (2010). Effetto del taglio e del condizionamento post-raccolta sulla shelf-life di zucca di IV gamma. *Italus Hortus*, *17*(3), 52–55.

Tibaldi, G., Fontana, E., & Nicola, S. (2010). Influence of maturity stage at harvest on essential oil composition of dill leaves (*Anethum graveolens* L.) and of postharvest treatments on freshness of fresh-cut dill. *Acta Horticulturae*, *880*, 261–266.

Toivonen, P. M. A., & Hampson, C. R. (2009). Apple cultivar and temperature at cutting affect quality of fresh slices. *Horttechnology*, *19*, 108–112.

Torres-Contreras, A. M., Nair, V., Cisneros-Zevallos, L., & Jacobo-Velázquez, D. A. (2014). Plants as biofactories: Stress-induced production of chlorogenic acid isomers in potato tubers as affected by wounding intensity and storage time. *Industrial Crops and Products*, *62*, 61–66.

Tournas, V. H. (2005). Spoilage of vegetable crops by bacteria and fungi and related health hazards. *Critical Reviews in Microbiology*, *31*, 33–44.

Tsironi, T., Dermesonlouoglou, E., Giannoglou, M., Gogou, E., Katsaros, G., & Taoukis, P. (2017). Shelf-life prediction models for ready-to-eat fresh cut salads: Testing in real cold chain. *International Journal of Food Microbiology*, *240*, 131–140.

Tsouvaltzis, P., Deltsidis, A., & Brecht, J. K. (2011). Hot water treatment and pre-processing storage reduce browning development in fresh-cut potato slices. *HortScience: A Publication of the American Society for Horticultural Science*, *46*(9), 1282–1286.

Tzortzakis, N., Nicola, S., Savvas, D., & Voogt, W. (2020). Editorial: Soilless cultivation through an intensive crop production scheme. Management strategies, challenges and future directions. *Frontiers in Plant Science*, *11* (Article 363). Available from https://doi.org/10.3389/fpls.2020.00363, [10 April 2020].

Ukuku, D. O., & Sapers, G. M. (2007). Effect of time before storage and storage temperature on survival of *Salmonella* inoculated on fresh-cut melons. *Food Microbiology*, *24*(3), 288–295.

University of Arizona-Cooperative Extension. (2004a). More studies indicate *E. coli* O157:H7 can contaminate lettuce in the field. *Western Vegetable Newsletter*, *2*(1).

University of Arizona-Cooperative Extension. (2004b). Water stress may extend shelf life of vegetables. *Western Vegetable Newsletter*, *2*(2).

U.S. Food and Drug Administration. (2015). *Standards for the growing, harvesting, packing, and holding of produce for human consumption*. <https://federalregister.gov/documents/2015/11/27/2015-28159/standards-for-the-growing-harvesting.packing-and-holding-of-produce-for-human-consumption> Accessed 11.08.20.

Vargas, M., Chiralt, A., Albors, A., & González-Martínez, C. (2009). Effect of chitosan-based edible coatings applied by vacuum impregnation on quality preservation of fresh-cut carrot. *Postharvest Biology and Technology*, *51*, 263–271.

Villarreal-García, D., Nair, V., Cisneros-Zevallos, L., & Jacobo-Velázquez, D. A. (2016). Plants as biofactories: Postharvest stress-induced accumulation of phenolic compounds and glucosinolates in broccoli subjected to wounding stress and exogenous phytohormones. *Frontiers in Plant Science*, *7*, 45.

Voća, S., Duralija, B., Družić, J., Skendrović Babojelić, M., Dobričević, N., & Čmelik, Z. (2006). Influence of cultivation systems on physical and chemical composition of strawberry fruits cv. Elsanta. *Agriculturae Conspectus Scientificus*, *71*(4), 171–174.

Wall, N. M., Nishijima, K. A., Fitch, M. M., & Nishijima, W. T. (2010). Physicochemical, nutritional and microbial quality of fresh-cut and frozen papaya prepared from cultivars with varying resistance to internal yellowing disease. *Journal of Food Quality*, *33*, 131–149.

Waszczak, C., Carmody, M., & Kangasjärvi, J. (2018). Reactive oxygen species in plant signaling. *Annual Review of Plant Biology*, *69*, 209–236.

Wilson, C. T., Harte, J., & Almenar, E. (2018). Effects of sachet presence on consumer product perception and active packaging acceptability—A study of fresh-cut cantaloupe. *Lebensmittel-Wissenschaft & Technologie*, *92*, 531–539.

Wilson, M. D., Stanley, R. A., Eyles, A., & Ross, T. (2019). Innovative processes and technologies for modified atmosphere packaging of fresh and fresh-cut fruits and vegetables. *Critical Reviews in Food Science and Nutrition*, *59*(3), 411–422.

Wulfkuehler, S., Gras, C., & Carle, R. (2013). 'Sesquiterpene lactone content and overall quality of fresh-cut Witloof Chicory (*Cichorium intybus* L. var. *foliosum* Hegi) as affected by different washing procedures. *Journal of Agricultural and Food Chemistry*, *61*, 7705–7714.

Xiao, C., Zhu, L., Luo, W., Song, X., & Deng, Y. (2010). Combined action of pure oxygen pretreatment and chitosan coating incorporated with rosemary extracts on the quality of fresh-cut pears. *Food Chemistry*, *121*, 1003–1009.

Xiao, Z., Luo, Y., Luo, Y., & Wang, Q. (2011). Combined effects of sodium chlorite dip treatment and chitosan coatings on the quality of fresh-cut d'Anjou pears. *Postharvest Biology and Technology*, *62*, 319–326.

Yildiz, G., Palma, S., & Feng, H. (2019). Ultrasonic cutting as a new method to produce fresh-cut red delicious and golden delicious apples. *Journal of Food Science*, *84*(12), 3391–3398.

Yousuf, B., Qadri, O. S., & Srivastava, A. K. (2018). Recent developments in shelf-life extension of fresh-cut fruits and vegetables by application of different edible coatings: A review. *Lebensmittel-Wissenschaft & Technologie*, *89*, 198–209.

Yuan, M., Teo, C. H. M., & Yuk, H. G. (2019). Combined antibacterial activities of essential oil compounds against *Escherichia coli* O157:H7 and their application potential on fresh-cut lettuce. *Food Control*, *96*, 112–118.

Yuan, Z., Cao, Q., Zhang, K., Ata-Ul-Karim, S. T., Tian, Y., Zhu, Y., Cao, W., & Liu, X. (2016). Optimal leaf positions for SPAD meter measurement in rice. *Frontiers in Plant Science*, *7*, 719.

Zdunek, A., Konopacka, D., & Jesionkowska, K. (2010). Crispness and crunchiness judgment of apple based on contact acoustic emission. *Journal of Texture Studies*, *41*, 75–91.

Zhan, L., Hu, J., Ai, Z., Pang, L., Li, Y., & Zhu, M. (2013a). Light exposure during storage preserving soluble sugar and L-ascorbic acid content of minimally processed romaine lettuce (*Lactuca sativa* L.var. *longifolia*). *Food Chemistry*, *136*, 273–278.

Zhan, L., Hu, J., Li, Y., & Pang, L. (2012). Combination of light exposure and low temperature in preserving quality and extending shelf-life of fresh-cut broccoli (*Brassica oleracea* L.). *Postharvest Biology and Technology*, *72*, 76–81.

Zhan, L., Hu, J., Lim, L.-T., Pang, L., Li, Y., & Shao, J. (2013b). Light exposure inhibiting tissue browning and improving antioxidant capacity of fresh-cut celery (*Apium graveolens* var. *dulce*). *Food Chemistry*, *141*, 2473–2478.

Zhan, L., Hu, J., Pang, L., Li, Y., & Shao, J. (2014). Effect of light exposure on chlorophyll, sugars and vitamin C content of fresh-cut celery (*Apium graveolens* var. *dulce*) petioles. *International Journal of Food Science and Technology*, *49*, 347–353. Available from. Available from http://doi:10.1111/ijfs.12292.

Zhan, L., Li, J., Huang, W., Song, C., Li, J., Pang, L., & Li, Y. (2020). Light irradiation affects the total antioxidant capacity, total phenolic compounds, phenolic acids, and related enzyme activities of minimally processed spinach (*Spinacia oleracea* L.). *Journal of Food Processing and Preservation*, *44*(10), e14825.

Zhan, L., Li, Y., Hu, J., Pang, L., & Fan, H. (2012). Browning inhibition and quality preservation of fresh-cut romaine lettuce exposed to high intensity light. *Innovative Food Science and Emerging Technologies*, *14*, 70–76.

Zhan, L. J., Fontana, E., Tibaldi, G., & Nicola, S. (2009). Qualitative and physiological response of minimally processed garden cress (*Lepidium sativum* L.) to harvest handling and storage conditions. *Journal of Food, Agriculture and Environment*, *7*(3–4), 43–50.

Zhang, H., Baishao, Z., Fan, P., & Wei, L. (2020). Determination of soluble solids content in oranges using visible and near infrared full transmittance hyperspectral imaging with comparative analysis of models. *Postharvest Biology and Technology*, *163*, 111148.

Zhao, L., Fan, H., Zhang, M., Chitrakar, B., Bhandari, B., & Wang, B. (2019). Edible flowers: Review of flower processing and extraction of bioactive compounds by novel technologies. *Food Research International*, *126*, 108660.

Zude, M., Herold, B., Roger, J. M., Bellon-Maurel, V., & Landahl, S. (2006). Non-destructive tests on the prediction of apple fruit flesh firmness and soluble solids content on tree and in shelf life. *Journal of Food Engineering*, *77*, 254–260.

Zude-Sasse, M., Truppel, I., & Herold, B. (2002). An approach to non-destructive apple fruit chlorophyll determination. *Postharvest Biology and Technology*, *25*, 123–133.

CHAPTER

8

Multiomics approaches for the improvements of postharvest systems

Pietro Tonutti[1], *Claudio Bonghi*[2] *and Stefano Brizzolara*[1]

[1]Institute of Life Science, Scuola Superiore Sant'Anna, Pisa, Italy [2]Department of Agronomy, Food, Natural Resources, Animals and Environment (DAFNAE), University of Padova, Padua, Italy

Abbreviations

1-MCP	1-methylcyclopropene
2-DE	two-dimensional electrophoresis
2D-DIGE	two-dimensional difference gel electrophoresis
4CL	4-coumarate-CoA ligase
ABA	abscisic acid
BBD	Braeburn browning disorder
Bp	base pairs;
CA	controlled atmosphere
cDNA	complementary deoxyribonucleic acid
CHO	carbohydrate
CI	chilling injuries
CTols	conjugate triols
C4H	cinnamate-4-hydroxylase
DCA	dynamic controlled atmosphere
DCA-CF	dynamic controlled atmosphere monitored by chlorophyll fluorescence
DNA	deoxyribonucleic acid
DPA	diphenylamine
ERF	ethylene responsive factors
ESI	electrospray ionization
ESTs	expressed sequence tags
GC-MS	gas chromatography mass spectrometry
GR-RBP	glycine-rich RNA-binding protein
GS	"Granny Smith" apple cultivar
HSPs	heat shock protein
HS-SPME	Headspace Solid Phase Microextraction
HT	heat treatments

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00008-7

ILOS	initial low oxygen stress
KEGG	Kyoto encyclopaedia of genes and genomes
LC-MS	liquid chromatography mass spectrometry
LIT/LTQ	linear ion trap/linear trap quadrupole
LT	low temperature
MA	modified atmosphere
MALDI	matrix-assisted laser desorption ionization
MOI	multi-omics integration
MS	mass spectrometry
NAD^+	nicotinamide adenine dinucleotide
$NADP^+$	nicotinamide adenine dinucleotide phosphate
NMR	nuclear magnetic resonance
PAL	phenylalanine ammonia lyase
PPO	polyphenol oxidase
PR-4B	pathogenesis-related protein 4b
PTR-Tof-MS	proton transfer reaction - time of flight - mass spectrometer
QIT	quadrupole ion trap
qRT_PCR	Real-Time Quantitative Reverse Transcription PCR
RD	"Red Delicious" apple cultivar
RLOS	repeated low oxygen stress
RNA	ribonucleic acid
RNA-seq	ribonucleic acid sequencing,
ROS	reactive oxygen species
RQ	respiratory quotient
RT	room temperature
TFs	transcription factors
TOF	time of flight
UHPLC	ultra-high performance liquid chromatography
ULO	ultra low oxygen

8.1 Introduction

Postharvesters characterize quality of horticultural products using many descriptors. They measure attributes related, in general, to valued information on external or internal traits of the produce. Many variables influence decisions to buy (Kays & Paull, 2004). These include shape, size, and the absence of defects, diseases, and disorders. Socioeconomic issues play a role. For fruits, color or even aroma can dominate the decision. Consumers also evaluate quality in the light of flavor and texture as the product is consumed. Besides, there is today a growing emphasis on nutritional value and safety for human health (see also Chapter 19: Compositional Determinants of Fruit and Vegetable Quality and Nutritional Value, and Chapter 21: Measuring Consumer Acceptability of Fruits and Vegetables). Quality in fresh produce evolves as developmental processes interact with the environment. These processes respond to variations in gene expression, protein turnover, and metabolite concentrations.

In fruits, the transition from the immature to the mature stage is a crucial developmental step involving the acquisition of edible traits and organoleptic quality. The changes occurring during fruit ripening represent a wide spectrum of different genetically controlled biochemical processes (Seymour, Taylor, & Tucker, 1993; Seymour, Poole, Giovannoni, & Tucker, 2013). After harvest from the mother plant, ripening is strongly influenced by environmental factors that are also of paramount importance. Throughout the postharvest chain (from grower to consumer), environmental variables affect metabolism, shelf life, and taste of ripening fruits (or eating quality; see also Chapter 6: Challenges in Handling Fresh Fruits and Vegetables), as well as of other horticultural fresh produce represented by immature fruits, leaves, inflorescences, stems, tubers, and roots.

Environmental conditions shape both the internal and external phenotypes of harvested products. Postharvesters seek to characterize these effects. This helps them design postharvest systems that deliver high-quality products. Phenotypes are the results of the different level of expression of genetic information and regulatory mechanisms, also affected by external factors such as environment and management. Hence, understanding the genetic determinants and the metabolic processes and profiles that confer quality traits in fruits and other commodities is crucial for the optimization and the development of postharvest technologies. Delaying ripening and senescence, maintaining quality and, at the same time, avoiding the onset of physiological disorders and pathogen attacks are the main goals of postharvest technology, with benefits for all actors of the production and supply chains. These goals can be achieved through a strict integration and collaboration between biologists and technologists by combining applied and fundamental science, the latter exploiting and adopting technical tools and analytical protocols often developed in different research areas and/or model species.

8.2 Background and technologies

As the molecular mechanisms of phenotypes and the biological basis of quality are complex, the methods of analyzing genes and their products *en masse* offer a wider view of biological events and allow study of the network through which genes, proteins, and metabolites are related and communicate. The high-throughput techniques and new biotechnological approaches cover a broad field of disciplines such as chemistry, physics, biology, physiology, statistics, bioinformatics, and data science. Researchers construct complex data sets by exploiting different high-throughput biomolecular techniques such as transcriptomics, proteomics, and metabolomics, representing the frontiers of fundamental research in plant biology, including fruit science.

8.2.1 Transcriptomics

Transcriptomics approaches are used to investigate the transcriptome of an organism. The transcriptome can be assumed as the sum of all of the RNA transcripts produced by an organism. By using the transcriptomic technologies, it is possible to capture a snapshot in time of the total transcripts present in a cell.

The first important efforts at profiling plant transcriptomes started with the expressed sequence tags (ESTs), which are short nucleotide sequences (100–600 base pairs; bp) generated from complementary DNA (cDNA). Several thousands of ESTs have been produced for the most important species harboring fruits, and these allowed to depict the first transcriptome landscape during fruit ripening and postharvest (Alba et al., 2004).

Following the EST approach, another technique quickly became widely used for transcription profiling: the DNA microarray (or DNA chips). DNA chips are based on the concept of measuring the hybridization of the labeled target cDNA strands from sample with the fixed probes. Because of their high throughput and lower cost, microarrays were widely used starting in the early 2000s to improve our knowledge on fruit postharvest by comparing the transcriptome of fruit with opposite traits or different behavior [e.g., fruits with variable sensitivity to chilling injuries (CIs), fruits showing different responses to ethylene or ethylene inhibitors] (Alba et al., 2004).

However, the most important limitation in the use of DNA chips is the reduced accuracy of expression measurements for transcripts present in low abundance. Furthermore, a DNA array provides information only for those genes for which probes are designed and spotted on the chip. These limitations were overcome by the development of massive (high-throughput) sequencing techniques of transcriptome [RNA sequencing (RNA-seq)] and the transcriptome of different species bearing fleshy fruit has started to be investigated using this technique (Martin, Fei, Giovannoni, & Rose, 2013). About 40 million sequence reads from RNA-seq approaches can be assembled either using reference sequence (when available) or de novo. The latter case is applied in species in which is not available a reference genome, a common feature still shared by a number species bearing fleshy fruits undergoing more or less prolonged storage.

Genome-scale studies of gene expression patterns represent an appropriate strategy, particularly as a first step, given the cost−benefit ratio. However, reliance on this technique as the sole tool for describing the complexity of mechanisms responsible for the responses of perishable products to postharvest conditions has many limitations. Probably the most important of these is that changes in messenger RNA (mRNA) levels do not always correspond to changes in translation of cognate proteins (Ideker, Galitski, & Hood, 2001). To study quantitative and qualitative characteristics of global protein expression, including polypeptide synthesis, degradation, posttranslational modification, compartmentalization, and interactions with other cell components, proteomics approaches, or the study of the protein complement of the genome, allow to span the gap between genomic DNA sequence and the biological state (Shiratake & Suzuki, 2016).

8.2.2 Proteomics

To fill this gap, innovative or improved techniques have been developed and applied considering both proteomics and metabolomics (2.3). The proteomics approach is currently based on several analytical techniques such as in-gel proteolytic digestion of protein bands, high-resolution protein separation two-dimensional electrophoresis (2-DE), stable isotope labeling and mass spectrometry (MS) (Mathabe, Belay, Ndlovu, & Caleb, 2020). Proteomics focuses on the study of proteins expression level and their interactions with each other and with cellular components (e.g., deoxyribonucleic and ribonucleic acids) in biological samples. The most important functional information present at the genetic level can be approached and understood only through the study of the proteome since it includes all the dynamic processes, such as protein phosphorylation, trafficking, localization, and protein−protein interactions, which cannot be investigated studying only the genome (Chandramouli & Qian, 2009).

Moreover, one of the main advantages of proteomics is represented by the possibility of studying posttranslational modifications, which have a huge impact on protein function and regulation (Komatsu, Mock, Yang, & Svensson, 2013). Proteomic approaches are, in general, very challenging due to the interference of plant cell constituents with protein extraction, separation, and purification (Granier, 1988). Moreover, the recovering of high-quality proteins from fruit tissues is even more complicated given their low concentration and the presence of substrates that can denature and/or inactivate proteins.

Despite these critical aspects, protocols for proteomic investigation of fruit tissues have been established ensuring reliability and reproducibility (Chan, 2013). Different techniques may produce variable results, or different level of the same type of information. Indeed, different approaches are often used in combination to exceed the limitation of each specific technique and/or to get more complete and defined results.

As an example, 2-DE gels can be considered, in general, a very powerful tool. At the same time, the technique has limited capacity for analyzing highly hydrophobic and/or membrane proteins. It also shows limited sensitivity and repeatability, especially considering proteins at low concentrations. Moreover, in fruit tissue analysis, 2-DE gels protocols encounter technical problems due to the presence of compounds that can interfere with the analysis (e.g., pectins, phenolics, highly acidic molecules, and proteinases) (Barraclough, Obenland, Laing, & Carroll, 2004).

Considering other approaches, use of mass spectrometry (MS) is increasing in proteomics, mainly due to its ability to handle the high complexity of the proteome. MS provides sensitive, accurate, reliable, and rapid protein identification and quantification. As a consequence, with the increase of MS application for proteomics studies, the number of proteins that have been sequenced is also gradually rising. MS is particularly helpful to investigate protein expression, the interactions of proteins, and to detect sites of protein modification. The soft ionization techniques applied in proteomic studies via MS are electrospray ionization and matrix-assisted laser desorption/ionization (Fenn, Mann, Meng, Wong, & Whitehouse, 1990; Karas & Hillenkamp, 1988). On the other hand, four different kind of mass analyzers are normally employed in this field: (1) quadrupole; (2) quadrupole ion trap; (3) linear ion trap; (4) time-of-flight (TOF) (Scigelova, Hornshaw, Giannakopulos, & Makarov, 2011).

Since the ultimate goal of proteomics analysis is the identification (and quantification) of proteins, this result is largely dependent on the availability of an appropriate DNA sequence data set (Heazlewood & Millar, 2003). The increase in the available genomic resources is indeed facilitating and improving the use of proteomics in horticultural crop studies. In fact, in the last decades, gene expression and protein metabolism has been widely studied applying proteomics also in fruit postharvest storage (Agrawal et al., 2012; Feng, An, Zheng, Sun, & Wang, 2016; Marondedze, 2017; Pedreschi et al., 2013).

8.2.3 Metabolomics

Metabolomics differs from genomics, transcriptomics, and proteomics by focusing on metabolites. The link between genes and the functional phenotype is the final objective of all functional genomics investigations, and metabolomics has emerged as important tool to achieve this goal representing a fundamental analysis to unravel complex molecular interactions in biological systems (Bino et al., 2004; Hall et al., 2002; Obata & Fernie, 2012). The goal of plant metabolomics is to qualitatively and quantitatively investigate metabolites within samples (Withfield, German, & Noble, 2004).

Metabolites produced by a plant can be classified in different ways, but they are mainly of two types: primary metabolites derived from primary metabolism or secondary metabolites from secondary metabolism. It is estimated that about 100,000−200,000 different chemical molecules, mostly produced through secondary metabolism, characterize the plant metabolome (Dellapenna, 2001; Pickersky & Gang, 2000), that is responsible for most of the quality traits evaluated in fruits (Pott, Vallarino, & Osorio, 2020).

The complexity of plant composition, in general, and fruit matrixes, in particular, makes the simultaneous identification of all the constituents impossible (Lu et al., 2013; Rochfort, 2005). Several different technologies are applied to run metabolomics and, mainly due to the development of high-throughput analyses, the identification and quantification of a number of molecules playing a role in metabolome complexity are nowadays feasible, despite the fact that their functional role in the several cases still needs to be clarified (Kosmacz, Sokołowska, Bouzaa, & Skirycz, 2020; Shepherd, Fraser, & Stewart, 2011).

Among the different techniques, nuclear magnetic resonance (NMR) is gaining importance also in postharvest studies (Goulas et al., 2015; Yuan et al., 2017). NMR has some advantages, such as very quick and, often, noninvasive sample preparation together with the fact that this technique does not need compound separation before analysis. However, its sensitivity is low compared to MS techniques (Emwas et al., 2019). Moreover, the analysis of complex mixture, such as plant tissues, is very challenging due to the overlapping of NMR spectra from different compounds (Krishnan, Kruger, & Ratcliffe, 2005).

Another important tool for metabolomic investigations is MS, which can be coupled to different separation techniques. Gas chromatography coupled with MS (GC−MS) is commonly used to study both volatilome and metabolome and it is characterized by high capacity, excellent repeatability, and availability of reference compound libraries (Brizzolara, Hertog, Tosetti, Nicolai, & Tonutti, 2018; Mack et al., 2017; Putri, Yamamoto, Tsugawa, & Fukusaki, 2013). On the other hand, liquid chromatography coupled with MS (LC−MS) is typically used, also in postharvest studies, to measure a wide range of nonvolatile molecules (Vazquez-Hernandez, Navarro, Sanchez-Ballesta, Merodio, & Escribano, 2018).

In recent years, the development of ultrahigh-performance liquid chromatography has further improved speed of analysis and sensitivity, and MS innovations also greatly contributed to improve metabolomics tools efficacy. As an example, the application of tandem MS and ion traps further implemented the capability of analysis in terms of power of identification as well as sensitiveness and speed of analysis (Farcuh, Rivero, Sadka, & Blumwald, 2018; Maoz et al., 2019; Schulz et al., 2020; Xu et al., 2018).

The technologies used to run metabolomic approaches to investigate both primary and secondary metabolites are the same. Different equipment may be used, based upon the nature of the metabolites. As mentioned earlier, typically volatile and nonvolatile compounds are analyzed with different instruments (classically GC−MS and LC−MS, respectively) with diverse efficiency in detecting one or the other kind of molecules. Nevertheless, polar compounds with relatively low levels of volatility can be studied with instruments normally devoted to nonvolatile compounds (LC−MS, NMR). Vice versa nonvolatile molecules, with several precautions/pretreatment of the samples (e.g., derivatization), can be detected and quantified using gas chromatography, albeit with several limitations, the most important of which are the lower reliability, accuracy, and reproducibility of the results. Considering all these aspects, depending on the goal of the research, the best analytical protocol is based on the integration of a proper set of different instruments.

Many different metabolomics approaches can be applied based on the final goal of the researches. As an example, fingerprinting is applied to run "full" metabolome comparisons with no need to have an a priori knowledge of the identified compounds and so working in an untargeted metabolic environment. On the contrary, metabolite profiling considers the measurement of a set of specific metabolites in a given sample which are linked to/involved in specific pathways.

Specifically, targeted analysis can be directed to the detection and precise quantification of a single or small set of target compounds (Fiehn, 2002; Oms-Oliu, Odriozola-Serrano, & Martín-Belloso, 2013). Metabolomics analyses are increasingly used to assess quality (and safety) in the field of food production (Pott et al., 2020; Shepherd et al., 2011) including the effects of postharvest treatments on different fruit species (Brizzolara et al., 2018; Nilo et al., 2010; Oms-Oliu, Odriozola-Serrano, & Martin-Belloso, 2012) with promising applications in the field of early detection of storage-related disorders.

8.3 Multiomics approaches

The exponential availability of omics data required the development of user-friendly data analysis solutions for the integration of the results obtained from the different omics techniques for the identification of transcripts/proteins/metabolites hubs linked to important plant biological processes. In comparison to other organisms, this multiomics approach and the data integration is more difficult for plants due to their metabolic diversity and the presence of poorly annotated genomes for many species.

Amongst bioinformatics tools, specifically developed for plant, the most used, during the previous decade, was MapMan (Schwacke et al., 2019; Thimm et al., 2004) that displayed metabolite and transcript levels on predefined pathway bins. More recent is the development of Paintomics3 that allows the integrated visualization of transcriptomics and metabolomics data, generated by the same set of samples, on KEGG (Kyoto Encyclopedia of Genes and Genomes) pathway maps (Hernández-de-Diego et al., 2018).

A more systematic approach, named multiomics integration (MOI), has been proposed by Jamil et al. (2020) and for which three levels have been defined. The *first level* regards the integration of different omics data by a correlation, cluster, or multivariate analysis to point out possible correlations between level of transcripts and those of their cognate proteins or metabolites. Examples of software for integrating omics data are mixOmics (Rohart, Gautier, Singh, & Lê Cao, 2017) and Omicade4 (Meng, Kuster, Culhane, & Ghlami, 2014). Often the correlation analysis between transcripts and cognate proteins is weak due to posttranscriptional and posttranslation modifications for the majority of components of fruit ripening processes (Mata et al., 2018). However, proteins databases deduced from transcriptome can be useful for protein identification in proteomics.

The *second level* allows, throughout the pathway-based integration, the understanding of relation between omics data and their biological significance. For this goal can be retrieved metabolic pathways from different sources such as KEGG (https://www.genome.jp/kegg/), or more organism-specific databases such as AraCyc for Arabidopsis (https://www.arabidopsis.org/biocyc/), CitrusCyc for citrus (https://www.citrusgenomedb.org/node/1136703), and SolCyc for Solanaceae species (https://solgenomics.net/tools/solcyc/index.pl) (Foerster et al., 2018).

Omics data can be integrated in metabolic pathway by using Mapman3 (Schwacke et al., 2019) and similar software tools. Coexpression analysis of different omics data, determined in the first level of MOI, can be transformed into a weighted network visualized by Cytoscape tool (Savoi et al., 2016; Savoi et al., 2017) or similar software. This strategy allows the identification of important hub or modules for biological insights about specific pathways.

At the end, the *third level* is the mathematical-based approach. The goal of this level is the development of a well-defined differential equation and modeling for a system level understanding (Jamil et al., 2020). Main steps of this analysis have been defined by Voit (2017). Example of the application of this strategy is reported by Belouah et al. (2019) who developed an equation, by using the "glmnet" package (Friedman, Hastie, & Tibshirani, 2010) under the "R" environment (R Core Team, 2018), able to predict for transcript-protein pairs if the protein level is due to translation rate or degradation. In this case the development of functional mathematical model is obtained starting from experimental results, in alternative another way, based on opposite view, can be taken. In fact this second way, called genome-scale modeling (GSM), aims to build a model first from extensive curation before the experimental validation. This GSM approach can be carried out by constraint-based reconstruction and analysis and consists of following steps: reconstruction of metabolic pathways at genome layer by integrating annotated genome, pathway refinement based on experimental data and network modeling in mathematical format. Software developed for these purposes are PlantSEED that facilitates multiscale analysis for studying complex processes varying from single cells to multiple tissues up to a whole plant (Dal'Molin & Nielsen, 2017).

A comprehensive list of the most widely used sources, software tools, and web applications is reported in Table 8.1.

8.4 Fruit storage and multiomics approaches

After the earliest studies based on the use of single platforms, in the last few years, an increasing number of integrated omics approaches have been carried out in the postharvest field, with the goal of unraveling the complex and dynamic responses of horticultural produce to imposed postharvest stresses. In addition to identify processes affected by the storage conditions, these studies contributed to better understanding the regulatory mechanisms responsible for the physiological responses that play a central role in the transition from genotype to phenotype. These studies might also result in the identification of biochemical and molecular markers to be used for the optimization of the postharvest protocols to maintain quality and reduce the incidence and/or prevent the onset of storage-related disorders.

8.4.1 Impact of postharvest low temperature (LT) or heat treatment (HT) on fruit metabolism

Lowering temperature is the key factor for a successful postharvest management of horticultural produce as a result of a general decrease of metabolic activity, starting from

TABLE 8.1 Summary of software tools and web applications for MOI in plant system (modified from Jamil et al., 2020).

MOI level	Software	Supported Omics platforms	Functionality	Website	Metabolic Pathway sources website	References
1	mixOmics	Transcriptomic, Proteomics Metabolomics	Data Integration	http://www.mixOmics.org		Rohart et al. (2017)
	Omicade4	Transcriptomic, Proteomics Metabolomics	Analyze co-relationship between data sets	http://bioconductor.org/packages/release/bioc/html/omicade4.html		
2	Mapman4	Transcriptomic, Proteomics Metabolomic	Enrichment analysis Visualization of data expression	https://mapman.gabipd.org	KEGG https://www.genome.jp/kegg AraCyc (https://www.arabidopsis.org/biocyc/) CitrusCyc (https://www.citrusgenomedb.org/node/1136703) SolCyc (https://solgenomics.net/tools/solcyc/index.pl)	Thimm et al. (2004), Schwacke et al. (2019)
	Cytoscape	Transcriptomic, Proteomics Metabolomic	Visualization of the molecular interaction networks and biological pathways and integrating these networks with annotations, gene expression profiles	https://cytoscape.org		Savoi et al. (2016, 2017)
	Paintomics3	Transcriptomic, Proteomics Metabolomic	Data integration and visualization Pathway analysis and interaction	http://www.paintomics.org		Hernaández-de-Diego et al. (2018)
3	glmnet	Proteomics	Equation linear model	https://cran.r-project.org/web/packages/glmnet/index.htm		
	COBRA (Constraint-based reconstruction and analysis)	Transcriptomic, Proteomics Metabolomic	Genome-scale modeling	https://opencobra.github.io/cobratoolbox		Orth et al. (2010)
	Plantseed	Genomics Transcriptomics Metabolomics	Metabolic reconstruction	https://modelseed.org/		Seaver et al. (2018)

respiration, as clearly reported since the earliest studies carried out in particular on climacteric fruits. However, the appearance of cold-related physiological disorders is often a major constraint in prolonged cold storage.

Fruit of many species, in particular from subtropical and tropical areas, may undergo CI showing symptoms as irregular ripening, pitting, discoloration, necrotic areas, woolly, and dry flesh. Despite the wide application of cold storage to prolong shelf/commercial life of perishable fruits, only few integrated omics studies have been carried out so far to identify the overall changes occurring in primary and secondary metabolism processes affected by decreasing temperature storage. In fact most of the efforts and the information available concern the comparison between sound and injured fruits with CI symptoms.

Both primary and secondary metabolisms are affected by low-temperature (LT) storage (Brizzolara, Manganaris, Fotopoulos, Watkins, & Tonutti, 2020; Madani, Mirshekari, & Imahori, 2019). A transcriptomic and metabolomic study in oranges revealed that the limited changes in sugar concentration detected in fruit stored at 5°C for 90 days reflect the stable expression of genes associated with sugar metabolism, differently from what observed at room temperature (RT) where processes such as glycolysis, gluconeogenesis, fermentation were induced (Tang, Deng, Hu, Chen, & Li, 2016). RT storage induces calcium, abscisic acid (ABA), and ethylene signals, resulting in the acceleration of primary metabolism and fruit quality deterioration, while LT storage is related to auxin signaling that delays senescence.

Other studies on citrus fruits (Satsuma mandarin, Ponkan mandarin, sweet orange, and Shatian pomelo) carried out by means of network-based approaches of “omics” data mining and modeling (Ding et al., 2015) reported that the postharvest senescence behavior of the different genotypes resulted to be function of the degree of tightness of the flesh-rind anatomic structure. Citrus fruits with tight-skin (orange and pomelo) are characterized by longer storage life than loose-skin fruits (Satsuma and Ponkan).

In another nonclimacteric subtropical fruit (litchi), the rapid senescence and the pericarp browning observed in fruit after cold storage were associated, by both gene expression and metabolic profiling, with the oxidative process of lipids, polyphenols, and anthocyanins initiated by ABA (Yun et al., 2016). The respiratory burst was largely associated with increased production of reactive oxygen species (ROS), upregulated peroxidase activity and initiation of the lipoxygenase (LOX) pathway. In this fruit the energy status and the polyphenol metabolism have been identified as potential indicators to mark the postharvest browning process (Tang, Gallusci, & Lang, 2020).

Among the different secondary metabolism processes, the phenylpropanoid pathway appears to be one of the most sensitive to LT conditions as observed in a multiomics study carried out in grapes. Changes in the levels of levels of L-phenylalanine and the upregulation of phenylalanine ammonia lyase, as well as of cinnamate-4-hydroxylase and 4-coumarate-CoA ligase, involved in the earliest steps of the phenylpropanoid pathways, have been reported in table grape berries stored for 6 weeks at 0°C (Maoz et al., 2019). The cold-induced upregulation of stilbene synthases genes and the higher levels of viniferins demonstrated that this branch of phenylpropanoid pathway is highly sensitive to LT conditions: this behavior seems to be highly regulated by the specific involvement of cold-induced transcription factors (TFs), such as VvMYB14, which regulates stilbene biosynthesis. Interestingly, the modulation of phenylpropanoid metabolism is also a key physiological response of grapes to partial postharvest dehydration process.

The effect of this kind of stress—purposely applied for the production of special wines (Mencarelli & Tonutti, 2013)—has been analyzed by an exhaustive survey of transcriptomic and metabolomic responses of six grapevine genotypes (Zenoni et al., 2016). Although a distinct metabolic plasticity of genotypes was observed in relation to the phenylpropanoid/stilbene pathways, a core set of genes was consistently modulated in all genotypes, representing the common features of berries undergoing dehydration and/or commencing senescence. Ethylene and auxin metabolism as well as genes involved in oxidative and osmotic stress, defense responses, anaerobic respiration, and cell wall and carbohydrate metabolism were the common features in the different grape genotypes.

8.4.1.1 Chilling injury

As earlier reported, one of the major problems in LT storage is represented by the development and appearance of CI symptoms. Several integrated omics studies carried out on different fruit species have been published with the aim of elucidating the complex mechanisms and the metabolic changes responsible for the physiological alterations induced by the cold stress.

8.4.1.1.1 Peaches

One of the earliest and most studied species in which integrated "omics" technologies have been applied for this purpose is peach. After specific LT (the so-called killing zone ranging from 2.2°C to 7.6°C) storage, peaches develop physiological disorders such as internal browning and mealiness/woolliness (Lurie & Crisosto, 2005; Ramina, Tonutti, & McGlasson, 2008).

CI symptoms typically evolve during poststorage/shelf life conditions and can also compromise the fruit capability to ripen after storage, resulting in quality levels not compatible with marketability. Since the appearance of the earliest high-throughput tools, a common goal was that of identifying genes and metabolites associated with the onset of peach CIs, possibly before the appearance of the specific symptoms.

In the earliest steps of the functional genomics era, customized microarrays have been developed to investigate molecular mechanism responsible for this physiological disorder. Pons et al. (2005), using a subset of the Spanish Citrus EST repertoire (Gonzàlez-Candelas et al., 2005), printed a cDNA microarray to highlight changes in gene expression associated to CI of Fortune mandarin. They discovered that a group of fruit-specific genes is activated in response to cold and different storage pretreatments, thus allowing the use of this gene set as a molecular tool for identifying the best storage practices and helping in the selection of new cold-resistant cultivars.

The same approach was used to investigate molecular mechanism underlying tolerance to CI in peach (Granell et al., 2007). For this goal, a cDNA microarray, named CHILLPEACH, has been developed selecting targets from a database (ChillpeachDB) containing 8144 cDNA sequences obtained from mesocarp of sensitive and tolerant peaches. Microarray slides containing 4261 ChillPeach unigenes were printed and used in a pilot experiment to identify differentially expressed genes in cold-treated compared to control mesocarp tissues and in vegetative compared to mesocarp tissues (Ogundiwin et al., 2008).

Besides confirming the importance of cell-wall genes, this transcriptomic study pointed out that changes in endomembrane trafficking might also play a role in the appearance of CIs in peaches and nectarines. Cold-induced woolliness appears to be related to an upregulation of genes linked to the oxidative stress response, suggesting changes in redox status (Pavez, Hödar, Olivares, González, & Cambiazo, 2013). In addition, the upregulation of stress response genes in woolly fruit accompanied by downregulation of key components of metabolic pathways that are active during peach ripening indicating the presence of an abnormal ripening process.

Other candidate genes for CI tolerance have been identified by Falara et al. (2011) using the μPEACH 1.0 platform, the first microarray developed for studying peach (and other stone fruits) development and ripening (Manganaris et al., 2010; Manganaris et al., 2011; Trainotti et al., 2006). The transcriptome profiles of peach fruit from "Morettini No. 2" and "Royal Glory," two peach cultivars showing sensitivity and tolerance to CI, respectively, were compared. Genes encoding cell wall-modifying proteins (β-D-xylosidase and expansin) and stress proteins heat shock proteins (HSPs), dehydrin, and pathogeneis-related protein 4B (PR-4B) were found highly expressed at ripening without storage and after storage in the CI-resistant cultivar (Falara et al., 2011).

The same genes were also identified when, using both ChillPeach and μPEACH 1.0 platforms, the transcriptomes of a peach and its near-isogenic nectarine mutant showing high and low susceptibility to CI, respectively, were compared (Dagar et al., 2013). Interestingly, genes encoding a dehydrin, an HSP and cell-wall enzymes appeared to be expressed at higher level in the nectarine fruit already at harvest.

In parallel with the transcriptomics studies, specific proteomics analyses have been performed to study CIs in stored peaches. An early proteomic approach with two-dimensional difference gel electrophoresis has been used to compare healthy and chill injured peaches allowed to identify 43 spots representing proteins that significantly change after cold storage and the subsequent ripening that leads to the development of CI (Nilo et al., 2010). Among the differently accumulating proteins, endopolygalacturonase, catalase, NADP-dependent isocitrate dehydrogenase, pectin methylesterase, and dehydrins were identified and, based on gene ontology (GO) annotation, biological processes such as response to stress, cellular homeostasis, and metabolism of carbohydrates and amino acids were the categories more affected during the cold storage period.

A role of thaumatin proteins in protecting LT stored peaches against CI has been reported by Dagar, Friedman, and Lurie (2010) based on the results of a cell-wall proteomics approach. Altered cell-wall metabolism and composition, recognized to be strictly associated with woolliness since the earliest studies performed on CIs in peaches, has been confirmed, together with the involvement of ethylene signaling and polyphenol metabolism, in specific studies combining transcriptomics and metabolomics (Wang et al., 2017).

The lipid composition and the level of desaturation, which may modulate membrane stability, have been recognized to contribute to the alleviation of peach fruit to CI. Brizzolara et al. (2018) and Bustamante et al. (2018) showed that changes in the abundance of lipid classes (phosphatidylethanolamine, phosphatidylcholine, and digalactosyldiacylglycerol) and differential expression of genes involved in galactolipid metabolism are correlated with the tolerance to CI and the different incidence of CIs. Indeed, a specific modulation of aldehyde metabolism (LOX pathway) after cold storage also in relation to CIs onset has been reported by Brizzolara et al. (2018) in three different peach cultivars. These findings open interesting perspective for the identification of reliable lipid markers for chilling resistance. In addition to lipids, amino acids [Ala, Asn, Gly, Glu, Ile, Ser, Thr, Pro, Val, γ-aminobutyric acid (GABA)] and sugars (fructose 1, 1-fructose-6 phosphate, raffinose) have been identified by metabolomics analyses as compounds showing significant difference in peach genotypes reporting variable incidence and susceptibility to CIs (Brizzolara et al., 2018; Bustamante et al., 2018; Lillo-Carmona et al., 2020; Monti et al., 2019).

The coordinated metabolomic and proteomic profiling carried out by Monti et al. (2019) reported a marked proteome reconfiguration when comparing juicy with woolly fruit, with different levels of proteins involved in sugar catabolism, amino acid usage, ROS detoxification, all processes now recognized, as result of the new integrated "omics" approaches, together with cell wall and lipid metabolism, as relevant signature of CI development in peach fruit.

8.4.1.1.2 Apples and pears

Prolonged cold storage may induce, in apples and pears, the appearance of superficial and soft scald. Superficial scald, considered to be a type of CI induced by oxidative stress, develops during cold storage and intensifies after removal to market temperatures (Whitaker, 2013). Symptoms are brown or black patches on the fruit skin, but the biochemistry that leads to its development are not completely understood. Studies on scald etiology have focused almost exclusively on the involvement of α-farnesene and its oxidation, and little attention has been given to alternative options (reviewed by Lurie & Watkins, 2012).

Several evidences associate conjugate triols (CTols), compounds related to α-farnesene metabolism, to scald development and a model based on CTols accumulation dynamics during early stages of storage (<50 days) has been recently proposed to predict scald occurrence in Granny Smith (GS) apples (Bordonaba et al., 2013). Studies on the apple peel metabolome in fruit treated with chemicals (such as the ethylene antagonist 1-methylcyclopropene, 1-MCP, and the antioxidant diphenylamine, the latter not allowed to be used anymore in EU countries) to reduce or control the incidence of superficial scald are providing novel information on metabolic changes occurring in presymptomatic and symptomatic fruit.

In an early untargeted metabolic profiling study, Rudell, Mattheis, and Hertog (2009) reported that in cold-stored GS apples, besides the α-farnesene oxidation products (conjugated trienols, 6-methyl-5-hepten-2-one, and 6-methyl-5-hepten-2-ol, 6M5H21), a large group of putative triterpenoids with mass spectral features similar to those of ursolic acid and β-sitosterol are associated with presymptomatic as well as scalded fruit. In addition to the isoprenoids (squalene, tocopherols), a strict association between scald development and individual metabolites from the phenylpropanoid, and a coregulation within the volatile synthesis pathways producing methyl, propyl, ethyl, acetyl, and butyl alcohol and/or acid moieties for ester biosynthesis have also been observed in GS apples affected by superficial scald (Leisso, Buchanan, Lee, Mattheis, & Rudell, 2013; Rudell & Mattheis, 2009; Rudell, Mattheis, & Curry, 2008).

After a preliminary integrated quantitative real time-polymerase chain reaction qRT-PCR coupled with PTR−TOF−MS) study on the etiology of superficial scald (Busatto et al., 2014), Gapper et al. (2017) and Busatto et al. (2018) reported marked changes in the metabolome and transcriptome in apple fruit starting to develop specific symptoms. In particular, metabolic and transcriptomic shifts, representing multiple pathways and processes, occurred at the early stages together with α-farnesene oxidation and, later, when symptoms develop, methanol and methyl ester production accompanied by an upregulation of pectin methylesterases. These studies suggest that α-farnesene and its conjugated trienols (in particular 6M5H21) are more involved in the signaling system, rather than being the cause of superficial scald.

By comparing the metabolic and transcriptomic of cold-stored pears, Giné-Bordonaba et al. (2020) demonstrated that in fruit not developing superficial scald symptoms (treated with 1-MCP) a sort of a cold-acclimation-resistance mechanism, including the biosynthesis of very-long-chain fatty acids was present, together with a downregulation of polyphenol oxidase (PPO) gene expression, combined with higher sorbitol content. System-based approaches have been developed by Karagiannis et al. (2020) with the attempt of providing a global view of the gene−protein−metabolite interactome underlying scald prevention/sensitivity.

Differentially accumulated proteins involved in oxidative stress and protein trafficking were differentially accumulated prior to and during scald development. In addition to genes involved in photosynthesis, flavonoid biosynthesis, and ethylene signaling, analysis of regulatory module networks identified putative TFs that could be involved in scald. A transcriptional network of the genes−proteins−metabolites and the connected TFs has been finally proposed.

Soft scald is another physiological disorder affecting cold-stored apples, resulting in a browning of the flesh and the skin, and characterized by a sharp line of demarcation between the diseased and the healthy tissue. An untargeted metabolic profiling performed on cold-stored "Honeycrisp" apples revealed changes in several metabolites linked with the soft scald symptom development: these include GABA, 1-hexanol, acylated steryl glycosides, and free p-coumaryl acyl esters (Leisso et al., 2016). This approach was paralleled by RNA-seq analysis that showed a higher expression of genes involved in isoprenoid/brassinosteroid metabolism in fruit that did not develop soft scald. Affected fruit were characterized by an elevated expression of genes involved in lipid peroxidation, phenolic metabolism, as well as chlorophyll catabolism, cell-wall loosening, and lipid transport (Leisso et al., 2016).

8.4.1.1.3 Other fruit crops

Besides peaches and pome fruits, other fruit crops (both temperate and tropical/subtropical) are under investigation by means of integrated "omics" approaches to analyze their behavior under LT conditions. By coupling transcriptomics with proteomics analyses, based on digital gene expression and 2D electrophoresis, Yun et al. (2012) reported that, in *Citrus* (*Citrus grandis* × *Citrus paradisi*) fruit, long-lasting LT storage upregulates stress-responsive genes, arrests signal transduction and induces the accumulation of cold-related 15 (COR15) HSP. Under these stress conditions, fruit quality seems to be regulated by sugar-mediated auxin and abscisic acid signaling.

Similar results have been provided for pomegranate fruit, in which resistance to CI is accompanied by an upregulation of genes encoding for heat-shock proteins together with those responsible for jasmonic acid and ethylene hormone biosynthesis and their signaling pathway (Kashash, Doron-Faigenboim, Doron Holland, & Porat, 2019a, 2019b). A possible protective role played by small HSPs and glycine-rich RNA-binding protein (GR-RBP) has been postulated in cold-stored (4°C−5°C for about 20 days) tomato fruit. These conditions may induce the appearance of CI (rubbery texture, irregular ripening) and this is associated with changes in the pool of proteins including HSPs and GR-RBP (Page et al., 2010; Vega-Garcia et al., 2010).

8.4.1.2 Heat treatment

Related to temperature management, postharvest heat treatments (HT) have originally been proposed to control fungal diseases and pest infestation of horticultural crops, but they can also be used to inhibit the ripening process, induce resistance to CI during storage and, as physical elicitors, to modify the content of phytochemical and antioxidant properties (Valero & Serrano, 2010). In general, heat is applied as prestorage treatment before cold storage by using hot water, hot air, or vapor heat: all these treatments may induce marked changes in the physiology of the produce.

Based on a parallel expression analysis of a set of genes in LT- and heat-treated fruits, it is postulated that HT may induce a stress response effective to acclimate peaches to the following cold storage. This hypothesis is also supported by analyses of the peach fruit proteome showing that the heat-induced CI tolerance may be acquired by the induction of related stress proteins such as heat-shock proteins, cysteine proteases, and dehydrin and the repression of PPO (Lara et al., 2009).

Similar results have been obtained in postharvest heat-treated Satsuma mandarin (Yun et al., 2013) and tomato (Cruz-Mendívil et al., 2015) fruits by means of a comparative proteomic and metabolomic profiling. Resistance associated proteins such as beta-1,3-glucanase, Class III chitinase, 17.7-kDa HSP and low-molecular-weight HSP were upregulated in heat-treated pericarp, whereas redox metabolism enzymes (including isoflavone reductase, oxidoreductase, and superoxide dismutase) were downregulated.

Flavonoids were among the different metabolites that increased in heat-treated pericarp, suggesting that ROS and lignin play important roles in inducing resistance to postharvest pathogens and physiological disorders. On the contrary, a negative role of enzymes involved in oxidation−reduction potential and lignin biosynthesis has been claimed in the strawberry discoloration during postharvest at high temperature (Zhang et al., 2019). The negative impact of high temperature in peel coloration has been observed also in bananas that remained at stay-green ripening stage as result of HT influence on proteins/genes related to chlorophyll metabolism, fruit firmness, signal transduction, energy metabolism, and stress response and defense (Li, Wu, Duan, Yun, & Jiang, 2019).

8.4.2 The effects of controlled atmospheres

Changes in the atmosphere composition, in particular concerning oxygen (decreased) and carbon dioxide (increased) concentrations, are the fundamentals of the controlled atmosphere (CA) (and modified atmosphere) technologies used for the storage, transportation, and packaging of several types of horticultural produce. These environmental conditions have a marked effect on the product physiology, starting from altered primary metabolism and respiratory pathways, and involve changes in gene expression, protein accumulation, and metabolite concentrations (Cukrov, Brizzolara, & Tonutti, 2019; Kanellis, Tonutti, & Perata, 2009).

8.4.2.1 Controlled atmosphere technologies and stress monitoring

Generally speaking, CA conditions may result in beneficial effects (delayed ripening and senescence, prolonged commercial life, in some cases reduced susceptibility to CI) but can also have detrimental effects such as the development of physiological disorders such as internal browning in apples and pears, irregular ripening in commodities such as banana, mango, tomato, development of off flavors. It is evident that the effects on a specific genotype of changes in atmosphere compositions are mainly (although not exclusively) the result of the interaction of two parameters: duration of the treatment and O_2/CO_2 concentrations.

If we look at the evolution of the CA technology since its early practical applications for apple storage, one trend is evident: a steady decrease of oxygen and increase of CO_2 concentrations used in the storage rooms. The standard technology, based on an oxygen concentration of about 2−3 kPa, has, in the last 15 years, markedly changed and innovations are represented by CA-based methods characterized in particular by a reduction of O_2 levels. One example is represented by the ultralow-oxygen (ULO) technology where O_2 is maintained near 1 kPa, and initial low O_2 stress in which O_2 levels are maintained as low as 0.25−0.7 kPa for short-time periods after harvest. A further step, thanks to the advances in technology that allow sensing of fruit responses to stress hypoxic stress conditions, is represented by the dynamic CA (DCA). With this technology, fruit are kept at much lower O_2 concentrations than the “safe”—although not optimal—levels, but this concentration is promptly adjusted in relation to the fruit metabolic responses.

The main parameters used to monitor the metabolic responses and the stress level reached by the commodity are based on the measurement of ethanol production, the chlorophyll fluorescence, the respiratory quotient (Bessemans, Verboven, Verlinden, & Nicolaï, 2016; Prange, DeLong, Leyte, & Harrison, 2002; Prange, DeLong, Harrison, Leyte, & McLean, 2003; Schouten, Prange, Verschoor, Lammers, & Oosterhaven, 1997).

If for apple (and a few other crops) storage a constant decrease in oxygen concentration has been observed throughout the last recent decades, successful storage protocols for other fruit species are based on high (> 10 kPa) CO_2 concentrations. This is the case of cherries, blueberries, raspberry, and strawberry. Omics approaches are now helping us to unravel the molecular basis of the responses to such conditions and stress experience, better identify genotypes less susceptible to develop physiological disorders/off flavors, and optimize storage protocols.

8.4.2.2 High CO_2 concentrations

Pioneering transcriptomics works to study the effects of high CO_2 were carried out using microarrays in nonclimacteric fruit such as strawberries (Ponce-Valadez, Moore Fellman, Giovannoni, Gan, & Watkins, 2009) and grape berries (Becatti et al., 2010). In the latter study the functional categorization and gene enrichment analyses pointed out that in the berry skin, highly represented categories were fermentation, carbohydrate metabolism, and redox regulation, while the categories related to protein, stress, transcript, RNA, and hormone (ethylene, ABA) metabolism were highly represented in both skin and flesh tissues. High CO_2 treatment applied to table grapes resulted to be efficient in maintaining quality and this seems to be an active process requiring the activation of Transcription Factors (TFs), as well as protein kinases implicated in the regulation of protein function, as pointed out by Rosales et al. (2016) that performed a comparative large-scale transcriptional analysis using the custom-made GrapeGen GeneChip.

High CO_2 concentrations (coupled with low oxygen levels) may induce, in pear fruit, the appearance of a physiological disorder called core browning that is characterized by the development of brown spots and, eventually, cavities in the center of the fruit. The combination of different factors (including precooling period and harvest time) plays a key role in core breakdown development during CA storage. Early proteomics approaches on pears stored under 10% CO_2 to induce the appearance of this physiological disorder showed that the appearance of the specific symptoms is related to an unbalance of proteins involved in antioxidant system and ethylene biosynthesis (Pedreschi et al., 2007).

Upregulated characteristic proteins in brown tissue were mainly involved in energy metabolism and defense mechanisms. Using GC−ESI−TOF−MS, Pedreschi et al. (2009) showed that pear brown tissue was characterized by a decrease of malic acid and an increase in fumaric acid and GABA, which would indicate altered Krebs cycle and GABA shunt pathway, and an increased gluconic acid concentration. According to these authors, GABA and gluconic acid can be considered as metabolic markers for core breakdown.

Also, apples may develop internal browning during hypoxic cold storage under elevated levels of CO_2. An untargeted metabolic profiling (using GC−MS and LC−MS) revealed that flesh browning in Braeburn apples (Braeburn browning disorder; BBD) is associated with increases in the concentration of acetaldehyde, ethanol, and ethyl esters, together with several amino acids (Lee, Mattheis, & Rudell, 2012). The levels of metabolites in Braeburn apples kept under optimal CA and brown inducing CA conditions were also studied in one of pioneering approaches using the NMR technique in postharvest (Vandendriessche et al., 2013). The different storage conditions did result in significant changes in metabolite levels and differences in terms of pyruvate, citrate, fumarate, alanine, chlorogenate, methanol, ethanol, acetaldehyde, and acetone concentrations between brown and unaffected apples stored under the applied CA conditions were observed. In one of the earliest studies using RNA-seq technique in postharvest studies, Mellidou et al. (2014) reported that the BBD onset is related to the expression in the inner cortex of genes involved in lipid metabolism, secondary metabolism, and cell-wall modifications, while energy-related and stress-related genes were mostly altered in the outer cortex.

Recently, a combined transcriptomic and metabolomic approach has been used to dissect the impact of 30% CO_2 storage atmosphere on strawberries. The expression of genes encoding cell wall-degrading enzymes was downregulated in response to high CO_2, with polyuronide (insoluble pectin) content in cell walls significantly higher in treated fruit. This expression decrease resulted in the slowdown of middle lamella disintegration and the maintenance of flesh firmness (Bang, Lim, Yi, Lee, & Lee, 2019). In addition, glucose, quinic acid, and succinic acid increased in responses to the CO_2 treatment as well as the expression of heat-shock proteins already detected after 24 h of incubation.

8.4.2.3 Low oxygen

Despite the diffusion of CA storage facilities in apple (and, partially, pear) producing areas and the increasing trend of new plants equipped with DCA technology, only in the recent years, basic information started to be available concerning the changes of transcriptome and metabolome profiling of apple fruit under hypoxic conditions. The different behavior of apple and pear genotypes to the imposed CA conditions and the variable responses to the same cv to the different CA protocols represent important aspects to be considered when planning storage protocols.

Brizzolara et al. (2017) compared behavior of "GS" and "Red Delicious" (RD) apples stored in two low-oxygen protocols (ULO at 0.9 kPa oxygen, and DCA with oxygen level ranging between 0.2 and 0.55 kPa) for about 7 months. Of the 130 metabolites identified, 117 were in common, whereas 13 volatile compounds, identified via an integrated approach (^{1}H NMR, GC–MS, HS-SPME ME-GC–MS analyses), were specific for either GS (e.g., ethyl esters) or RD (2-methylbutyl derivatives).

Analyzing the accumulation pattern of pyruvate-derived metabolites (ethanol, acetaldehyde, lactate, alanine), these authors hypothesized that there are two main metabolic reconfiguration strategies in GS and RD to regenerate NAD^+ and cope with energy crisis under hypoxia. The different behavior of the same apple cv to different CA protocols such as ULO, DCA monitored by chlorophyll fluorescence, repeated low-oxygen stress, and 1-MCP in ULO has been pointed out by Ciesa et al. (2013) who discriminated the four storage conditions applied to "RD" apples according to the PTR fingerprint mass spectra, considering in particular esters and terpenes.

An integrated study, combining RNA-seq and NMR analyses, has been carried out by Cukrov et al. (2016) on "GS" apples stored under an experimental protocol simulating the DCA conditions, with oxygen levels ranging between 0.4 and 0.8 kPa and applied for 60 days. The products of the pyruvate catabolism (alanine and ethanol) were identified as the major metabolites induced by hypoxic conditions. The upregulation of alcohol dehydrogenase, lactate dehydrogenase, pyruvate decarboxylase, alanine aminotransferase gene expression was detected under both hypoxic conditions with a more pronounced effect induced by the lowest (0.4 kPa) oxygen concentration. RNA-seq data indicated that the apparently slight difference in oxygen concentration was effective in selectively regulating the expression of more than 1000 genes. These genes are involved in cell wall, minor and major CHO, amino acid and secondary metabolisms, as well as in fermentation and glycolysis, transport, defense responses, and oxidation–reduction.

In addition, a number of TFs (belonging to AUX/IAA, WRKY, HB, Zinc-finger MADSbox gene families) resulted differentially expressed in relation to the applied oxygen level. Other genes involved in phenylpropanoid and isoprenoid pathways appear to be differentially expressed, thus representing potential candidates as molecular markers to monitor the metabolic responses of apples under hypoxia.

The different expression of specific ethylene responsive factors (ERFs) and the selective accumulation of specific ERF protein belonging to the group VII (RAP2.12), that have been shown to be involved in low-oxygen signaling in plants through the N-end rule pathway (Gibbs, Lee, Isa, Gramuglia, & Fukao, 2011; Licausi et al., 2011), would indicate that in apple fruit, the oxygen sensing mechanisms are similar to those detected in model species (*Arabidopsis*) (Cukrov et al., 2016).

The high sensitivity of apple tissues to low-oxygen conditions has been demonstrated by Brizzolara et al. (2019) by means of metabolomics and transcriptomics analyses of "GS" cortex sampled immediately after a partial reoxygenation (from 0.4 to 0.8 kPa oxygen), as in the case of DCA protocols. The oxygen shift induced a rapid downregulation of fermentative metabolism, of the GABA shunt, and the free phenylpropanoid pathway genes together with decreases of specific amino acids (valine, methionine, glycine, phenylalanine, and GABA), organic acids (arachidic and citric acids), and secondary metabolites (catechin and epicatechin). The partial reoxygenation induced, on the other hand, increases of glyceric, palmitic, and stearic acids and of several phosphatidylcholines and phosphatidylethanolamines.

8.5 Final remarks and future perspectives

Quality attributes in ripening fruit evolve as the result of modulation of gene expression, protein accumulation and enzyme activity, changes in physicochemical properties, and metabolite concentrations. These events are genetically programmed. At the same time, environmental conditions (on- and off-plant) have profound effects on their evolution. Considering the postharvest phase, this results in a diversity of responses in relation to the application of specific storage protocols, where different treatments are applied, and the genetic background of species and cultivar response.

A better understanding of the effects of the postharvest protocols applied to specific crops/genotypes is now facilitated by the availability of large data sets with genomic, proteomic, and metabolomic information related to fruit physiological and biophysical parameters of single crops. With the tremendous advancements in bioinformatics, we already entered the so-called post genomics era. Indeed, the challenge now is the integration of multiomics data set to produce a complete but understandable picture of cellular processes and pathways involved in the fruit responses to postharvest conditions. The expected implementation and development of these approaches will help to tailor and optimize the storage protocols, in particular those based on extreme conditions (LT, hypoxia). These postharvest techniques are known to be, on one hand, beneficial in terms of maintaining specific quality attributes (e.g., firmness) but, on the other hand, risky in terms of the appearance of physiological disorders. The availability of molecular and/or metabolic markers effective in tracing the behavior of the commodity under such storage protocols and identifying presymptomatic conditions can be expected as one of the practical result of multiomics studies in the field of postharvest.

Combining multiomics data to generate a flow of information is aimed to fill the gap from genotype and phenotype, thus addressing the responses of different genotypes to postharvest conditions in the frame of a holistic phenomics approach. Phenomics refers to the characterization of phenotypes via the acquisition of high-dimensional phenotypic data and traits measured at different spatial and temporal resolutions (Houle, Govindaraju, & Omholt, 2010).

Platforms such as Phenom-network (http://phnserver.phenome-networks.com) where omics data and phenotyping are integrated with the aim of studying the same trait in different populations represent additional tools to be exploited in postharvest science. Pioneering work in this direction is the untargeted metabolic analysis used for the phenotyping of genetically mapped populations to reveal multiple metabolic Quantitative Trait Loci (QTLs) related to components of fruit quality parameters such as specific flavor notes (Dunemann, Ulrich, Boudichevskaia, Grafe, & Weber, 2009).

In the holistic approach, the multiomics techniques and physiological phenotyping are starting to be integrated with data regarding epigenetic mechanisms based on small noncoding RNAs, DNA methylation variations, and chromatin modifications, obtained from developing and senescent fruits coming both in model and crop plants (Farinati, Rasori, Varotto, & Bonghi, 2017: Großkinsky, Syaifullah, & Roitsch, 2018; Tang et al., 2020). In this view, recently, it has been reported that the loss of tomato fruit quality induced by postharvest handling went along with the alterations in global DNA methylation state (Zhou, Chen, Albornoz, & Beckles, 2020).

To convert all this information into possible applications, and implement gene and metabolite annotation for the crops of interest, will require a uniform framework and develop user-friendly tools and algorithms to process, correlate, and analyze multiomics data and implement MOI strategies in postharvest science.

References

Agrawal, G. K., Pedreschi, R., Barkla, B. J., Bindschedler, L. V., Cramer, R., Sakar, A., ... Rakwal, R. (2012). Translational plant proteomics: A perspective. *Journal of Proteomics*, *75*, 4588−4601.

Alba, R., Fei, Z. J., Payton, P., Liu, Y., Moore, S. L., Debbie, P., ... Giovannoni, J. (2004). ESTs, cDNA microarrays, and gene expression profiling: Tools for dissecting plant physiology and development. *Plant Journal*, *39*, 697−714.

Bang, J., Lim, S., Yi, G., Lee, J. G., & Lee, E. J. (2019). Integrated transcriptomic-metabolomic analysis reveals cellular responses of harvested strawberry fruit subjected to short-term exposure to high levels of carbon dioxide. *Postharvest Biology and Technology*, *148*, 120−131.

Barraclough, D., Obenland, D., Laing, W., & Carroll, T. (2004). A general method for two- dimensional protein electrophoresis of fruit samples. *Postharvest Biology and Technology*, *32*, 175−181.

Becatti, E., Chkaiban, L., Tonutti, P., Forcato, C., Bonghi, C., & Ranieri, A. M. (2010). Short-term postharvest carbon dioxide treatments induce selective molecular and metabolic changes in grape berries. *Journal of Agricultural and Food Chemistry*, *58*, 8012−8020.

Belouah, I., Blein-Nicolas, M., Balliau, T., Gibon, Y., Zivy, M., & Colombié, S. (2019). Peptide filtering differently affects the performances of XIC-based quantification methods. *Journal of Proteomics*, *193*, 131−141.

Bessemans, N., Verboven, P., Verlinden, B. E., & Nicolaï, B. M. (2016). A novel type of dynamic controlled atmosphere storage based on the respiratory quotient (RQ-DCA). *Postharvest Biology and Technology*, *115*, 91−102.

Bino, R. J., Hall, R. D., Fiehn, O., Kopka, J., Saito, K., Draper, J., ... Summer, L. W. (2004). Potential of metabolomics as a functional genomics tool. *Trends in Plant Science*, *9*, 418−425.

Bordonaba, J. G., Matthieu-Hurtiger, V., Westercamp, P., Coureau, C., Dupille, E., & Larrigaudière, C. (2013). Dynamic changes in conjugated trienols during storage may be employed to predict superficial scald in "Granny smith" apples. *LWT—Food Science and Technology*, *54*, 535−541.

Brizzolara, S., Cukrov, D., Mercadini, M., Martinelli, F., Ruperti, B., & Tonutti, P. (2019). Short-term responses of apple fruit to partial reoxygenation during extreme hypoxic storage conditions. *Journal of Agricultural and Food Chemistry*, *67*(17), 4754−4763.

Brizzolara, S., Hertog, M., Tosetti, R., Nicolai, B., & Tonutti, P. (2018). Metabolic responses to low temperature of three peach fruit cultivars differently sensitive to cold storage. *Frontiers in Plant Science*, *9*, 706.

Brizzolara, S., Manganaris, G. A., Fotopoulos, V., Watkins, C. B., & Tonutti, P. (2020). Primary metabolism in fresh fruits during storage. *Frontiers in Plant Science*, *11*, 80.

Brizzolara, S., Santucci, C., Tenori, L., Hertog, M., Nicolai, B., Stürz, S., ... Tonutti, P. (2017). A metabolomics approach to elucidate apple fruit responses to static and dynamic controlled atmosphere storage. *Postharvest Biology and Technology*, *127*, 76–87.

Busatto, N., Farneti, B., Commisso, M., Bianconi, M., Iadarola, B., Zago, E., ... Costa, F. (2018). Apple fruit superficial scald resistance mediated by ethylene inhibition is associated with diverse metabolic processes. *Plant Journal*, *93*, 270–285.

Busatto, N., Farneti, B., Tadiello, A., Vrhovsek, U., Cappellin, L., Biasioli, F., ... Costa, F. (2014). Target metabolite and gene transcription profiling during the development of superficial scald in apple (Malus × domestica Borkh). *BMC Plant Biology*, *14*, 193.

Bustamante, C. A., Brotman, Y., Monti, L. L., Gabilondo, J., Budde, C. O., Lara, M. V., ... Drincovich, M. F. (2018). Differential lipidome remodeling during postharvest of peach varieties with different susceptibility to chilling injury. *Physiologia Plantarum*, *163*(1), 2–17.

Chan, Z. (2013). Proteomic responses of fruits to environmental stress. *Plant Proteomics*, *3*, 1–10.

Chandramouli, K., & Qian, P. Y. (2009). Proteomics: Challenges, techniques and possibilities to overcome biological sample complexity. *Human Genomics Proteomics*, *2009*, 239204.

Ciesa, F. D., Via, J., Wisthaler, A., Zanella, A., Guerra, W., Mikoviny, T., ... Oberhuber, M. (2013). Discrimination of four different postharvest treatments of 'Red Delicious' apples based on their volatile organic compound (VOC) emissions during shelf-life measured by proton transfer reaction mass spectrometry (PTR-MS). *Postharvest Biology and Technology*, *86*, 329–336.

Cruz-Mendívil, A., López-Valenzuela, J. A., Calderón-Vázquez, C. L., Vega-García, M. O., Reyes-Moreno, C., & Valdez-Ortiz, A. (2015). Transcriptional changes associated with chilling tolerance and susceptibility in 'Micro-Tom' tomato fruit using RNA-Seq. *Postharvest Biology and Technology*, *99*, 141–151.

Cukrov, D., Brizzolara, S., & Tonutti, P. (2019). *Physiological and biochemical effects of controlled and modified atmospheres'*. *Postharvest physiology and biochemistry of fruits and vegetables* (pp. 425–441). Woodhead Publishing.

Cukrov, D., Zermiani, M., Brizzolara, S., Cestaro, A., Licausi, F., Luchinat, C., ... Tonutti, P. (2016). Extreme hypoxic conditions induce selective molecular responses and metabolic reset in detached apple fruit. *Frontiers in Plant Science*, *7*, 146.

Dagar, A., Friedman, H., & Lurie, S. (2010). Thaumatin-like proteins and their possible role in protection against chilling injury in peach fruit. *Postharvest Biology and Technology*, *57*, 77–85.

Dagar, A. P., Puig, C., Marti Ibanez, C., Ziliotto, F., Bonghi, C., Crisosto, C. H., ... Granell, A. (2013). Comparative transcript profiling of a peach and its nectarine mutant at harvest reveals differences in gene expression related to storability. *Tree Genetics and Genomes*, *9*, 223–235.

Dal'Molin, C., & Nielsen, L. K. (2017). Plant genome-scale reconstruction: From single cell to multi-tissue modelling and omics analyses. *Current Opinion in Biotechnology*, *49*, 42–48.

Dellapenna, D. (2001). Plant metabolic engineering. *Plant Physiology*, *125*, 160–163.

Ding, Y., Chang, J., Ma, Q., Chen, L., Liu, S., Jin, S., ... Cheng, Y. (2015). Network analysis of postharvest senescence process in citrus fruits revealed by transcriptomic and metabolomic profiling. *Plant Physiology*, *168*(1), 357–376.

Dunemann, F., Ulrich, D., Boudichevskaia, A., Grafe., & Weber, W. E. (2009). QTL mapping of aroma compounds analysed by headspace solid-phase microextraction gas chromatography in the apple progeny 'Discovery' × 'Prima'. *Molecular Breeding*, *23*, 501–521.

Emwas, A., Roy, R., Mckay, R. T., Tenori, L., Saccenti, E., Gowda, G. A. N., ... Wishart, D. S. (2019). NMR spectroscopy for metabolomics research. *Metabolites*, *9*(7).

Falara, V., Manganaris, G. A., Ziliotto, F., Manganaris, A., Bonghi, C., Ramina, A., & Kanellis, A. K. (2011). A ß-D-xylosidase and a PR-4B precursor identified as genes in accounting for differences in peach cold storage tolerance. *Functional Integrative Genomics*, *11*, 357–368.

Farcuh, M., Rivero, R. M., Sadka, A., & Blumwald, E. (2018). Ethylene regulation of sugar metabolism in climacteric and non-climacteric plums. *Postharvest Biology and Technology*, *139*, 20–30.

Farinati, S., Rasori, A., Varotto, S., & Bonghi, C. (2017). 'Rosaceae fruit development, ripening and post-harvest: An epigenetic perspective'. *Frontiers in Plant Science*, *8*(1247).

Feng, X., An, Y., Zheng, J., Sun, M., & Wang, L. (2016). Proteomics and SSH analyses of ALA- promoted fruit coloration and evidence for the involvement of a MADS-Box gene, MdMADS1. *Frontiers in Plant Science*, *7*, 1−19.

Fenn, J. B., Mann, M., Meng, C. K., Wong, S. F., & Whitehouse, C. M. (1990). Electrospray ionization−principles and practice. *Mass Spectrometry Reviews*, *9*(1), 37−70.

Fiehn, O. (2002). Metabolomics—the link between genotypes and phenotypes. *Plant Molecular Biology*, *48*, 155−171.

Foerster, H., Bombarely, A., Battey, J. N. D., Sierro, N., Ivanov, N., & Mueller, L. A. (2018). SolCyc: A database hub at the Sol Genomics Network (SGN) for the manual curation of metabolic networks in Solanum and Nicotiana specific databases. *Database*, *2018*, 2018.

Friedman, J., Hastie, T., & Tibshirani, R. (2010). Regularization paths for generalized linear models via coordinate descent. *Journal of Statistical Software*, *33*(1), 1−22.

Gapper, N. E., Hertog, M. L., Lee, J., Buchanan, D. A., Leisso, R. S., Fei, Z., … Rudell, D. R. (2017). Delayed response to cold stress is characterized by successive metabolic shifts culminating in apple fruit peel necrosis. *BMC Plant Biology*, *17*(1), 1−18.

Gibbs, D. J., Lee, S. C., Isa, N. M., Gramuglia, S., & Fukao, T. (2011). Homeostatic response to hypoxia is regulated by the N-end rule pathway in plants. *Nature*, *479*, 415−418.

Giné-Bordonaba, J., Busatto, N., Larrigaudière, C., Lindo-García, V., Echeverria, G., Vrhovsek, U., … Costa, F. (2020). Investigation of the transcriptomic and metabolic changes associated with superficial scald physiology impaired by lovastatin and 1-methylcyclopropene in pear fruit (cv. "Blanquilla"). *Horticulture Research*, *7*(1), 1−17.

Gonzalez-Candelas, L., Sànchez-Torres, S., Alamar, B., Establés, A. R., Ballester, M. T., Sànchez-Ballesta, Y. L., … Granell, A. (2005). Genomics approaches to postharvest biotic and biotic stresses of Citrus fruit. *Acta Horticulturae*, *682*, 247−254.

Goulas, V., Minas, I. S., Kourdoulas, P. M., Lazaridou, A., Molassiotis, A. N., Gerothanassis, I. P., & Manganaris, G. A. (2015). 1H NMR metabolic fingerprinting to probe temporal postharvest changes on qualitative attributes and phytochemical profile of sweet cherry fruit. *Frontiers in Plant Science*, *6*, 1−11.

Granell, A., Pons, C., Marti, C., Forment, J., Royo, C., Gradziel, T. M., … Crisosto, C. H. (2007). Genomic approaches—Innovative tools to improve quality of fresh cut produce. *Acta Horticulturae*, *746*, 203−211.

Granier, F. (1988). Extraction of plant proteins for two-dimensional electrophoresis. *Electrophoresis*, *9*, 712−718.

Großkinsky, D. K., Syaifullah, S. J., & Roitsch, T. (2018). Integration of multi-omics techniques and physiological phenotyping within a holistic phenomics approach to study senescence in model crop plants,'. *Journal of Experimental Botany*, *69*, 825−844.

Hall, R., Beale, M., Fiehn, O., Hardy, N., Sumner, L., & Bino, R. (2002). Plant metabolomics: The missing link in functional genomics strategies. *The Plant Cell*, *14*, 1437−1440.

Heazlewood, J. L., & Millar, A. H. (2003). Integrated plant proteomics − putting the green genomes to work. *Functional Plant Biology*, *30*, 471−482.

Hernández-de-Diego, R., Tarazona, S., Martínez-Mira, C., Balzano-Nogueira, L., Furió-Tarí, P., Pappas, G. J., & Conesa, A. (2018). PaintOmics 3: A web resource for the pathway analysis and visualization of multi-omics data. *Nucleic Acids Research*, *46*(W1), W503−W509.

Houle, D., Govindaraju, D. R., & Omholt, S. (2010). Phenomics: The next challenge. *Nature Reviews. Genetics*, *11*, 855−866.

Ideker, T., Galitski, T., & Hood, L. (2001). A new approach to decoding life: Systems biology. *Annual Review Genome and Human Genetic*, *2*, 343−372.

Jamil, I. N., Remali, J., Azizan, K. A., Nor Muhammad, N. A., Arita, M., Goh, H.-H., & Aizat, W. M. (2020). Systematic multi-omics integration (MOI) approach in plant systems biology. *Frontiers in Plant Science*, *11*, 944.

Kanellis, A., Tonutti, P., & Perata, P. (2009). Biochemical and molecular aspects of modified and controlled atmospheres. In E. M. Yahia (Ed.), *Modified and controlled atmospheres for the storage, transportation, and packaging of horticultural commodities* (pp. 553−567). Boca Raton, FL: CRC Press.

Karagiannis, E., Tanou, G., Scossa, F., Samiotaki, M., Michailidis, M., Manioudaki, M., … Molassiotis, A. (2020). Systems-based approaches to unravel networks and individual elements involved in apple superficial scald. *Frontiers in Plant Science*, *11*, 8.

Karas, M., & Hillenkamp, F. (1988). Laser desorption ionization of proteins with molecular masses exceeding 10,000 daltons. *Analytical Chemistry*, *60*(20), 2299−2301.

Kashash, Y., Doron-Faigenboim, A., Doron Holland, D., & Porat, R. (2019a). Effects of harvest time on chilling tolerance and the transcriptome of Wonderful pomegranate fruit. *Postharvest Biology and Technology*, *147*, 10−19.

Kashash, Y., Holland, D., & Porat, R. (2019b). Molecular mechanisms involved in postharvest chilling tolerance of pomegranate fruit. *Journal of the Science of Food and Agriculture*, *99*, 5617−5623.

Kays, S. J., & Paull, R. E. (2004). *Postharvest biology*. Athens, GA: Exon Press.

Komatsu, S., Mock, H. P., Yang, P., & Svensson, B. (2013). Application of proteomics for improving crop protection/artificial regulation. *Frontiers in Plant Science*, *4*, 522.

Kosmacz, M., Sokołowska, E. M., Bouzaa, S., & Skirycz, A. (2020). Towards a functional understanding of the plant metabolome. *Current Opinion in Plant Biology*, *55*, 47–51.

Krishnan, P., Kruger, N. J., & Ratcliffe, R. G. (2005). Metabolite fingerprinting and profiling in plants using NMR. *Journal of Experimental Botany*, *56*(410), 255–265.

Lara, M. V., Borsani, J., Budde, C. O., Lauxmann, M. A., Lombardo, V. A., Murray, R., … Drincovich, M. F. (2009). Biochemical and proteomic analysis of Dixiland peach fruit (*Prunus persica*) upon heat treatment. *Journal of Experimental Botany*, *60*, 4315–4333.

Lee, J., Mattheis, J. P., & Rudell, D. R. (2012). Antioxidant treatment alters metabolism associated with internal browning in Braeburn' apples during controlled atmosphere storage. *Postharvest Biology and Technology*, *68*, 32–42.

Leisso, R., Buchanan, D., Lee, J., Mattheis, J., & Rudell, D. (2013). Cell wall, cell membrane, and volatile metabolism are altered by antioxidant treatment, temperature shifts, and peel necrosis during apple fruit storage. *Journal of Agricultural and Food Chemistry*, *61*, 1373–1387.

Leisso, R. S., Gapper, N. E., Mattheis, J. P., Sullivan, N. L., Watkins, C. B., Giovannoni, J. J., … Rudell, D. R. (2016). Gene expression and metabolism preceding soft scald, a chilling injury of 'Honeycrisp'apple fruit. *BMC Genomics*, *17*(1), 798.

Li, T., Wu, Q., Duan, X., Yun, Z., & Jiang, Y. (2019). Proteomic and transcriptomic analysis to unravel the influence of high temperature on banana fruit during postharvest storage. *Functional and Integrative Genomics*, *19*(3), 467–486.

Licausi, F., Kosmacz, M., Weits, D. A., Giuntoli, B., Giorgi, F. M., Voesenek, L. A. C. J., … van Dongen, J. T. (2011). Oxygen sensing in plants is mediated by an N-end rule pathway for protein destabilization. *Nature*, *479*, 419–422.

Lillo-Carmona, V., Espinoza, A., Rothkegel, K., Rubilar, M., Nilo-Poyanco, R., Pedreschi, R., … Meneses, C. (2020). Identification of metabolite and lipid profiles in a segregating peach population associated with mealiness in Prunus persica (L.) Batsch. *Metabolites*, *10*(4), 154.

Lu, Y., Lam, H., Pi, E., Zhan, Q., Tsai, S., Wang, C., … Ngai, S. (2013). Comparative metabolomics in Glycine max and Glycine soja under salt stress to reveal the phenotypes of their offspring. *Journal of Agricultural and Food Chemistry*, *61*(36), 8711–8721.

Lurie, S., & Crisosto, C. (2005). Chilling injury in peach and nectarine. *Postharvest Biology and Technology*, *37*, 195–208.

Lurie, S., & Watkins, C. B. (2012). Superficial scald, its etiology and control. *Postharvest Biology and Technology*, *65*, 44–60.

Mack, C., Wefers, D., Schuster, P., Weinert, C. H., Egert, B., Bliedung, S., … Kulling, S. E. (2017). Untargeted multi-platform analysis of the metabolome and the non-starch polysaccharides of kiwifruit during postharvest ripening. *Postharvest Biology and Technology*, *125*, 65–76.

Madani, B., Mirshekari, A., & Imahori, Y. (2019). *Physiological responses to stress*. *Postharvest physiology and biochemistry of fruits and vegetables* (pp. 405–423). Woodhead Publishing.

Manganaris, G. A., Jajo, A., Holford, P., Jones, M. R., McGlasson, B., Ziosi, V., … Tonutti, P. (2010). 'Comparative transcriptomic analysis of plum fruit treated with 1-MCP. *Acta Horticulturae*, *877*, 1105–1109.

Manganaris, G. A., Rasori, A., Bassi, D., Geuna, F., Ramina, A., Tonutti, P., & Bonghi, C. (2011). Comparative transcript profiling of apricot (*Prunus armeniaca* L.) fruit development and on-tree ripening. *Tree Genetics and Genomes*, *7*(3), 609–616.

Maoz, I. De, Rosso, M., Kaplunov, T., Vedova, A. D., Sela, N., Flamini, R., … Lichter, A. (2019). Metabolomic and transcriptomic changes underlying cold and anaerobic stresses after storage of table grapes. *Scientific Report*, *9*, 1–14.

Marondedze, C. (2017). Date fruit proteomics during development and ripening stages. *Methods in Molecular Biology*, *1638*, 381–398.

Martin, L. B. B., Fei, Z., Giovannoni, J. J., & Rose, J. K. C. (2013). Catalyzing plant science research with RNA-seq. *Frontiers in Plant Science*, *4*, 66.

Mata, C. I., Fabre, B., Parsons, H. T., Hertog, M. L., Van Raemdonck, G., Baggerman, G., et al. (2018). 'Ethylene receptors, CTRs and EIN2 target protein identification and quantification through parallel reaction monitoring during tomato fruit ripening. *Frontiers in Plant Science*, *9*, 1626.

Mathabe, P. M., Belay, Z. A., Ndlovu, T., & Caleb, O. J. (2020). Progress in proteomic profiling of horticultural commodities during postharvest handling and storage: A review. *Scientia Horticulturae*, *261*, 108996.

Mellidou, I., Buts, K., Hatoum, D., Ho, Q. T., Johnston, J. W., Watkins, C. B., ... Nicolai, B. M. (2014). Transcriptomic events associated with internal browning of apple during postharvest storage. *BMC Plant Biology*, *14*(1), 328.

Mencarelli, F., & Tonutti, P. (2013). *Sweet, reinforced and fortified wines* (p. 357) West Sussex: Wiley-Blackwell.

Meng, C., Kuster, B., Culhane, A. C., & Ghlami, A. M. (2014). 'A multivariate approach to the integration of multi-omics datasets. *BMC Bioinformatics*, *15*(1), 162.

Monti, L. L., Bustamante, C. A., Budde, C. O., Gabilondo, J., Müller, G. L., Lara, M. V., & Drincovich, M. F. (2019). Metabolomic and proteomic profiling of Spring Lady peach fruit with contrasting woolliness phenotype reveals carbon oxidative processes and proteome reconfiguration in chilling-injured fruit. *Postharvest Biology and Technology*, *151*, 142−151.

Nilo, R., Saffie, C., Lilley, K., Baeza-Yates, R., Cambiazo, V., Campos-Vargas, R., ... Orellana, A. (2010). Proteomic analysis of peach fruit mesocarp softening and chilling injury using difference gel electrophoresis (DIGE). *BMC Genomics*, *11*, 43.

Obata, T., & Fernie, A. R. (2012). The use of metabolomics to dissect plant responses to abiotic stresses. *Cellular and Molecular Life Science*, *69*, 3225−3243.

Ogundiwin, E. A., Marti, C., Forment, J., Pons, C., Granell, A., Gradziel, T. M., ... Crisosto, C. H. (2008). Development of ChillPeah genomic tools and identification of cold-responsive genes in peach fruits. *Plant Molecular Biology*, *68*, 379−397.

Oms-Oliu, G., Odriozola-Serrano, I., & Martin-Belloso, O. (2012). Using metabolomics to improve the quality of harvested fruit (Review). CAB reviews: Perspectives in agriculture. *Veterinary Science, Nutrition and Natural Resources*, *7*, A45.

Oms-Oliu, G., Odriozola-Serrano, I., & Martín-Belloso, O. (2013). Metabolomics for assessing safety and quality of plant-derived food. *Food Research International*, *54*, 1172−1183.

Orth, J. D., Thiele, I., & Palsson, B.Ø. (2010). What is flux balance analysis? Nature Biotechnology, 28(3), 245−248. Available from https://doi.org/10.1038/nbt.1614

Page, D., Gouble, B., Valot, B., Bouichet, J. P., Callot, C., Kretzschmar, A., ... Faurobert, M. (2010). Protective proteins are differentially expressed in tomato genotypes differing for their tolerance to low-temperature storage. *Planta*, *232*, 483−500.

Pavez, L., Hödar, C., Olivares, F., González, M., & Cambiazo, V. (2013). Effects of postharvest treatments on gene expression in *Prunus persica* fruit: Normal and altered ripening. *Postharvest Biology and Technology*, *75*, 125−134.

Pedreschi, R., Hertog, M., Robben, J., Lilley, K. S., Karp, N. A., Baggerman, G., ... Nicolai, B. (2009). Gel-based proteomics approach to the study of metabolic changes in pear tissue during storage. *Journal of Agricultural and Food Chemistry*, *57*, 6997−7004.

Pedreschi, R., Lurie, S., Hertog, M., Nicolai, B., Mes, J., & Woltering, E. (2013). Post-harvest proteomics and food security. *Proteomics*, *13*, 1772−1783.

Pedreschi, R., Vanstreels, E., Carpentier, S., Hertog, M., Lammertyn, J., Robben, J., ... Nicolaï, B. M. (2007). Proteomic analysis of core breakdown disorder in Conference pears (*Pyrus communis* L.). *Proteomics*, *7*, 2083−2099.

Pickersky, E., & Gang, D. (2000). Genetics and biochemistry of secondary metabolites: An evolutionary perspective. *Trends in Plant Science*, *5*, 439−445.

Ponce-Valadez, M., Moore Fellman, S., Giovannoni, J., Gan, S. S., & Watkins, C. B. (2009). Differential fruit gene expression in two strawberry cultivars in response to elevated CO_2 during storage revealed by a heterologous fruit microarray approach. *Postharvest Biology and Technology*, *51*, 131−140.

Pons, C., Royo, C., Forment, J., Gadea, J., Lluch, Y., Granell, A., ... Kanellis, A. K. (2005). A customized citrus cDNA microarray and its use in postharvest. *Acta Horticulturae*, *682*, 225−232.

Pott, D. M., Vallarino, J. G., & Osorio, S. (2020). Metabolite changes during postharvest storage: Effects on fruit quality traits. *Metabolites*, *10*(5), 187.

Prange, R., DeLong, J., Harrison, P., Leyte, J., & McLean, S. D. (2003). Oxygen concentration affects chlorophyll fluorescence in chlorophyll-containing fruit and vegetables. *Journal of American Society for Horticultural Science*, *128*, 603−607.

Prange, R., DeLong, J., Leyte, J., & Harrison, P. (2002). Oxygen concentration affects chlorophyll fluorescence in chlorophyll-containing fruit. *Postharvest Biology and Technology*, *24*, 201−205.

Putri, S. P., Yamamoto, S., Tsugawa, H., & Fukusaki, E. (2013). Current metabolomics: Technological advances. *Journal of Bioscience and Bioengineering*, *116*(1), 9–16.

R Core Team. (2018). *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing. Available at https://www.R-project.org/.

Ramina, A., Tonutti, P., & McGlasson, B. (2008). Ripening, nutrition, and postharvest physiology. In R. L. Desmond, & B. Daniele (Eds.), *The peach botany, production and uses* (pp. 550–574). Oxfordshire: CABI.

Rochfort, S. (2005). Metabolomics reviewed: A new "omics" platform technology for systems biology and implications for natural products research. *Journal of Natural Products*, *68*(12), 1813–1820.

Rohart, F., Gautier, B., Singh, A., & Lê Cao, K. A. (2017). mixOmics: An R package for omics feature selection and multiple data integration. *PLoS Computational Biology*, *3*(11), e1005752.

Rosales, R., Romero, I., Fernandez-Caballero, C., Escribano, M. I., Merodio, C., & Sanchez-Ballesta, M. T. (2016). Low temperature and short-term high-CO_2 treatment in postharvest storage of table grapes at two maturity stages: Effects on transcriptome profiling. *Frontiers in Plant Science*, *7*, 1020.

Rudell, D. R., & Mattheis, J. P. (2009). Superficial scald development and related metabolism is modified by postharvest light irradiation. *Postharvest Biology Technology*, *51*, 174–182.

Rudell, D. R., Mattheis, J. P., & Curry, E. A. (2008). Prestorage ultraviolet-white light irradiation alters apple peel metabolome. *Journal of Agricultural and Food Chemistry*, *56*, 1138–1147.

Rudell, D. R., Mattheis, J. P., & Hertog, M. L. A. T. M. (2009). Metabolomic change precedes apple superficial scald symptoms. *Journal of Agricultural and Food Chemistry*, *vol.57*, 8459–8466.

Savoi, S., Wong, D. C., Degu, A., Herrera, J. C., Bucchetti, B., Peterlunger, E., et al. (2017). Multi-omics and integrated network analyses reveal new insights into the systems relationships between metabolites, structural genes, and transcriptional regulators in developing grape berries (*Vitis vinifera* L.) exposed to water deficit. *Frontier in Plant Science*, *8*, 1124.

Savoi, S., Wong, D. C. J., Arapitsas, P., Miculan, M., Bucchetti, B., Peterlunger, E., et al. (2016). 'Transcriptome and metabolite profiling reveals that prolonged drought modulates the phenylpropanoid and terpenoid pathway in white grapes (*Vitis vinifera* L.). *BMC Plant Biology*, *16*, 67.

Schouten, S. P., Prange, R., Verschoor, J. A., Lammers, T. R., & Oosterhaven, J. (1997). Improvement of quality of "Elstar" apples by dynamic control of ULO conditions. In *Proceedings of the 7th international controlled atmosphere research conference* (Vol. 2; pp. 71–78). Davis, CA.

Schulz, M., Seraglio, S. K. T., Della Betta, F., Nehring, P., Valese, A. C., Daguer, H., ... Fett, R. (2020). Determination of phenolic compounds in three edible ripening stages of yellow guava (*Psidium cattleianum* Sabine) after acidic hydrolysis by LC–MS/MS. *Plant Foods for Human Nutrition*, *75*(1), 110–115.

Schwacke, R., Ponce-Soto, G. Y., Krause, K., Bolger, A. M., Arsova, B., Hallab, A., et al. (2019). MapMan4: A refined protein classification and annotation framework applicable to multi-omics data analysis. *Molecular Plant*, *12*(6), 879–892.

Scigelova, M., Hornshaw, M., Giannakopulos, A., & Makarov, A. (2011). Fourier transform mass spectrometry. *Molecular and Cellular Proteomics*, *10*(7).

Seaver, S.M., Lerma-Ortiz, C., Conrad, N., Mikaili, A., Sreedasyam, A., Hanson, A.D., et al. (2018). Plant SEED enables automated annotation and reconstruction of plant primary metabolism with improved compartmentalization and comparative consistency. *Plant Journal*. 95(6), 1102–1113. Available from https://doi.org/10.1111/tpj.14003.

Seymour, G. B., Poole, M., Giovannoni, J. J., & Tucker, G. (2013). *The molecular biology and biochemistry of fruit ripening*. Ames, IA: Wiley-Blackwell.

Seymour, G. B., Taylor, J. E., & Tucker, G. A. (1993). *Biochemistry of fruit ripening*. London: Chapman and Hall.

Shepherd, L. V. T., Fraser, P., & Stewart, D. (2011). Metabolomics: A second-generation platform for crop and food analysis. *Bioanalysis*, *3*, 1143–1159.

Shiratake, K., & Suzuki, M. (2016). Omics studies of citrus, grape and rosaceae fruit trees. *Breed Science*, *66*(1), 122–138.

Tang, D., Gallusci, P., & Lang, Z. (2020). Fruit development and epigenetic modifications. *New Phytologist*, *228*, 839–844.

Tang, N., Deng, W., Hu, N., Chen, N., & Li, Z. (2016). Metabolite and transcriptomic analyses reveal metabolic and regulatory features associated with Powell orange pulp deterioration during room temperature and cold storage. *Postharvest Biology and Technology*, *112*, 75–86.

Tang, R., Zhou, Y., Chen, Z., Wang, L., Lai, Y., Chang, S. K., … Huang, H. (2020). Regulation of browning and senescence of litchi fruit mediated by phenolics and energy status: A postharvest comparison on three different cultivars. *Postharvest Biology and Technology*, *168*, 111280.

Thimm, O., Bläsing, O., Gibon, Y., Nagel, A., Meyer, S., Krüger, P., … Stitt, M. (2004). MAPMAN: A user-driven tool to display genomics data sets onto diagrams of metabolic pathways and other biological processes. *Plant Journal*, *37*, 914–939.

Trainotti, L., Bonghi, C., Ziliotto, F., Zanin, D., Rasori, A., Casadoro, G., … Tonutti, P. (2006). The use of microarray mPEACH1.0 to investigate transcriptome changes during transition from pre-climacteric to climacteric phase in peach fruit. *Plant Science*, *170*, 606–613.

Valero, D., & Serrano, M. (2010). Heat treatments. In Valero, & Serrano (Eds.), *Postharvest biology and technology for preserving fruit quality* (pp. 91–108). Boca Raton, FL: CRC Press.

Vandendriessche, T., Schäfer, H., Verlinden, B. E., Humpfer, E., Hertog, M. L. A. T. M., & Nicolaï, B. M. (2013). High-throughput NMR based metabolic profiling of Braeburn apple in relation to internal browning. *Postharvest Biology and Technology*, *80*, 18–24.

Vazquez-Hernandez, M., Navarro, S., Sanchez-Ballesta, M. T., Merodio, C., & Escribano, M. I. (2018). Short-term high CO_2 treatment reduces water loss and decay by modulating defense proteins and organic osmolytes in Cardinal table grape after cold storage and shelf-life. *Science Horticulturae*, *234*, 27–35.

Vega-Garcia, M. O., Lopez-Espinosa, G., Ontiversos, J. C., Caro-Corrales, J. J., Vargas, F. D., & Lòpez-Valenzuela, J. A. (2010). Changes in protein expression associated with chilling injury in tomato fruit. *Journal of American Society Horticultural Science*, *135*, 83–89.

Voit, E. O. (2017). The best models of metabolism. *WIRES Systems Biology and Medicine*, *9*(6), e1391.

Wang, K., Yin, X. R., Zhang, B., Grierson, D., Xu, C. J., & Chen, K. S. (2017). Transcriptomic and metabolic analyses provide new insights into chilling injury in peach fruit. *Plant, Cell and Environment*, *40*(8), 1531–1551.

Whitaker, B. D. (2013). Genetic and biochemical bases of superficial scald storage disorder in apple and pear fruits. *Acta Horticulturae*, *989*, 47–60.

Withfield, P. D., German, A. J., & Noble, P. J. (2004). Metabolomics: An emerging post-genomic tool for nutrition. *British Journal of Nutrition*, *92*, 549–556.

Xu, J., Zhang, Y., Qi, D., Huo, H., Dong, X., Tian, L., … Cao, Y. (2018). Postharvest metabolomic changes in *Pyrus ussuriensis* Maxim. wild accession. Zaoshu Shanli. *Journal of Separation Science*, *41*, 4001–4013.

Yuan, Y., Zhao, Y., Yang, J., Jiang, Y., Lu, F., Jia, Y., & Yang, B. (2017). Metabolomic analyses of banana during postharvest senescence by 1H-high resolution-NMR. *Food Chemistry*, *218*, 406–412.

Yun, Z., Gao, H., Liu, P., Liu, S., Luo, T., Jin, S., … Deng, X. (2013). Comparative proteomic and metabolomic profiling of citrus fruit with enhancement of disease resistance by postharvest heat treatment. *BMC Plant Biology*, *13*, 44.

Yun, Z., Jin, S., Ding, Y., Wang, Z., Gao, H., Pan, Z., … Deng, X. (2012). Comparative transcriptomics and proteomics analysis of citrus fruit, to improve understanding of the effect of low temperature on maintaining fruit quality during lengthy post-harvest storage. *Journal of Experimental Botany*, *63*, 2873–2893.

Yun, Z., Qu, H., Wang, H., Zhu, F., Zhang, Z., Duan, X., … Jiang, Y. (2016). Comparative transcriptome and metabolome provide new insights into the regulatory mechanisms of accelerated senescence in litchi fruit after cold storage. *Scientific Reports*, *6*, 19356.

Zenoni, S., Fasoli, M., Guzzo, F., Dal Santo, S., Amato, A., Anesi, A., … Tornielli, G. B. (2016). Disclosing the molecular basis of the postharvest life of berry in different grapevine genotypes. *Plant Physiology*, *172*(3), 1821–1843.

Zhang, L., Wang, L., Zeng, X., Chen, R., Yang, S., & Pan, S. (2019). Comparative transcriptome analysis reveals fruit discoloration mechanisms in postharvest strawberries in response to high ambient temperature. *Food Chemistry, X*, *2*, 100025.

Zhou, J., Chen, B., Albornoz, K., & Beckles, D. M. (2020). Postharvest handling induces changes in fruit DNA methylation status and is associated with alterations in fruit quality in tomato (*Solanum lycopersicum* L.). *bioRxiv*, 331819. Available from https://doi.org/10.1101/2020.10.08.331819, 2020.10.08.

CHAPTER

9

Postharvest quality properties of potential tropical fruits related to their unique structural characters

Chalermchai Wongs-Aree[1,2] *and Sompoch Noichindra*[3]

[1]Division of Postharvest Technology, School of Bioresources and Technology, King Mongkut's University of Technology Thonburi, Bangkok, Thailand [2]Postharvest Technology Innovation Center, Ministry of Higher Education, Science, Research and Innovation, Bangkok, Thailand [3]Division of Agro-Industrial Technology, Faculty of Applied Science, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand

Abbreviations

1-MCP	1-methylcyclopropene
AAT	alcohol acyltransferase
C_{12}	lauric acid
C_{14}	myristic acid
C_4-C_{10}	butanoic—butanoic decanoic acids
CaC_2	calcium carbide
$CaCl_2$	calcium chloride
CAD	cinnamyl alcohol dehydrogenase
CoA	coenzyme A
DAA	days after anthesis
gFW	grams fresh weight
LOX	lipoxygenase
MeJA	methyl jasmonate
OTR	oxygen transmission rate
POD	peroxidase
PPO	polyphenol oxidase
ROS	reactive oxygen species
SMS	sodium metabisulfite
WAP	weeks after pollination

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00009-9

9.1 Introduction

9.1.1 General information

Tropical plants typically grow on the land between latitudes 23° North and South of the equator, where the climate is usually warm throughout the year (Samson, 1986). Tropical fruits are outstanding in both visual appearance and flavor. The fruit is visually unique, and the edible part is typically developed from other parts than the fertilized ovary wall (except in mangosteen, which develops parthenocarpy). Here in this chapter, five tropical fruits, durian, mangosteen, mango, papaya, and young coconut, are detailed in the fruit characteristics related to their quality. The physiological development of the fruits directly affects quality. However, the fruit quality delivered is attributed to consumer preferences, including fruit phenotypes of shape, color, flavor, and textures, which can vary widely among different nationalities. Due to the physiology itself or postharvest-handling procedures, changes in quality attributes decrease the marketable value after harvest. The value of the fruits in world markets is shown in Table 9.1. Although these five tropical fruits are in a minor group on the new volume demanded in global markets (Wongs-Aree & Noichinda, 2014), the global trade dramatically increases year by year. The appropriate postharvest handling and technology to maintain and improve the quality are contributing to this economic expansion.

General botanical information and consumer preference of five high potential tropical fruits grown in South-East Asia are shown next.

Durian (*Durio zibethinus* Murr.) (Fig. 9.1A) belongs to the Bombacaceae Family. Malaysian or Indonesian consumers like eating overripe durians with very soft pulp texture and intense fragrance, whereas Thais prefer ripe firm pulp with much less aroma. For China, the biggest durian market, Chinese female consumers account for a significant population of durian consumers, and more than half of them like a strong durian aroma, whereas the level of soft texture is unclear (Anon, 2021).

TABLE 9.1 Marketing distribution of five potential tropical fruits in 2018.

Fruit	Global trade	Main importers	Main exporters
Durian	USD 1.97 billion	China (65%), Hong Kong (19%), Taiwan (4%)	Thailand (95%), Malaysia, Vietnam
Mangosteen	USD 363 million	China, the United States, Germany	Thailand, Mexico, Vietnam, Peru
Mango	USD 2.8 billion	China, the United States, the Netherlands	Mexico, Brazil, Thailand
Papaya	USD 308 million	The United States (40.6%), Germany (9.19%), Canada (6.97%)	Mexico (30.2%), Brazil (18.6%), Guatemala (11.6%)
Coconut (fresh and dried)	USD 1.37 billion	China (12.7%), the United States (12.6%), the Netherlands (5.85%)	Philippines (27%), Indonesia (23%), Thailand (10.2)

Market Analysis Report (2019). Durian fruit market size and share, global industry report, 2019–2025 *(Report ID: GVR-3–68038-511-3) (80 p.). https://www.grandviewresearch.com/industry-analysis/durian-fruit-market Accessed 12.02.21 (Market Analysis Report, 2019); https://www.tridge.com/; The Observatory of Economic Complexity (OEC), https://oec.world/en.*

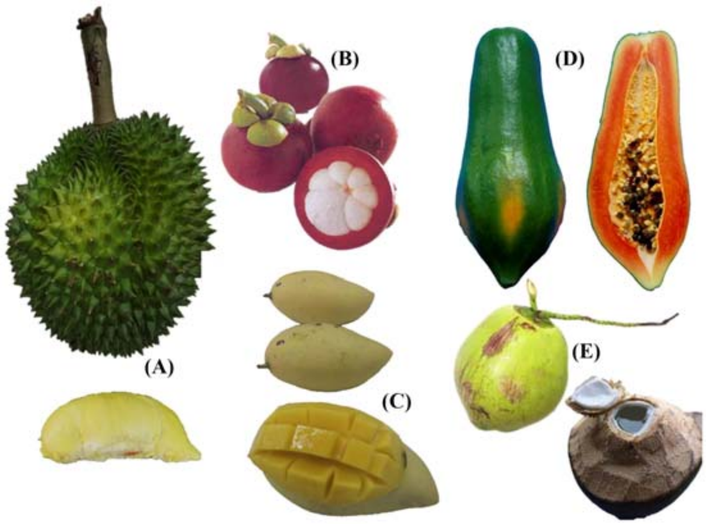


FIGURE 9.1 Visual appearance of the whole fruit and the edible parts of "Chanee" durian (A), mangosteen (B), "Nam Dokmai" mango (C), "Khaek Dam" papaya (D), and young coconut (E).

Mangosteen (*Garcinia mangostana* Linn.) (Fig. 9.1B) is a tropical evergreen tree in the Clusiaceae or Guttiferae Family. Healthy mangosteen fruit must have clean-clear smooth skin with bright purple color and fresh green calyx. Although translucent flesh is a physiological disorder in mangosteen fruit, some people like the crispy, firm flesh. Fruit with this defect has, however, a short shelf life due to flesh fermentation.

Mango (*Mangifera indica* Linn.) (Fig. 9.1C) is in the Anacardiaceae Family. Most consumers prefer ripe mangoes, but Thais like both green eating-type and ripe mangoes. Thus there are many cultivars both for green eating-type and ripe mangoes.

Papaya (*Carica papaya* Linn.) (Fig. 9.1D) is in the Caricaceae Family. Most Thais like ripe fruit with not mushy flesh. Thus "Maradol" or "Holland" cultivar becomes popular at present due to its firm-ripe flesh.

Young coconut (*Cocos nucifera* Linn.) or tender coconut (Fig. 9.1E) is a member of the palm tree family (Arecaceae) and is the most naturally widespread fruit plant on Earth. While foreigners usually consume only the water (liquid endosperm) of young coconut for a refreshing drink, Asians are concerned about the meat's quality (solid endosperm).

9.1.2 Fruit type and structure

Fruit typically develops after the fertilization of the flower blooming stage. In most fertilized flowers, the ovary wall changes to an edible part of the fruit pericarp as the fruit pulp. Fruit flesh typically develops from the ovary wall, but the flesh of some tropical fruits is derived from special tissue, called "aril." In mangosteen and rambutan, the aril develops from the seed integument (Fig. 9.2A and B), whereas durian and longan's arils are from the funiculus (Fig. 9.2C and D) when the ovary walls develop into the fruit rind. Papaya is a real berry fruit that contains many seeds in the cavity, whereas the exocarp develops to the peel, the mesocarp is the flesh, and the endocarp is the placenta (Fig. 9.2H). The endocarp of coconut and mango develops to a stone seed shell as a drupe

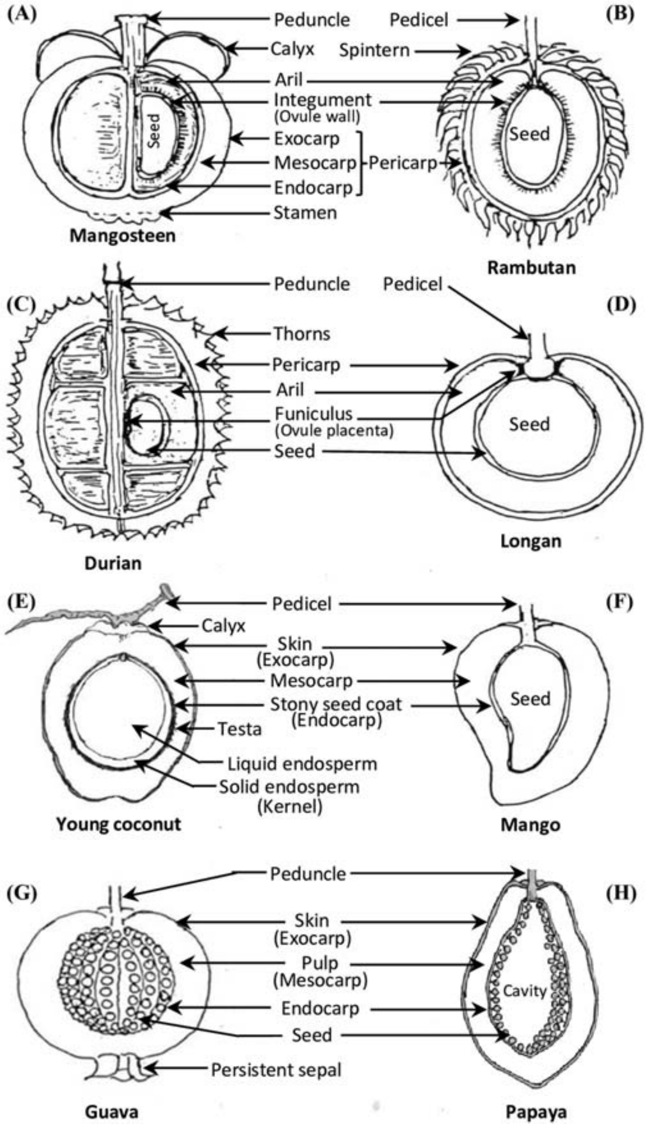


FIGURE 9.2 The basis structural development of edible parts in selected tropical fruits of mangosteen (A), rambutan (B), durian (C), Longan (D), young coconut (E), mango (F), guava (G), and papaya (H).

fruit (Fig. 9.2E and F). The mesocarp develops to fruit flesh, where the exocarp develops to peel in mango. For young coconut, the edible parts are the liquid and solid endosperm located in the shell that the maturity is crucial for the quality. On the other hand, although guava is a true fruit, the flesh is mainly developed from the receptacle (Fig. 9.2G).

Durian and mangosteen are a single flower comprising many carpels. Durian fruit contains three to five locules with several seeds in each locule, while mangosteen generally contains five to seven segments of arils. Mango and coconut are flowering inflorescences containing many florets. The fruits are classified as a one-seeded drupe by their physical traits because the fruit is derived from one carpel with a single seed when the exocarp, mesocarp, and endocarp develop into peel, flesh/coir, and hard stony shell covering the seed, respectively. Papaya fruit is a pepo berry fruit type because, although the pericarp is fleshy, the skin is thick and chewy. It is derived from a single ovary wall from a single flower containing many seeds.

9.2 Changes in quality attributes of five tropical fruits during fruit maturation and the postharvest phase

9.2.1 Durian

Durian aril contains a high nutritional value and expresses typical bright yellow, sweet taste, and fragrance. It exhibits a different texture of softening from coarse to creamy depending on variety and maturity and can even vary in the same fruit. Durian eating quality is dependent on consumer preference from each country. For Thai durian cultivars, ripe “Chanee” pulp produces an intense yellow, smooth custard-like texture with a strong odor, “Kanyao” is the same as “Chanee” but a weak odor, whereas “Monthong” exhibits coarse, firm texture, and thick, pale yellow flesh with an oily sweet and moderate odor.

9.2.1.1 Fruit anatomy

Durian, derived from a perfect flower, is a capsule fruit comprising five locules containing several seeds in each locule. It is a climacteric fruit. As the whole fruit ripens, the rind and the flesh behave independently during fruit maturation. In durian, rapid changes in the pericarp rind shorten the storage life of the fruit. Durian husk (pericarp), pulp, and seeds are anatomically connected only at the fruit placenta (Figs. 9.2C and 9.3A). The

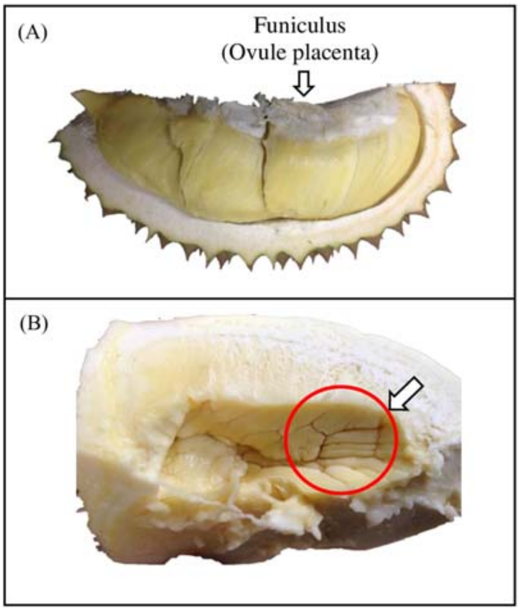


FIGURE 9.3 Visual appearance of the edible aril of durian derived from ovule placenta (A) and development of aril individually wrapped of the seed as twisted edible parts (pointing arrow) (B).

ripening of durian fruit is associated with its respiration and endogenous ethylene production rates. The ethylene production and respiration rates of durian pulp during ripening are much lower than those from the husk (Brooncherm & Siriphanich, 1991; Chayprasat, 1993). ACC oxidase, the last step of ethylene biosynthesis, is a rate-limiting step of the ethylene production in the husk, which is crucial for whole fruit ripening (Amornputti, Ketsa, & van Doorn, 2016). Ethylene from the husk thus is required for normal ripening of the fruit and aril. High endogenous ethylene levels in durian husk induce the biological process of fruit ripening, including a disorder of husk dehiscence. Unlike the whole fruit, fresh-cut durian needs to reach a suitable maturity before husk removal. Due to the low level of ethylene biosynthesis, ready-to-eat durian pulp removed from the husk often fails to ripen normally (Boonthanakorn, Daud, Aontee, & Wongs-Aree, 2020). Since the pulp is developed from the twisted overlap of several layers of aril (Fig. 9.3B), the aril pulp can ripen unevenly.

9.2.1.2 *Fruit development and harvest index*

The five primary cultivars of durian in Thailand include "Kradoom Thong" and "Chanthaburi I", which are early harvesting cultivars; "Chanee" is moderate; and "Monthong" and "Kanyao" are late harvesting cultivars. There are two systems of durian fruit harvest index in the global markets. One is a traditional index: the fruit is collected when dropped fully ripe (100% maturation) from the mother plant. This stage is preferred by local people in the most South-East Asian countries. The other system has been developed for the modern postharvest handling and logistics of whole fresh fruit and is used by all Thai commercial durian operators. Mature green fruit at about 80%−85% maturation is harvested at the preclimacteric stage. Consequently, a ripening induction process is required for the latter to induce the complete ripening.

Since Thai durians are harvested at the mature green stage, immature fruit harvesting is a crucial problem for the market. The structure and shape of durian can be used as criteria for a maturity index. Mature durian, which can generally ripen to produce a good aril quality, can be observed by visual appearance. Thorn ends are withered with brown color, and the spaces between thorns become wider. Furthermore, the fruit peduncle skin is corky with a rough feeling by touching, and the separation zone between peduncle and stem or the abscission layer is bulging. On the other hand, the standardization for Thai durian use dried pulp weight as the criteria for commercial maturity: minimum pulp dry weight of 30% for "Chanee" and 32% for "Monthong" (Thai Agricultural Standard: TAS 3-2013, 2013). Durian passing the minimum pulp dry weight is acceptable of ripe durian by consumers. However, the fresh-cut durian is now in fashion at retail as the consumer can inspect the visual quality. The ready-to-eat durian reduces logistical costs from the agricultural waste as the husk can be as much as 70% of total fruit weight.

9.2.1.3 *Aroma volatiles and color*

9.2.1.3.1 Aroma volatiles

Aroma is an essential character and indicator for fruit maturity and quality. Furthermore, the aroma of durian is a significant problem for distribution and logistics. When ripening, the aril releases strong fragrances of two broad types. The fruity flavor notes are due to an abundance of ethyl and methyl esters, especially durian aroma character (odor active compound), ethyl-2 methyl butanoate, which is sweetly fruity, apple-like odor. The second is the pungent smell of onion-like due to comprising sulfur-containing thiols and thioesters. Thiols include ethanethiol, propanethiol, whereas thioester is such ethyl thioacetate. "Monthong" Thai durian and "Ajimah" Indonesian durian contain thioesters more than thiols, but "Segamat" durian (Malaysia) contains thiols more than thioesters (Chawengkijwanich, Sa-nguanpuag, & Tanprasert, 2008; Voon, Hamid, Rusul, Osman, & Quek, 2007). Monthong contains esters modified from methanol, ethanol, and propanol, in which ethanol is the major. The esters' cosubstrate is derived from C_4–C_{10} carboxylic acids, straight short- to medium-chain acids when C_4 and C_6 carboxylic acids are major compounds (Fig. 9.4).

Four durian cultivars from Thailand, Malaysia, Indonesia, and Philippines share ripe pulp volatiles of at least 15 compounds, including ethyl propanoate, methyl-2-methyl butanoate, ethyl butanoate, ethyl-2-methyl butanoate, propyl-2-methyl butanoate, ethyl hexanoate, ethyl heptanoate, ethyl octanoate, ethyl decanoate, ethanethiol, 1-propanethiol, diethyl disulfide, diethyl trisulfide, 1,1-bis (ethylthio) ethane, 3,5-dimethyl-1,2,4-trithiolane (Table 9.2). The main active volatiles in Thai durians ("Monthong," "Chanee," and "Kanyao") include ethyl-2 methyl butanoate and ethyl hexanoate, which exhibit an apple-like odor character of durian (unpublished data). Pungent smell in durian relates to sulfur-containing compounds. Sulfur-containing compounds comprising diethyl disulfide, trisulfide (onion garlic), 3,5-dimethyl-1,2-thrithiolane (sulfury onion) synergic with the ester give a strong fragrancy. Thus, if the sulfide compounds are silent, ripe durian may smell like ripe apple mixed with ripe pineapple.

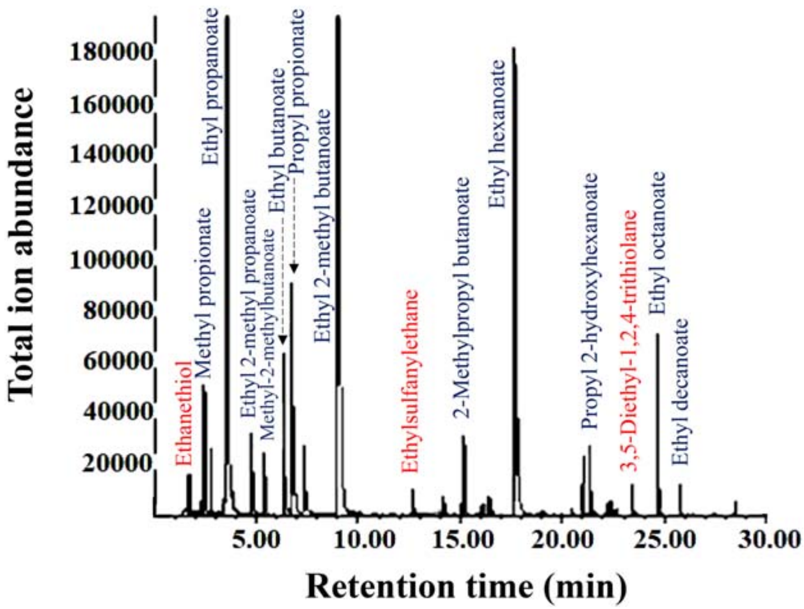


FIGURE 9.4 Volatile profile trapped by SPME from aril of "Monthong" durian stored at 25°C for 4 days. *SPME*, Solid phase microextraction. Red alphabets indicate sulfur-containing compounds, while dark blue alphabets indicate ester compounds.

TABLE 9.2 Comparison of volatile components in four durian cultivars from four countries.

Contributory flavor compound	"Monthong" Thai durian Chawengkijwanich et al. (2008), Li, Schieberle, and Steinhaus (2017)	"D2" Malaysian durian Voon et al. (2007)	"Ajimah" Indonesian durian Belgis et al. (2017)	"Puyat" Philippine durian Dantes, Maninang, Elepano, and Gemma (2013)
Esters				
Ethyl acetate	✓	✓	✓	–
Methyl propanoate	✓	✓	–	✓
Ethyl propanoate	✓	✓	✓	✓
Ethyl-2-methyl propanoate	✓	✓	–	–
Methyl butanoate	–	✓	–	–
Methyl-2-methyl butanoate	✓	✓	✓	✓
Ethyl butanoate	✓	✓	✓	✓
Propyl propanoate	✓	✓	–	✓
Ethyl-2-methyl butanoate	✓	✓	✓	✓
Ethyl-3-methyl butanoate	–	–	✓	–
Propyl butanoate	–	✓	–	✓
Propyl-2-methyl butanoate	✓	✓	✓	✓
Ethyl-2-butenoate	–	–	✓	–
Methyl hexanoate	–	✓	–	–
Ethyl hexanoate	✓	✓	✓	✓
Ethyl-3-hexenoate	–	–	✓	–
Propyl hexanoate	–	✓	–	✓
Ethyl heptanoate	✓	✓	✓	✓
Methyl octanoate	✓	✓	–	✓
Ethyl octanoate	✓	✓	✓	✓
Propyl octanoate	–	–	–	✓
Ethyl decanoate	✓	✓	✓	✓
Alcohols				
Ethanol	✓	✓	✓	–

(*Continued*)

TABLE 9.2 (Continued)

Contributory flavor compound	"Monthong" Thai durian Chawengkijwanich et al. (2008), Li, Schieberle, and Steinhaus (2017)	"D2" Malaysian durian Voon et al. (2007)	"Ajimah" Indonesian durian Belgis et al. (2017)	"Puyat" Philippine durian Dantes, Maninang, Elepano, and Gemma (2013)
1-Propanol	✓	✓	–	–
1-Butanol	–	✓	–	–
2-Methyl-1-butanol	–	✓	✓	–
3-Methyl-1-butanol	–	✓	–	–
1-Hexanol	–	✓	–	–
Thiols				
Methanethiol	✓	–	–	–
Ethanethiol	✓	✓	✓	✓
Ethanedithiol	✓	–	–	–
1-Propanethiol	✓	✓	✓	✓
1-(Methylsulfanyl) ethanethiol	✓	–	–	–
1-(Ethylsulfanyl) ethanethiol	✓	–	–	–
1-(Ethylsulfanyl) propanethiol	✓	–	–	–
3-Methylbutenethiol	✓	–	–	–
Thioesters				
Methyl (2*S*)-2-methyl butanoate	✓	–	–	–
Ethyl (2*S*)-2-methyl butanoate	✓	–	–	–
S-Ethyl ethanethioate	✓	–	–	–
Other sulfur compounds				
Methyl ethyl disulfide	–	✓	–	✓
Diethyl disulfide	✓	✓	✓	✓
Methyl propyl disulfide	–	✓	–	–

(*Continued*)

TABLE 9.2 (Continued)

Contributory flavor compound	"Monthong" Thai durian Chawengkijwanich et al. (2008), Li, Schieberle, and Steinhaus (2017)	"D2" Malaysian durian Voon et al. (2007)	"Ajimah" Indonesian durian Belgis et al. (2017)	"Puyat" Philippine durian Dantes, Maninang, Elepano, and Gemma (2013)
Ethyl propyl disulfide	–	✓	✓	–
Dipropyl disulfide	–	✓	–	–
Diethyl trisulfide	✓	✓	✓	✓
1,1-bis (Ethylthio) ethane	✓	✓	✓	✓
3,5-Dimethyl-1,2,4-trithiolane	✓	✓	✓	✓

Recently, a new hybrid in the "Chanthaburi" bred series produces weaker odors. "Chanthaburi 1" is a cross between "Chanee" and "Monthong" and produces a deep yellow flesh with little of the typical aroma when ripe and is suitable for logistics and export (Somsri, 2008). "D101" Malaysian durian and "Hejo" and "Sukarno" Indonesian durians are also produced with a low level of aroma volatiles (Belgis, Wijaya, Apriyantono, Kusbiantoro, & Yuliana, 2017; Voon et al., 2007). In the less fragrant Thai variety, "Chanthaburi I," the level of odor compounds is low. Ethyl-2 methyl butanoate is four times higher in "Chanee" compared to the "Chanthaburi I" and "Monthong." Nevertheless, "Monthong" contains ethyl hexanoate 15 times higher than the hybrid (Aschariyaphotha, Wongs-Aree, Bodhipadma, & Noichinda, 2021). Sulfur-containing compounds are still produced in the fruit but fewer components.

Durian's typical aroma is mainly derived from the ripe aril, not the husk. The aroma profile is mostly esters mainly derived from ethanol and short-chain (C_4-C_{10}) acids in acyls coenzyme A (CoA) forms. Durian aril contains many fatty acids, and during ripening, lipid degradation and carotenoid biosynthesis are high. The whole fruit's respiration rate is dramatically high, and with a thick husk (pericarp) as a gas barrier. The inside fruit condition ships to a hypoxic condition, and then ethanol is induced to accumulate in the aril. Thus, as the primary substrate for ester biosynthesis in durian aril, ethanol will react with some acyls CoA from amino acid metabolisms and lipid degradation. 2-Methyl butyric acid and 3-methyl butyric acid, changed from isoleucine and leucine, are modified to the acyl CoA derivatives by 2-oxoacid dehydrogenase in fruit (Allwood et al., 2014), whereas C_6-C_{10} acyls CoA could be derived from lipoxygenase (LOX) pathway (Contreras & Beaudry, 2013) and/or from increasing β-oxidation during fruit ripening (der Agopian, Fabi, & Cordenunsi-Lysenko, 2020). Some ethyl esters with short-chain acyls produce a rancid odor. Moreover, cysteine metabolism is high, related to the production of sulfur-containing compounds (Panpetch & Sirikantaramas, 2021). The synergistic effect of rancid esters and sulfur-containing volatiles results in the strong, pungent aroma. Furthermore, harvesting "Chanee" durian at 75% maturity causes a reduction in some volatiles, especially sulfur-containing compounds, compared to 100% abscised fruit (Maninang, Wongs-Aree, Kanlayanarat, Sugaya, & Gemma, 2011).

9.2.1.3.2 Pulp color

"Chanee" ripe aril has an intense yellow color and a strong odor, whereas "Monthong" is pale yellow with a mild fragrance. Carotenoids initially accumulate in the aril from 10 weeks after pollination (WAP) and sharply increase after 15 WAP (the harvesting week). Carotenoids gradually increase in "Monthong" aril until 17 WAP (the harvesting week). Mature "Chanee" aril contains total carotenoids at 45 μg/gFW (grams fresh weight), while Monthong contains 8 μg/gFW. Subsequently, ripe "Chanee" aril contains 55 μg/gFW, while "Monthong" is 10 μg/gFW (Wisutiamonkul, Promdang, Ketsa, & van Doorn, 2015). Beta-carotene is high in mature "Chanee" aril (35 μg/gFW) and increases to 43 μg/gFW when ripe. Alpha-carotene in mature "Chanee" aril is at 8 μg/gFW and slightly increases to 10 μg/gFW in the ripe aril. Lutein and zeaxanthin are few in the aril. Beta-carotene in Chanee is four times higher than "Monthong" (Charoenkiatkul, Thiyajai, & Judprasong, 2016; Wisutiamonkul et al., 2015). In contrast, phenolics accumulate four times higher in "Monthong" aril than "Chanee" related to 2,2-diphenyl-1-picrylhydrazyl, and ferric reducing antioxidant power of "Monthong" is approximately two times higher than "Chanee" (Charoenkiatkul et al., 2016). "Monthong" contains vanillic acid at mature, ripe, and overripe is 300, 250, 970 μg/100 gFW, respectively, whereas Campherol is 1100, 2200, 8500 μg/100 gFW, respectively. Quercetin is found only in ripe aril at 1200 μg/100 gFW (Arancibia-Avila et al., 2008).

9.2.1.4 Physiological disorders

9.2.1.4.1 Fruit dehiscence

Fruit dehiscence or pericarp dehiscence is typically found in most durian cultivars during late ripening. In most cultivars, fruit at dehiscent stages indicates the overripe maturity, when the aril released a strong aroma and very soft with a juicy and bitter taste. However, in some varieties such as "Monthong," the aril at the early stage of fruit dehiscence remains firm. For durian fruit dehiscence, each fruit segment's abscission layer at the middle is split, starting at the capsule's end (Fig. 9.5). The endogenous ethylene, produced in a large volume from the husk, is crucial to induce the separation evidence when the relative humidity is low in the atmosphere and can increase the degree of fruit dehusking (Ketsa & Pangkool, 1994). Fruit dehiscence of durian starts as they approach full ripeness and increases in severity toward overripeness. Although the increased activities

FIGURE 9.5 Pericarp dehiscence of durian fruit at overripe stages from the vertical side.

of pectin methylesterase and polygalacturonase were related to increased levels of water-soluble pectin in the dehiscent abscission zone of "Monthong," both play only a minor role in the fruit de-husking process (Khurnpoon & Siriphanich, 2005). Fruit dehiscence can cause a problem of disease contamination to the aril.

9.2.1.4.2 Uneven aril ripening

Arils in locules within a single whole fruit can vary in maturation and ripening. Durian arils comprise various layers starting from the funiculus and developed to wrap up at the seed. Uneven ripening is often found in "Monthong" durian flesh which is thick, but the defect cannot be detected visually from the external appearance (Chaiprasart & Siriphanich, 2000). As harvested at the mature green stage when being at the preclimacteric stage (the lowest ethylene production rate), Thai durian typically exhibits the uneven ripening of whole fruit segments, especially without postharvest ethylene induction. There are various phenotypes of each segment in a whole fruit if the plant is grown among various durian cultivars and naturally pollinated. Male pollen from different varieties affects the aril of each segment in the color and/or texture. Uneven ripening was frequently found in durian trees 50% sunlight shaded (Pakcharoen, Tisarum, & Siriphanich, 2013). Uneven fruit ripening may be overcome by harvesting at the proper maturity and treating ethylene, ethephon, or calcium carbide (CaC_2) for regular ripening.

9.2.1.4.3 Water core

Wet core or water core is an internal fruit disorder in durian. The aril flesh connected to the seeds and the fruit placenta is very moist caused by overwater supply just prior to harvest. The disorder is usually found in late harvesting cultivars grown in Eastern Thailand. During fruit maturation, typical heavy rains lead to plants absorbing water from the soil to the fruit. Water is translocated from the mother tree through the placental xylem and accumulates at the connection of aril with the placenta, and then fruit develops the water core disorder (Ketsa, Wisutiamonkul, Palapol, & Paull, 2020; Nanthachai, 1994). The ripe aril close to the seed is soaked and softened. The ripe aril rapidly decays and senesces faster than unaffected aril. Thus "Monthong" and "Kanyao," late-maturing durian varieties that mature during the heavy rainy season, generally encounter the problem. Covering the stem base with plastic sheets at least a month before harvesting during the heavy rainy season reduces the wet core incidence (Hau & Hieu, 2017).

9.2.1.4.4 Aril tip burn

The disorder starts from the end of pulp wrapping (aril tip) by turning dark brown tissue. The texture is dried, hard, and the taste is not sweet. The disorder usually occurs during rapid aril growth and formation with insufficient nutrient supply or insufficient water. On the other hand, during fruit maturation on the tree, when there is heavy rain (excessive water supply), the plant can produce some shoots. The leaf flushing and young leaves compete with fruit development. The plant could translocate some nutrients from the fruit to supply the new shoot (Punnachit, Kwangthong, & Chandraparnik, 1992). Young trees and unhealthy trees bearing many fruits tend to generate aril tip burn (Arceo, 2008). Covering the stem base with plastic sheets at least a month before harvesting during the heavy rainy season can reduce the aril tip burn (Hau & Hieu, 2017). The procedure could prevent water loss from the soil or protect the excess water from rainfall.

9.2.1.5 Postharvest quality and applications

Artificial ripening is required for Thai durians as they are harvested unripe. Currently, ethephon (2-chloroethyl phosphonic acid) is ordinarily used as a ripening solution for durian to induce ripening. The maximum acceptable remaining residue of ethephon is less than 2 mg/kgFW [Codex Alimentarius Commission (Joint FAO/WHO Food Standards Programme), 2016]. One practical procedure is to apply by pasting 13%−52% ethephon on the peduncle's cut surface for a week at 15°C, and the remaining residue is less than the standard (Sangwanangkul, 2017). However, ethylene gas application could be used for commercial for more safety and efficiency.

"Monthong" aril is low in carotenoid. The content can be improved by artificial ripening. An increase in b* value of ripened aril is higher in 480 mL/L ethephon treatment compared to untreated control. Ethephon-induced ripening is 2 days shorter than control (Thongkum et al., 2018). However, the carotenoid content is not significant to control that carotenoid accumulation during ripening is regulated by endogenous ethylene controlling the gene expression (Wisutiamonkul, Ampomah-Dwamena, Allan, & Ketsa, 2017). Since durian aril contains many layers (Fig. 9.3B), the increasing carotenoids induced by exogenous ethylene may result in its substantial accumulation in the outer layer.

9.2.2 Mangosteen

Mangosteen fruit develops as a parthenocarpic fruit. It contains some apomictic seeds in large segments and aborted seeds in small segments. Mangosteen plants are derived from a single clone. Fruit shape is round and flat with a green calyx on top as a crown. A fresh green calyx is an indicator of fruit freshness. From mature to ripe, the fruit skin turns from green to dark purple. Thick rind (0.5−1.0 cm) develops from the ovary wall containing latex ducts. The flesh (aril) is crispy white with sour and sweet at early ripening and turns to soft white with sweet and sour at fully ripening. Fruit weight 10−12 fruit/kg is the commercial grade.

9.2.2.1 Fruit anatomy

Fruit rind develops from the ovary wall when the flesh is late developed from the integument of apomictic seed or aborted seed (Fig. 9.2A). In general, mangosteen fruit contains five to eight segments. The large segments usually contain an apomictic seed inside the aril, and the small segments contain an aborted seed. The mesocarp contains groups of vascular bundles and fiber, connected to aril and seeds and linked to the stem peduncle. At initial growth stages, the pericarp and aril are tightly connected. During fruit ripening, the rind starts softening before the arils, which will come later. The rind accumulates high phenolics and lignins to protect from unsuitable environments. For example, fruit exposed to intense light that being outer canopy is more colorful than in the shade. Furthermore, it protects from diseases and insects. However, the rind receiving mechanical impacts will rapidly accumulate lignin, resulting in the pericarp hardening. The rind contains plenty of latex secretory ducts, connected as a network in the exocarp, mesocarp, and endocarp of mangosteen fruit (Dorly, Tjitrosemito, Poerwanto, & Juliarni, 2008), are released through the pericarp and aril when the pericarp is physically damaged. The seed in a translucent segment is higher vigor than the seed in a normal segment. Then, it is a highly energetic metabolism that is easy to be found in the translucent flesh. Aril comprises parenchyma bound with some fibrous integument. Low-temperature storage induces the accumulation of fibrous tissues, easily attaching to the teeth grooves during consumption.

9.2.2.2 *Fruit development and harvest index*

Mangosteen is commercially harvested at the red-pad stage (fruit skin turns from green to about 20% red). Mangosteen is a climacteric fruit, but the preclimacteric stage is at the mature green fruit (Fig. 9.6D) on the tree (Noichinda, 1992). The harvesting index is at the red pad because the fruit has already created the abscission layer, making it easy to remove from the tree (Fig. 9.6E). Harvesting fruit at the green stage could damage shoots on the tree and affect flowering for the following season. The aril begins ripening as the skin becomes purple. As the aril becomes sweet and soft, the calyx starts senescing (turning to yellow and red). The reducing sugars significantly increase in the aril from the red-pad to the dark purple stages (Ratanamarno, Uthaibutra, & Saengnil, 1999). After the purple stage (Fig. 9.6F), the fruit harvested develops a red calyx (Fig. 9.6H), which downgrades them from the export standard. Fruit harvested at early-mature green cannot develop to dark purple color of the fully ripe stage; they turn to only reddish-purple peel. The accumulation of anthocyanins, including cyanidin-3-glucoside, pelargonidin-3-glucoside, cyanidin-3-sophoroside, in the pericarp is related to the color changes during ripening (Zerena & Sankar, 2012). Furthermore, ripe pericarp accumulates high levels of xanthones, including mangostingone, mangostenol, cudraxanthone G, 8-deoxygartanin, 8-hydroxycudraxanthone G, garcimangosone B, garcinone D, garcinone E, gartanin, 1-isomangostin, α-mangostin, γ-mangostin, mangostinone, garcimangosxanthone H, garcimangosxanthone I, smeathxanthone A, and tovophyllin A (Jung, Su, Keller, Mehta, & Kinghorn, 2006; Li et al., 2020), whereas α-mangostin and γ-mangostin are the major xanthones accumulating in the ripe aril (Sukatta et al., 2013). As xanthones are a class of phenolic compounds showing antioxidant properties and potential medicinal benefits, the ripe mangosteen pericarp is widely used as a component in many healthy foods, cosmetics, and medicines.

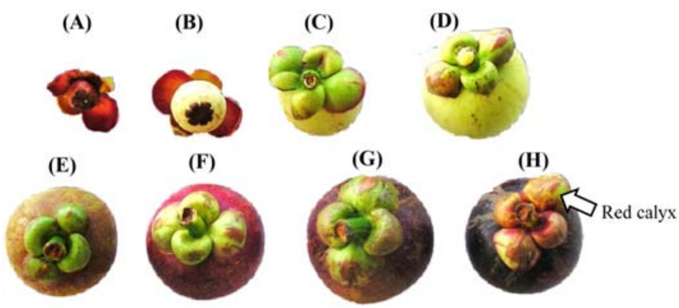


FIGURE 9.6 Stages of fruit development in mangosteen: fruit setting (A), fruit enlargement (B), immature fruit (C), mature green fruit (D), red-pad fruit (E), pink fruit (F), purple fruit (G), and fully ripe fruit (H). The arrow indicates the red calyx.

TABLE 9.3 Major volatile components of mangosteen fruit (Macleod & Pieris, 1982; Laohakunjit, Kerdchoechuen, Matta, Silva, & Holmes, 2007).

Terpene	Aldehyde	Alcohol	Ester
α-Copaene	Hexanal	Hexanol	Hexyl acetate
α-Terpineol	(*E*)-2-Hexenal	(*Z*)-3-Hexenol	(*Z*)-3-Henenyl acetate
Guaiene	2,2-Dimethyl-4-octanal		Hexyl-*n*-valerate
Valencene	Nonanal		Cyclohexyl 4-ethylbenzoate
Cadiene	Benzyl aldehyde		
α-Caryophyllene	Phenyl acetaldehyde		
α-Muurolene			
Methoprene			
Xylene			

9.2.2.3 Aroma volatiles

Although ripe aril of mangosteen performs few fragrances, it is synergistic with the fresh taste for the peculiar flavor. The odor character of mangosteen pulp includes hexyl acetate, (*Z*)-3-hexenyl acetate, and (*Z*)-3-hexenol (Macleod & Pieris, 1982). The major mangosteen volatiles from Table 9.3 suggest that terpenoid biosynthesis and fatty acid oxidation are influentially involved in the production. Six sesquiterpenes are derived from the mevalonate pathway, whereas C_6- and C_9-volatile derivatives indicate the oxidation of unsaturated fatty acids by LOX. Alcohol dehydrogenase and alcohol acyltransferase (AAT) play further roles in producing the alcohol and ester derivatives.

9.2.2.4 Physiological disorders

9.2.2.4.1 Pericarp hardening

Mangosteen has a thick rind containing high phenolics. When these are released by mechanical damage during harvest and postharvest handling, the pericarp hardens. This hardening can occur within just 3 h of the impact caused by a drop of at least 80 cm. Phenolics and lignins in the pericarp increase (Ketsa & Atantee, 1998). However, the pericarp hardening could be partially derived from the browning reaction as coumaric, and sinapic acids are used to form browning by polyphenol oxidase (PPO) (Ketsa & Atantee, 1998). Furthermore, pericarp hardening of mangosteen fruit getting an impact is delayed by keeping at low O_2 (Bunsiri, Ketsa, & Paull, 2003) or high N_2 (Ketsa, 2005). As evidence of hardening control, lignification and browning generation is involved in the pericarp's injured cells. Cell death and water loss follow. However, low O_2 affects cinnamyl alcohol dehydrogenase (CAD) and PPO since PPO needs O_2 to modify free phenolics to quinone and then polymerization to brown pigment and induce to death of the cells. Furthermore, chilling injury during fruit storage can induce pericarp hardening. Low temperature causes the accumulation of lignins in the pericarp related to reducing free phenolics (Ketsa, 2005; Noichinda, Bodhipadma, & Wongs-Aree, 2019).

9.2.2.4.2 Translucent flesh

Translucent flesh, an internal disorder, develops during mangosteen fruit ripening, such that aril firmness increases resulting in a crispy texture and a change in flesh color

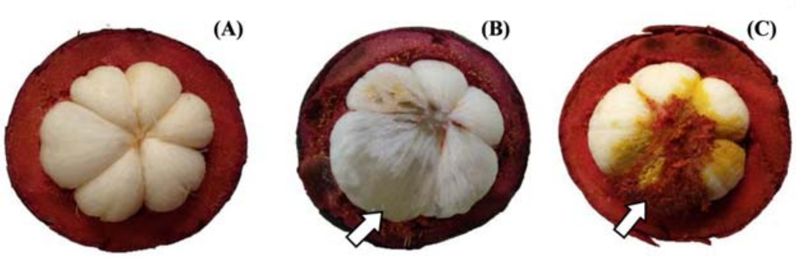


FIGURE 9.7 Normal aril (A), translucent flesh (B), and gamboge affecting the inner flesh (C).

from white (Fig. 9.7A) to translucent (Fig. 9.7B). The disorder is usually found in the aril flesh of large carpels containing an apomictic seed. Pectin turns to water-soluble pectin, but translucent tissue contains a high content of pectin dissolved in the Na_2CO_3 fraction of fruit extracts. The Na_2CO_3-soluble pectin comprises structural esterified-pectin. Since cinnamic acid biosynthesized from the phenylpropanoid pathway is converted to monolignol by CAD, the monolignol is then bound to the cell wall by peroxidase (POD) together with H_2O_2 and create a stiff and translucent texture. The flesh turns from white to translucent because lignins accumulate highly in the cell wall of parenchyma tissue. The affected cells still alive, but their cell walls are thickened by lignification (Wongs-Aree, Siripirom, Satipongchai, Bodhipadma, & Noichinda, 2021). Translucent flesh disorder is widespread and developed in fruit during fruit maturation on-tree during rain or water supply (Noichinda, Bodhipadma, & Kong-In, 2017; Sdoodee & Chairawipa, 2005). White normal aril tissue contains higher numbers of intact protoplasts, whereas, in natural translucent aril, the protoplasts are cracked and lost.

Water vacuum infiltration can affect the translucency of treated mangosteen ripe aril (Pankasemsuk, Garner, Matta, & Silva, 1996) that the high pressure broke the cells. However, the water-treated aril is soft, unlike the firm, crispy translucent flesh found naturally. This uncharacteristic softening indicates that the translucent disorder is directly induced by a high accumulation of secondary lignification walls. During rainfall, rainwater is absorbed into the fruit pericarp by capillary force and circulated in the pericarp, generating a hypoxic condition in the fruit. A high level of reactive oxygen species (ROS) is induced in the aril by anaerobic respiration and the pentose phosphate pathway, which intermediates the Shikimic pathway to produce phenolics and lignins. In the phenylpropanoid pathway, monolignols are produced by CAD, and POD transfers the monolignols to bind to the cell wall. Subsequently, other monolignols polymerize to the lignino-cell wall as lignification of the second cell wall as the putative ROS-defensive function by hypoxia shown in Fig. 9.8 (Wongs-Aree et al., 2021). ROS, in particular O_2^-, is detoxified to H_2O_2, which is reactivated of lignification in the cell wall resulting in stiff-crispy texture by lignin complex esterification in the pectin (Noichinda et al., 2017, 2019; Wongs-Aree & Noichinda, 2018). Fruits with a high specific gravity above 1.0 have a high probability of translucent flesh inside (Chaisrichonlathan & Noomhorm, 2011).

Applications of chitosan spray on fruit on the tree during field cultivation could reduce the translucent flesh and ripening due to its high oxygen transmission rate (OTR) and its water protection of water diffusion into the pericarp.

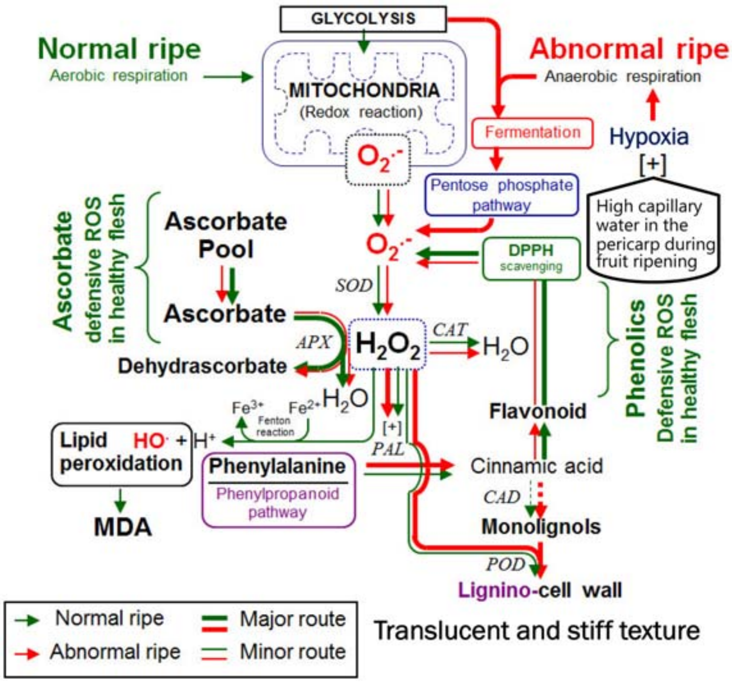


FIGURE 9.8 Putative pathways of lignin formation in translucent mangosteen aril related to an increase in phenolics accumulation and the failure of ROS-defensive mechanism. ROS, reactive oxygen species. Source*: Redrawn from Wongs-Aree, C., Siripirom, P., Satipongchai, A., Bodhipadma, K., & Noichinda, S. (2021). Increasing lignification in translucent disorder aril of mangosteen related to the ROS defensive function. Food Quality*, 2021, *6674208.*

9.2.2.4.3 Gamboge/latex leak

Mangosteen pericarp damage induced by any physical impact during maturation causes latex leaking called "gamboge," both on the outer and the flesh's inner pericarp. Latex secretory ducts are found in all pericarp parts, including exocarp, mesocarp, and endocarp. Large secretory ducts are usually detected in the endocarp—the latex ducts connected from the peduncle to the fruit. Yellow latex collected from the fruit pericarp to the arils contains terpenoids, flavonoids, and tannins, and in the young aril, the latex contains some sterols (Dorly, Tjitrosemito, Poerwanto, & Juliarni, 2008). The latex covers the flesh aril leading to a yellow color and a bitter taste (Fig. 9.7C). Fruit pericarp damaged by aphids during development results in rough skin of yellow hard spot latex. On the other hand, a high level of underground water during the heavy rainy season causes high water potential and pressure in the fruit that can break the latex ducts (Chuennakorn, Paiboon, & Yingjajaval, 2011). The evidence is responsible for pericarp discoloration that the anthocyanin biosynthesis is disrupted, although the aril is still normal. Reduction of yellow latex spots on the outer and inside the fruit pericarp was demonstrated by applying $CaCl_2$ spray during the immature fruit stage developing on trees. Latex disorders were significantly reduced both on the outer fruit and inside the fruit on the aril (Dorly et al., 2011) due mainly to increasing the strength of cell walls.

9.2.2.4.4 Red calyx

Not only is fruit size and bright purple skin of mangosteen required, but the fresh green of calyx on top of the fruit is an essential criterion of mangosteen export. Fruit for export will be harvested at the red-pad stage (15%–20% red shading on the skin). Red calyx of mangosteen fruit develops as the fruit ripens on the tree, typically appearing after the skin turns purple (Fig. 9.6G). An accumulation of anthocyanins in the calyx results in the disorder (Sirikul, Noichinda, Bodhippadma, & Sangudom, 2015). Sunlight exposure during fruit ripening can induce anthocyanin biosynthesis in the calyx. As a result, fruits in the outer canopy tend to develop more red coloration on the calyx.

9.2.2.5 Postharvest quality and applications

Red pad mangosteen will turn fully ripe in several days at room temperature (25°C). In general, fruits at full ripeness can store for a week, but the aril becomes juicy, soft, and has a mild fermented flavor. This cause may come from the thick rind switching on anaerobic respiration. Storage potential can be extended to 4 weeks by keeping at low temperature in perforated modified atmosphere (MA) bags at 13°C (Noichinda, 1992). Eating quality can be compromised in this long-stored fruit the aril becomes juicy and fibrous; it lacks typical sweet and sour (acid) flavors and can take on a fermented flavor.

Mangosteen fruit coated with commercial materials has brighter peel during storage. In Thailand, chitosan is commercially sprayed on fruit during box packing to export mangosteen to prevent calyx browning and water loss (Wongs-Aree & Noichinda, 2014).

9.2.3 Mango

There are two types of mangoes classified by original locations, namely, Indian mango and Indo-Chinese mango. Indian mangoes are monoembryonic and reddish and fragrant when ripe. On the other hand, Indo-Chinese mangoes, located in South-East Asia, are characteristically polyembryonic, and the ripe fruits exhibit bright yellow peel. There are three types of mangoes classified by utilization in Thailand, including ripe-eating type such as "Nam Dokmai," "Naeng Klangwan," and "Khaew Sawoey." Second, green-eating type harvested at the mature green is crispy and sweet when the sour is highly reduced, such as "Khaew Sawoey," "Pim Saen Mun," "Pha Lun," and "Rad." The last is suitable for food processing, such as "Kaew" and "Pim Saen," that the mature green is sour and firm and, when ripe, is not sweet.

9.2.3.1 Fruit anatomy

The mango's edible parts are developed from the ovary wall of pollinated flowers. When the exocarp develops to the peel, the mesocarp is the flesh, and the endocarp develops to the stony seed coat (Fig. 9.2F).

9.2.3.2 Fruit development and harvest index

Mango fruit shows a typical single sigmoid curve of fruit development. The pulp turns yellow from 60 days after anthesis (DAA), whereas peel color changes from green to colorful from 70 DAA. The seed coat becomes hard after 75 DAA. Fruit harvest index is approximately 110–120 DAA. Fruit reaches stable fresh weight at 90 DAA, but the dry weight continues to increase until harvest. In "Nam Dokmai #Seethong," which is a selection of "Nam Dokmai," a fruit becomes bright yellow like ripe fruit since the immature green stage so that the fruit is difficult to indicate the maturation by visual appearance. If the region adjacent to the stem of ripe mango fruit becomes shriveled, the fruit is harvested at the immature stage.

9.2.3.3 *Aroma volatiles and color*

9.2.3.3.1 Aroma volatiles

Indo-Chinese-type mango exhibits yellow peel and pulp and strong turpentine flavor, whereas many ripe mangoes in the Indian type comprise intense colorful peel color, a strong fragrance, and high nutrition value of the pulp (Tharanathan, Yashoda, & Prabha, 2006). In Thailand, Indo-Chinese-type mangoes are dominant. Ripe "Nam Dokmai" fruit contains plenty of terpenes both in monoterpenes and sesquiterpenes but very rare in esters and sulfur-containing compounds (Table 9.4). "Carabao" of the Philippines contains fewer terpenes and many esters. For an Indian-type mango, "Alphonso" is enriched in aroma volatiles that contains high levels of alcohols, aldehydes, esters, and some terpenes. "Mahachanaka," a hybrid bred from Indo-Chinese-type ("Naeng Klangwan") and Indian-type ("Sunset") mango, delivers a mixture of terpenoid compounds and esters. However, Thais do not prefer the odor of "Mahachanaka" for fresh consumption; most of the fruit production is made into processed products.

Furthermore, "Alphonso" and "Carabao" exhibit sulfury odor characteristics when the former contains (methylthio) phenyldehyde and benzothaizol (Engel & Tressl, 1983) and the latter contain 2-propanethiol (Naef, Velluz, & Jaquier, 2006). Although these sulfur-containing compounds present at trace components, they express the fruits' key aroma compounds contributing to the sulfur flavor.

9.2.3.3.2 Peel and pulp colors

In mango peel, high contents of β-carotene and violaxanthin are found in yellow cultivars when anthocyanin content (cyanidin, peonidin, petunidin, pelargonidin, and delphinidin) is increased in red types during maturation (Ranganath et al., 2018). On the other hand, the most important pigments of mango flesh include β-carotene and chlorophylls (*a* and *b*) (Maldonado-Celis et al., 2019). The colors of mango peel typically turn from green to colorful during fruit maturation in the field. Preharvest bagging improves the development and quality of mango fruits and prevents disease and insect attacks. Paper bagging of "Nam Dokmai" mango resulted in a pale-yellow peel beginning at 65 DAA, while plastic bagging improved peel glossiness (Chonhenchob et al., 2011). However, in some cultivars such as "Lily" and "Mahachanaka," bagging during fruit maturation in the field reduces red color development on the peel by reducing anthocyanin content (Karanjalker, Ravishankar, Shivashankara, & Dinesh, 2018; Suwannachot, Kondo, & Setha, 2016).

9.2.3.4 *Physiological disorders*

9.2.3.4.1 Jelly flesh

Jelly flesh of a mango fruit is an internal breakdown during fruit ripening of the flesh around the seed. The flesh tissues surrounding the hard shell turn into transparent, gelatinous cellular tissue with yellow color. The disorder is surrounded by normal ripe tissues (Fig. 9.9). The disorder is often found in fruit ripening on the tree (Wongs-Aree & Noichinda, 2018). A mango fruit gradually generates a cuticle wax covering the peel

TABLE 9.4 Aroma volatiles of ripe mango fruit from four cultivars.

Volatile components	Thai mango "Nam Dokmai" Laohaprasit, Ambadipudi, and Srzednicki (2011)	Thai mango "Mahachanaka" Laohaprasit, Kukreja, and Arunrat (2012)	Indian mango "Alphonso" Engel and Tressl (1983)	Philippine mango "Carabao" Naef et al. (2006), An, Keum, and Lee (2015)
Aldehydes and Ketones				
Benzene acetaldehyde	✓	–	✓	–
Hexanal	–	–	✓	–
(*E*)-2-Hexenal	✓	–	✓	✓
(*Z*)-3-Hexenal	✓	–	–	✓
Heptanone	–	–	✓	–
Furfural	✓	–	✓	–
(*E*,*Z*)-2,6-Nonadienal	–	–	✓	–
β-Ionone	–	–	✓	–
(Methylthio) phenyldehyde	–	–	✓	–
Alcohols		–		
1-Butanol	–	–	✓	–
2-Methyl propanol	–	–	✓	–
2-Propanethiol	–	–	–	✓
2-Methyl-3-butenol	–	–	✓	–
3-Methyl butanol	–	–	✓	–
1-Hexanol	✓	–	✓	–
3-Hexanol	✓	–	–	–
(*Z*)-3-Hexen-1-ol	✓	–	✓	✓
(*E*)-3-Hexen-1-ol	–	–	✓	✓
1-Hexadecanol	–	–	✓	–
Phenethyl alcohol	–	–	–	✓
Benzothaizol	–	–	✓	–
Monoterpene hydrocarbons				
Limonene	✓	–	✓	–

(*Continued*)

TABLE 9.4 (Continued)

Volatile components	**Thai mango "Nam Dokmai"** Laohaprasit, Ambadipudi, and Srzednicki (2011)	**Thai mango "Mahachanaka"** Laohaprasit, Kukreja, and Arunrat (2012)	**Indian mango "Alphonso"** Engel and Tressl (1983)	**Philippine mango "Carabao"** Naef et al. (2006), An, Keum, and Lee (2015)
trans-Ocimene	✓	–	✓	✓
cis-Ocimene	✓	✓	✓	–
cis-Linaloloxide	✓	–	–	–
δ-2-Carene	✓	✓	–	✓
α-Pinene	–	✓	✓	✓
β-Pinene	–	✓	✓	–
Myrcene	–	–	✓	✓
β-Phellandrene	–	–	–	✓
α-Terpinolene	–	–	–	✓
α-Terpinene	–	✓	–	–
Sesquiterpene hydrocarbons				
δ-Elemene	✓		–	–
α-Copaene	✓	–	✓	–
α-Bourbonene	✓	–	–	–
β-Bourbonene	✓	–	–	–
β-Elemene	✓	–	–	–
β-Caryophyllene	✓	–	✓	✓
Humulene	✓	✓	✓	–
β-Cubebene	–	–	–	–
α-Guaiene	✓	–	–	–
α-Caryophyllene	✓	–	–	✓
α-Cubebene	✓	✓	–	–
γ-Muurolene	✓	–	–	✓
Germacrene D	✓	–	–	✓
α-Bulnesene	✓	–	–	–
allo-Aromadendrene	✓	–	–	–
α-Cadinene	✓	–	–	✓
β-Silenene	✓	✓	–	–

(*Continued*)

TABLE 9.4 (Continued)

Volatile components	Thai mango "Nam Dokmai" Laohaprasit, Ambadipudi, and Srzednicki (2011)	Thai mango "Mahachanaka" Laohaprasit, Kukreja, and Arunrat (2012)	Indian mango "Alphonso" Engel and Tressl (1983)	Philippine mango "Carabao" Naef et al. (2006), An, Keum, and Lee (2015)
Esters				
Ethyl acetate	–	–	–	✓
Ethyl butanoate	–	✓	–	–
Ethyl dodecanoate	–	–	✓	–
Ethyl hexadecanoate	–	–	✓	–
Butyl acetate	–	–	✓	–
Isobutyl acetate	–	–	✓	–
Hexyl acetate	–	–	✓	–
(*Z*)-3-Hexenyl acetate	–	–	✓	–
(*Z*)-3-Hexenyl butanoate	–	–	✓	✓
(*Z*)-3-Hexenyl butenoate	–	–	✓	–
Ethyl-3-hydroxyl butanoate	–	–	✓	–
Methyl hexanoate	–	–	–	✓
Ethyl-(*E*)-2-hexenoate	–	–	–	✓
Methyl octanoate	–	–	–	✓
Methyl-(*E*)-octenoate	–	–	–	✓
Ethyl octanoate	–	✓	–	✓
Ethyl-(*E*)-octenoate	–	–	–	✓
Ethyl isovalerate	–	✓	–	–
Ethyl decanoate	–	✓	–	–

FIGURE 9.9 Jelly flesh disorder surrounding the seed (pointing arrow) in ripe mango.

during fruit maturation to prevent water loss from the flesh. As maturity progresses, the layers of the cuticle become thicker. The thick cuticle at maturation could reduce gas transmission, leading to a substantially modified internal atmosphere as respiration increases during ripening. Together with a blockage of intercellular spaces within the fruit flesh, this could potentially lead to tissues deep in the inner flesh entering a hypoxic condition. This evidence is consistent with the observation that this fruit can accumulate fermented flavors, which taste slightly fizzy.

9.2.3.4.2 Unripe starchy tissue

Fluctuating weather conditions in the field can induce some disorders in mango fruit. Fruit maturing under hot weather and affected by high levels of rainfall can generate starchy flesh tissues during fruit ripening. The starchy tissue is surrounded by ordinary ripe flesh. The disorder symptom exhibits white-dry tissue, and the texture is not turning soft. Moreover, the symptom is synergistically found in mango treated by postharvest heat vapor during quarantine prior to export to Japan and Korea or when treated by gamma radiation for export to the United States.

9.2.3.5 Postharvest quality and applications

Red-pad coloration on the cheek of "Mahajanaka" fruit is an important quality attribute for the consumer. The fruit develops red color when the outer canopy is exposed to sunlight. Shaded fruit, as well as bagged fruit, rarely develops red color on the exocarp. Phenylalanine ammonia lyase activity is related to phenolic compounds and anthocyanin content during late "Mahajanaka" mango maturation on the tree (Chanchara, Saengnil, & Uthaibutra, 2006). Mature green "Mahajanaka" mango postharvest treated with UV and white light could induce anthocyanin accumulation in the peel at initial stages (first 10 days) of 13°C storage (Thi-utit, Saengnil, & Uthaibutra, 2006). Spray of 10 mM methyl jasmonate (MeJA) on fruit a month before harvest induced the higher accumulation of anthocyanins in the peel (Chanwijit, Whangchai, Saengnil, & Uthaibutra, 2010). Furthermore, pretreatment by 30 ppm MeJA induces ethylene production of "Nam Dokmai" stored at 20°C that β-carotene is higher in peel and pulp of treated fruit (Buanong & Kanlayanarat, 2010).

Mature green fruit is required for ethylene treatment to induce complete ripening. Interestingly, "Khaew Sawoey" mango treated with 1-methylcyclopropene (1-MCP) (500 ppb) maintained α-pinene four times higher than control. Nontreated 1-MCP "Khaew Sawoey" mature green mango accumulated a high amount of hexanal but low α-pinene at 13°C.

Although mango kept in a controlled atmosphere of 3% O_2 and 5% CO_2 maintained α-pinene, ethanol was generated (Piromruen, Jirapong, Techavuthiporn, & Wongs-Aree, 2009). Interestingly, ripe "Nam Dokmai" mango produces new emerging esters when kept in artificial hypoxia of saturated ethanol vapor (Phakawan, 2018). The mango tissues absorbed high amounts of ethanol. Typical ripe "Nam Dokmai" releases no esters (Fig. 9.10A), but treated fruits accumulate a range of ethyl esters (Fig. 9.10B). This result suggests that AAT can play a crucial role in detoxifying fermented intermediates by converting ethanol to ethyl esters under the stress condition (Wongs-Aree & Noichinda, 2018).

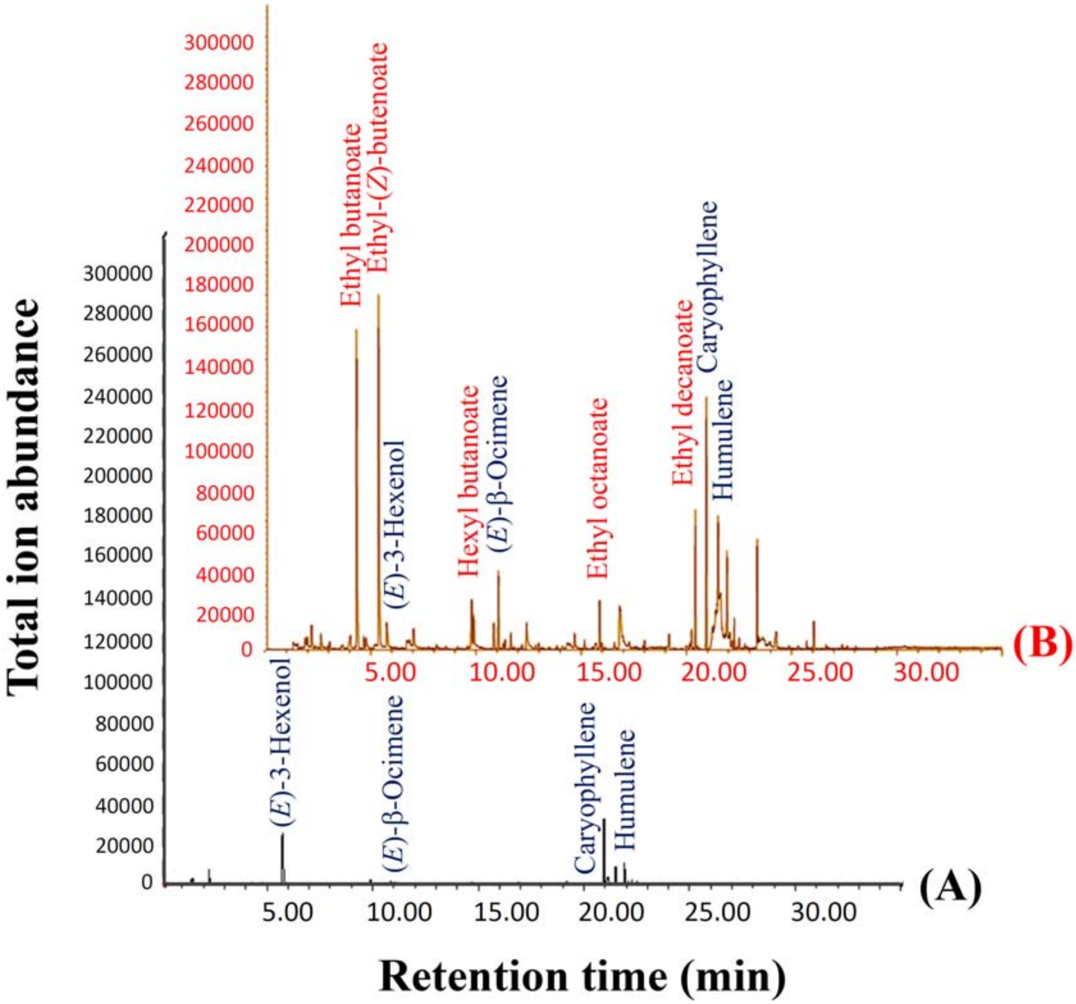


FIGURE 9.10 Volatile profile using HS-SPME/GC−MS detected from mango fruit kept in a retail package without (A) and with ethanol releasing sachet (B) on day 7 of 25°C storage. *HS-SPME/GC−MS*, Headspace solid phase microextraction/gas chromatography−mass spectrometry. Red alphabets indicate new emerging ester compounds in ripe mango under ethanol vapor on day 7.

9.2.4 Papaya

Fresh papaya in Thailand can be used for consumption in two ways. One is an ingredient for making salads. The fruit of any variety can be used for salads, but "Khaek Dam" and "Kheak Nual" are proper for the ingredient due to their firm and crispy texture. The other is a ripe-eating type such as "Kheak Dam" and "Maradol" harvested at the breaking stage.

9.2.4.1 *Fruit anatomy*

Papaya is native of tropical America but now widespread across tropical areas. It is a climacteric fruit, but the photosynthetic compounds accumulate as cellular structural carbohydrates instead of starch, lipid, or sugars and acids in other fruits (der Agopian et al., 2020). A papaya fruit is a true berry developed from a single flower with one carpel. The exocarp develops to the fruit skin, endocarp to the flesh, and endocarp to the placenta with a cavity and numerous seeds (Fig. 9.2H).

9.2.4.2 *Fruit development and harvest index*

Papaya should be harvested at the breaker stage, as maturity affects the soluble solids (SS). The fruit needs to be harvested at proper maturity as a yellowing sign at least 5% on the peel which is passed from the preclimacteric stage (Nakasone & Paull, 1998). "Pluk Mai Lai or Maradol" papaya ripening on tree contains 14% SS. Fruit harvested at the mature green stage and allowed to ripen at room temperature contains 12% SS. The firmness of fruit ripening on and off-tree is not significantly different. Papaya skin changes from green to greenish-yellow can be used as a harvest index before turning yellow at the fully ripe stage (Nakasone & Paull, 1998).

9.2.4.3 *Aroma volatiles and color*

9.2.4.3.1 Aroma volatiles

When ripening, papaya fruit does not obviously release the aroma. The volatile profiles are altered during fruit development and can be used as fruit maturation indicators. Fuggate, Wongs-Aree, Noichinda, and Kanlayanarat (2010) reported in "Maradol" papaya that benzyl isothiocyanate was the most abundant volatile and was present in fruit at every stage except full ripening. 2-Ethyl-1-hexanol was found specifically in green fruit, and ethyl octanoate emerged only in fully ripe fruit. Limonene sharply increased at the breaker stage, whereas ethyl esters were plenty at the full ripening (Fig. 9.11). During ripening, the flesh pectin is methylated, which could provide methanol levels for synthesizing methyl esters. Butanol and hexanol gradually increase from mid to fully ripe. The production of total esters of "Maradol," is directly correlated with a loss of firmness and an increase in cavity ethylene. Accumulation of ethylene is about 10-fold higher in fruit ripened off the tree. Total esters in off-tree ripening are much higher. Methyl butanoate, ethyl butanoate, 3-methyl-1-butanol, and 1-butanol are predominant in the ripe papaya (Fuggate et al., 2010). This is consistent with Pino, Almora, and Marbot (2003) that esters and alcohols are prominent in papaya, but the esters are lower fatty acid contributing to the typical papaya flavor.

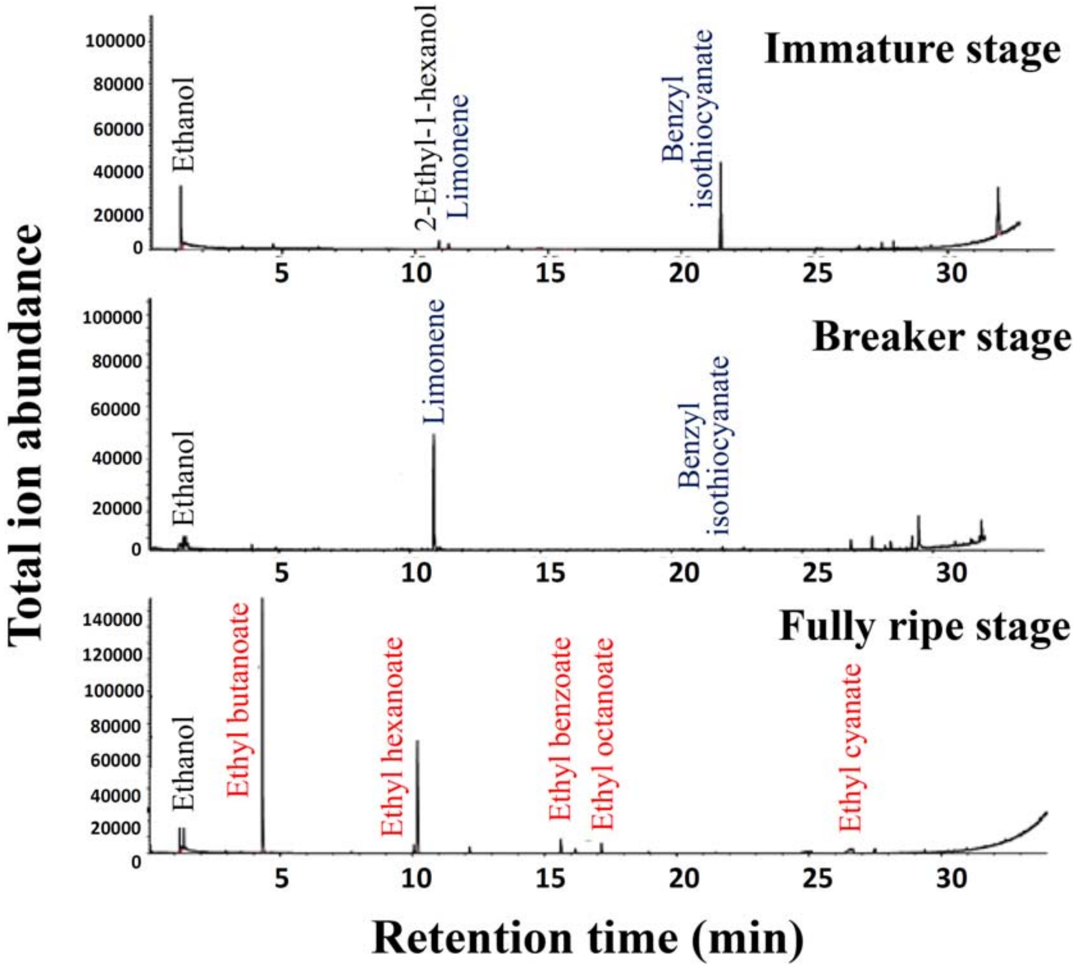


FIGURE 9.11 SPME/GC–MS total ion chromatograms of volatiles of three different maturities of "Pak-Mai-Lai" (Maradol) papaya. *SPME/GC–MS*, Solid phase microextraction/gas chromatography–mass spectrometry. Red alphabets indicate ethyl ester compounds.

9.2.4.3.2 Peel and pulp colors

"Maradol" papaya fruits ripened on trees develop a redder peel than those harvested at breaker color and ripened at room temperature (Fuggate et al., 2010). Sunlight exposure is a crucial factor to induce the carotenoid biosynthesis in fruit peel during maturation in many fruits (Lado et al., 2019; Llorente et al., 2016; Solovchenko, Avertcheva, & Merzlyak, 2006). On the other hand, the main carotenoids in the red-fleshed papaya are lycopene, β-carotene, and β-cryptoxanthin, which lycopene accumulation in papaya is found only in the red flesh (Schweiggert, Steingass, Heller, Esquivel, & Carle, 2011). Carotenoid contents and components in papaya grown in different geographical locations are different due reportedly to different climate factors (Almeida, Bernardo, Sousa, Marin, & Grippa, 2003; Wall, 2006). In Thailand, the red-fleshed papayas' lack of red intensity is a significant problem for fresh consumption and processed food. Higher carotenoid contents, especially lycopene, were detected in the papayas grown in oxisols soil (clay), high in organic matter and phosphorus, as compared to Alfisols (loam with high pH and moderate organic matter) and Ultisols soil (loam with low organic matter) types (Sangsoy, Mongkolporn, Imsabai, & Luengwilai, 2017).

9.2.4.4 Physiological disorders

9.2.4.4.1 Peel freckles

The disorder appears on the papaya with skin blemishes visual in mature green and ripe fruit. The size of blemished spots is expanded during fruit maturation and can overwhelm the smaller spots, resulting in a larger area of the symptom. The symptoms develop at the late stages of fruit maturation. The defects are mainly caused by direct sunlight exposure, while the blemishes disorder is highly reduced in fruits that were not exposed to the sun (de Oliveira & Vitória, 2011). Cultivation procedure can reduce the blemishes by bagging fruit with a sheet of aluminized polyethylene a month before the harvest (de Oliveira & Vitória, 2011).

9.2.4.4.2 Pulp gelling

Gelled pulp or translucent pulp in papaya fruit occurs when fruit ripens. The flesh tissue becomes translucent (gel-like) and bland. The gelling tissues develop from the endocarp to the exocarp. Liquid usually accumulates in the fruit cavity when the gelled tissues are sectioned (de Oliveira et al., 2010). These disorder symptoms are similar to mechanical injury, but the injury starts from the outer tissue and develops to the endocarp. The disorder is not associated with tissue premature ripening, but the inhibition of water distribution to the vacuole and the loss of cellular turgor pressure affect the disorder. Water soaking in the tissue is due to water accumulation in the apoplast or intercellular spaces, resulting in water soaking in the mesocarp (de Oliveira & Vitória, 2011; de Oliveira et al., 2010).

9.2.4.5 Postharvest quality and applications

1-MCP treatment reduces aroma synthesis, especially the key volatile of papaya. In the commercial, 1-MCP is applied to mature green papaya for long logistics. In Brazil, 1-MCP (to inhibit ripening) combined with ethylene (to induce ripening and restore the aroma) results in better quality during postharvest handling (Facanha, Spricigo, Purgatto, & Jacomino, 2019). Furthermore, aliphatic ester production derived from fatty acid was effectively inhibited by 1-MCP (Sundaram & Prabhakaran, 2017).

9.2.5 Young coconut

The harvest index of young coconut for export or fruit de-husking is about 2.5 layers when the stem end's meat is still translucent jelly. The fruit exported in the forms of whole fruit or trimmed fruit can be harvested at stages younger than 2.5 meat layers.

9.2.5.1 Fruit anatomy

Young coconut, or so-called tender coconut, is classified as a palm plant producing a drupe fruit in which the liquid (water) and solid endosperms (meat) can be eaten. Coconut fruit comprises exocarp, fibrous mesocarp, and endocarp developed to be a hard shell (Fig. 9.2E). During fruit development, the mother plant's nutrient translocation passes the husk to the shell through the testa. The solid endosperm is generated layer-by-layer by the meristematic cell inside the shell when the liquid endosperm at the initial development stages contains more acids and sugars.

At the initial stages of fruit development, meristematic cells inside the shell undergo cell division forming the structural layer forming colossal cells containing short-chain fatty acids (Fig. 9.12). The developing fruit is characterized by a very high respiration rate and the release of CO_2 into the liquid. As a result, young coconut liquid comprises high CO_2 related to the higher pressure (Jirapong et al., 2018). At the initial stages of development, the young shell is alive and soft. The liquid endosperm accumulates to total capacity, whereas the solid endosperm starts developing at the fruit stylar end. The solid endosperm develops from the young shell tissue covering the inside shell as the first jelly meat layer. Then the second jelly layer continuously develops in parallel with the shell, which becomes hard by accumulating sclereid cells to protect the fruit cracking from the high pressure of the liquid endosperm. The sclereids consist of principal stone cells of roundish sclereid cells and some long sclereid fibers (Schmier, Hosoda, & Speck, 2020). The shell contains high levels of phenolics when it is dried and turns brown during maturation, which is related to the reducing liquid endosperm and the loss of pressure.

The liquid endosperm at primary stages exhibits high pressure as it dissolves high CO_2 concentration (Changprasert, Noichinda, Bodhipadma, & Wongs-Aree, 2011), as the surrounding mesocarp protects the shell from cracking due to the pressure. During the solid endosperm

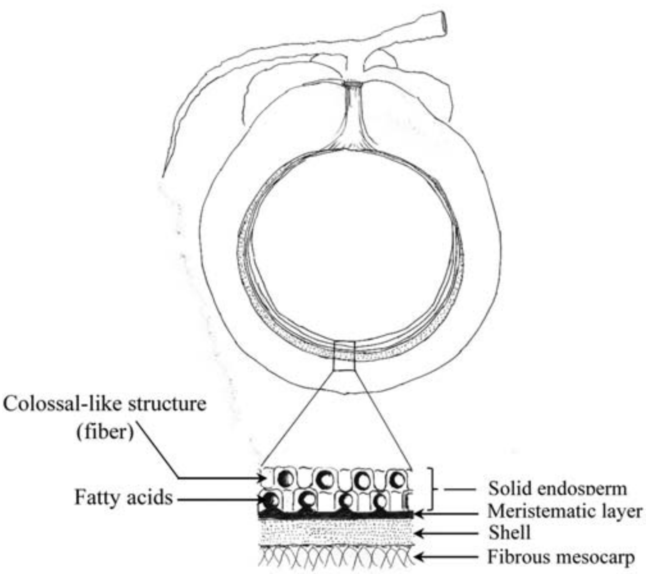


FIGURE 9.12 Colossal cell structure of meristematic cell inside the shell of young coconut.

development of the thickness to two to three layers, when the top of the shell is still soft, dehusking fruit is easy to crack the shell because of the liquid's high pressure. The handmade apparatus for liquid endosperm pressure measuring is shown in Fig. 9.13. The solid endosperm continuously develops and becomes white, thick, and firm, unsuitable for fresh consumption in later development. The coconut fruit's maturation indicates that the outer skin turns brown, the fibrous testa becomes brownish, and the meat is thick and turns white. The liquid portion reduces, allowing a room of air space in the shell. The sound of water passing through the air when the fruit is shaken can indicate fruit maturation. The optimum index for fresh consumption is at the 2–2.5 layers of solid endosperms (ca. 8 months after fruit setting) when the solid endosperm is soft and jelly-like, and the liquid endosperm is sweet and fragrant, tasting fizzy.

As bunch fruit, the fruit maturity in the harvested bunch is different. The oldest fruit starts from the stem end through the end of the bunch. Furthermore, when a bunch is harvested, fruits on the bunch are still continuously developing (Jirapong et al., 2018). The solid endosperm creates increasing thickness, and the husk becomes dried and brown.

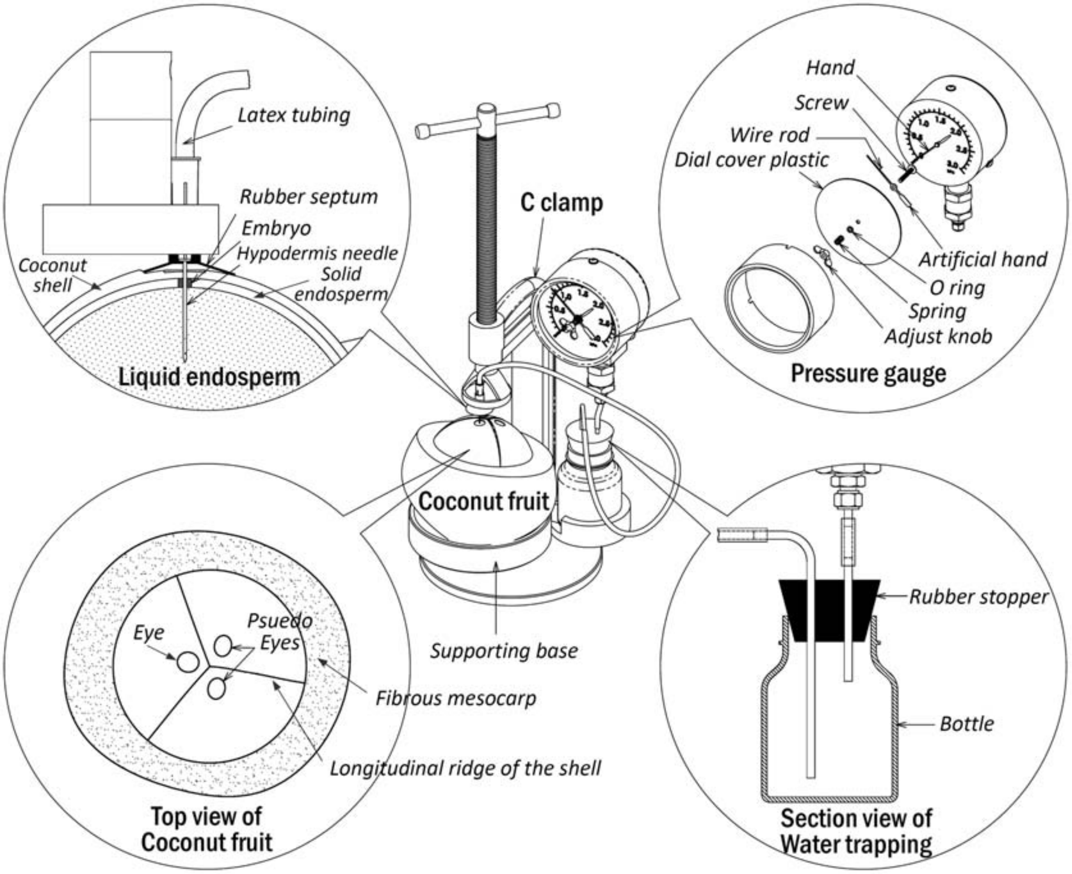


FIGURE 9.13 Coconut liquid endosperm pressure measuring apparatus.

Incubated at ambient conditions, the solid endosperm in fruit continuously develops to thicker, and the liquid is less sweet (Jirapong et al., 2018). For more extended storage periods, the exocarp on top of the fruit visually exhibits shriveling, turns brown, and the calyx is easy to remove. When the top exocarp turns black, the liquid becomes off-favor and turbid. The top of kernel contains three eyes of two pseudo-eyes and a natural eye. The embryo is located under the actual eye. Fruit maturation is indicated by turning white and thick solid endosperm and reducing liquid endosperm when the mesocarp is dehydrated, and the outer skin turns brown. At this stage, the embryo is ready to develop into the plant.

Young coconut fruits are classified into three groups based on weight: small (1.2–1.5 kg), medium (1.51–1.80 kg), and large fruit (> 1.8 kg). Fruit shape is globular and pale green outer skin. The liquid endosperm contains high turgor pressure in the nut kernel cavity. The portion of fruit parts depends on fruit size. Small fruit develops a thicker kernel than medium and large fruit. The small fruit held a thick shell but a thin husk. The fruit shell and mesocarp could protect fruit cracking from the high pressure of liquid endosperm. As far as the dimension of whole and de-husked fruits was concerned, a higher circumference/height ratio of de-husked fruit indicates a rounder fruit. These data imply how deep of husk trimming for designing a suitable young coconut fruit packaging. The large fruit had the highest kernel thickness at the stem end compared to other sizes. Consequently, the kernel can better tolerate the high pressure of the liquid and the outside compression force during transportation (Changprasert et al., 2011).

9.2.5.2 *Fruit development and harvest index*

Development of "Nam Hom" aromatic coconut fruit takes 8–9 months from the fruit set. The fruit weight significantly increases from month 3 to month 5 and then stable to month 7. The thickness of husk and shell increases from month 2. The shell thickness gradually increased through month 7 and then is stable. The liquid endosperm is at 3% SS and 0.03% titratable acidity (TA) in month 3. The SS reaches a peak of 9% in month 7, whereas the highest TA is at 0.07% in month 5. In terms of a good taste of the water, fruit harvested at month 7–8 giving the best value of SS/TA of 128 (Changprasert et al., 2011; Chuntarat, na Jom, & Tongchitpakdee, 2015). The young aromatic coconut's liquid endosperm contains high levels of medium-chain saturated fatty acids of lauric acid (C_{12}) and myristic acid (C_{14}). The portion of these two fatty acids is about 55% of the total fatty acids in the water. The liquid fatty acid components are slightly changed in the liquid of one-layered flesh and two-layered flesh fruit when in the advanced stage, lauric acid increases but myristic acid declines (Jirapong, Wongs-Aree, Noichinda, Uthairatanakij, & Kanlayanarat, 2015). In the liquid endosperm of "King" coconut in month 6, the water contains 1.52 mg/mL of ascorbic, which increases to 2.18 mg/mL by month 8 (Wijeratnam, Jeyachandran, Karunanithy, Hewajulige, & Perera, 2006). There are two groups of soluble sugars in "Nam Hom" liquid endosperm, including the major group (80% of sugar content) of sorbitol and sucrose and the minor group of fructose, glucose, galactose, and myo-inositol. The major group increases and reaches a peak of 25 g/100 gFW in month 7. The minor group is at 140 mg/100 gFW in month 7 and sharply drops to 18 mg/100 gFW in month 9 (Jaroonchon et al., 2017). The commercial stage of young coconut for fresh consumption is typically considered of the color change from dark green to pale green at the outer skin (exocarp), or about 8 months after the fruit set.

The solid and liquid endosperms of young coconut can be consumed as jelly-like meat and soft drink. The coconut meat at the stylar end is thicker than the stem end. The kernel is thickest at the stylar end, and the thickness gradually decreases from the middle to the stem end. The SS/TA ratio of solid endosperm of coconut fruit is highest at the top of the fruit compared to the middle and the bottom (Changprasert et al., 2011). The meat firmness is about 67 N in month 6 to 103.9 N in month 8. In month 6, the total carbohydrates content in meat is 18.7% and is reduced to 5.1% in month 8, whereas in contrast, the fatty acid content is 45.7% in month 6 and is increased to 51.2% in month 8 (Chuntarat et al., 2015).

9.2.5.3 *Aroma volatiles*

For aroma aspects, there are three groups of coconuts in Thailand. First, "aromatic coconut" is a small fruit type. The scent expresses in fruit pericarp and liquid endosperm and root. Second, "Nam Wan" coconut comprises sweet and fresh water but no aromatic fragrance. The last one is "oil coconut" used as "Sawi" for industrial uses. Aromatic coconut is famous across the world as energetic tonic water. Odor character of aromatic coconut is 2-acetyl pyroline (2-AP), a unique Pandan leaf-like smell. 2-AP initially produced in a trace amount in the water on month 2 when in the meat, is accumulated at 2000 ng/gFW on month 6 and then sharply increase to 6000 ng/gFW in month 7, whereas 2-AP in water gradually increase (Jaroonchon, Krisanapook, & Imsabai, 2017; Fig. 9.14). The volatile of 2-AP can be used as the specific indicator of aromatic coconut since it is never found in other coconuts (Jaroonchon et al., 2017).

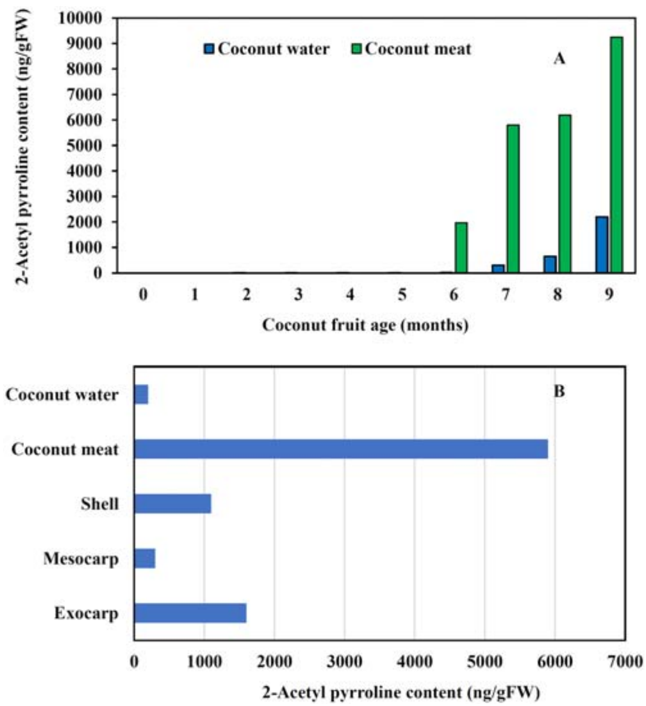


FIGURE 9.14 The content of 2-AP in coconut meat and coconut water during fruit development after pollination (A) and in a different part of the fruit (B). *2-AP*, 2-Acetyl-1-pyrroline. Source*: Redrawn from Jaroonchon, N. (2017). Fruit Development and Expression of Genes Associated with 2-Acetyl-1-Pyrroline Synthesis in Aromatic Coconut., Ph.D. Thesis. Thailand: Kasetsart University.*

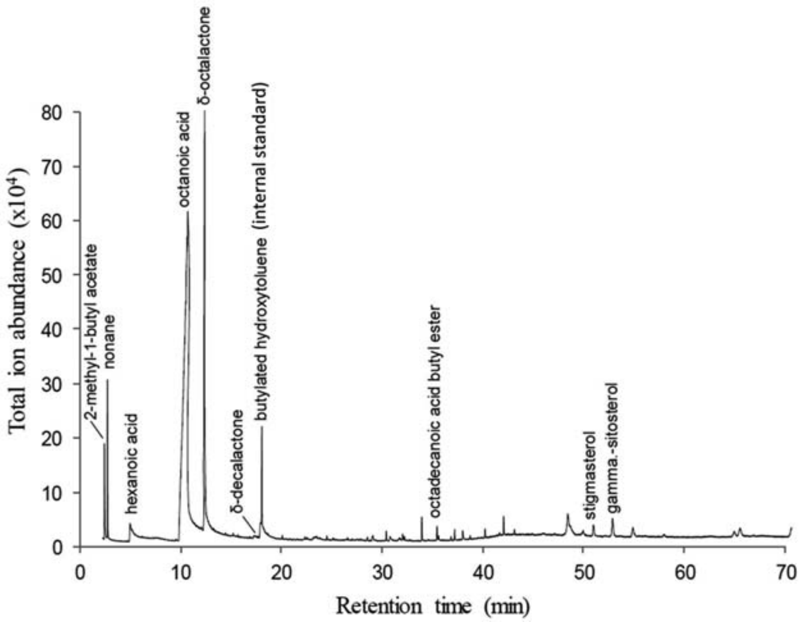


FIGURE 9.15 Ion spectra of aroma volatile compounds identified by GC−MS in the extract of the liquid endosperm of "Sawi" coconut (a variety used for coconut milk processing) at the two-layer stage of flesh maturity. *GC−MS*, Gas chromatography−mass spectrometry.

2-Methyl-1-butyl acetate, α-pinene, 3-carene, and D-limonene are predominant in the liquid endosperm of aromatic young coconut at the first layer meat stage, whereas squalene, γ-sitosterol, and stigmasterol dramatically increase at the two layers of meat at stage (Jirapong et al., 2015). In "Sawi," coconut for making coconut milk, the tender fruit's liquid endosperm contains some fragrant volatiles of 2-methyl-butyl acetate and butyl octadecenoate, and δ-decalactone. Moreover, it comprises short-chain fatty acids (C_6−C_8) and some sterols (stigmasterol and γ-sterol) (Fig. 9.15).

To improve the aroma of liquid in the case of "Nam Wan" coconut, a sweet liquid variety, some heat processing procedures are locally applied. Young coconut fruit is either boiled in water or burnt in a bonfire. The liquid of heat-processed coconut is changed in the aromatic flavor, including roasted flavor. δ-Octalactone, 2-hydroxy-cyclopentadecanone appear when the whole fruit is heated. However, LOX and PPO activity in the liquid is still high after heating (Jirapong, Uthairatanakij, Noichinda, Kanlayanarat, & Wongs-Aree, 2012). This could be the main reason for the degradation of lipids in the water, resulting in reduced drink quality during storage. As a result, the quality of liquid endosperm of young coconut either keeping at low temperature (Jirapong et al., 2018) or processing by heat (Jirapong et al., 2012) could be changed quickly. There is a limitation of the quality of liquid endosperm for consumption, which is challenged for postharvest technology.

9.2.5.4 Physiological disorders

9.2.5.4.1 Incomplete developing meat

It is an internal physiological in coconut fruit at the early stages of fruit development. The meat is found only at the stylar end and not wholly covered all inside the shell. The condition is related to less liquid endosperm in the shell. The meat is not oily when the water is not sweet but sour.

9.2.5.4.2 Makapuno

It is a physiological disorder of coconut during fruit development. Fruit contains high cytokinins, promoting cell proliferation and expansion, resulting in tumorigenesis and greater solid endosperm thickness (Islam, Cedo, Namuco, Borromeo, & Aguilar, 2009). Makapuno also lacks galactosidase activity, which induces the accumulation of the water-soluble galactomannan rather than the water-insoluble mannan found in typical fruit, expressing alteration and adhesion of cell wall of the meat to high viscous endosperm (Mujer, Ramirez, & Mendoza, 1984). Although it is a physiological disorder of coconut, Thais eat Makapuno coconut as desserts or process it into sweets. Partial de-husked Makapuno coconut packed in a high OTR plastic bag and stored at 5°C was best for extended the quality and storage life (Luengwilai, Beckles, Pluemjit, & Siriphanich, 2014).

9.2.5.5 Postharvest quality and applications

Dissolving CO_2 in the liquid of "Nam Hom" aromatic coconut harvested at month 8 is at about 300 mg/mL and increases to about 450 mg/mL on day 4 when the fruit is stored at 25°C. This matter is related to an increase in the liquid end pressure from 0.75 kPa at initial to 1.5 kPa on day 4 (Changprasert et al., 2011). The inclining CO_2 in the liquid should be derived from β-oxidation of the free fatty acids. The meat thickness increases in every fruit part (top, middle, and stylar end). After 10 days at 25°C the thickness of every part is equal. In the liquid endosperm, there is cell suspension. Thus the liquid endosperm is a source for the meat development for increasing thickness.

At 25°C, whole young coconut can be stored for 12 days, whereas at 13°C, fruit has a storage life of 28 days, but a fruit stored at 4°C shows outer skin browning after 8 days. Inappropriate low temperature at 4°C induces LOX activity in the liquid endosperm at the initial stages of storage, resulting in the turbidity of liquid endosperm later on (Jirapong et al., 2018). Whole young aromatic coconut at 6.5 months respires at 45–60 mg CO_2/kg/h at 25°C. C_2H_4 production rate of the fruit is 50 nL/kg/h at initial and increased to 300 nL/kg/h on day 7 (Meethaworn & Siriphanich, 2015). At 4°C, thiobarbituric acid content in the liquid endosperm increased from 100 to 200 nM/mL on day 7, faster than at 25°C. This result is consistent with Jirapong et al. (2018), who report the high activity of LOX in the liquid of fruit stored at 4°C. The evidence leads to the water's rancidity quickly occurring in the fruit kept at 4°C.

Young coconut containing moist husk and a large portion of liquid endosperm is intensively heavy. The shape and size of coconut are big compared to economics when the edible part is less. The trade of whole fruit requires high logistical costs for the disposal of nonedible parts as agricultural waste. The fruit usually requires some minimal processing, such as husk trimming or husk polishing. Trimmed fruit or polished coconut efficiently reduces the fruit weight. Although polished coconut, in which most husk is removed (Fig. 9.16A), is lighter than the trimmed one (Fig. 9.16B), the husk removal significantly decreases the shell rupture resistance (Terdwongworakul, Chaiyapong, Jarimopas, & Meeklangsean, 2009) due to high pressure for the liquid endosperm. Thus a polished coconut has a high loss of cracked fruit from the postharvest handling and the logistics period.

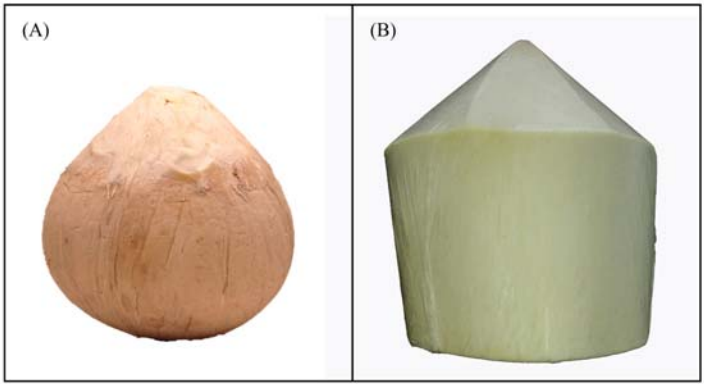


FIGURE 9.16 Polished (A) and trimmed coconut (B).

As a coconut matures, husk rupture resistance decreases. Fruit trimming will remove some mesocarp parts. The remaining mesocarp of the top can protect the fruit from breaking from the high pressure of the liquid. Consequently, the loss from fruit cracking is minimized. However, the cut surface of the husk can be easily contaminated by microorganisms or can generate browning symptoms. At 25°C, the trimmed fruit's respiration rate is almost twice to whole fruit, whereas it is 0.6-old higher at 4°C. Ethylene production of trimmed fruit was 4- to 10-fold higher than the whole fruit during storage. The rancidity of trimmed fruit's liquid is faster than the whole fruit (Meethaworn & Siriphanich, 2015). This mark could probably be due to O_2 diffusion into the liquid easier in trimmed fruit.

Dipping trimmed coconut of 6-month fruit in 5% sodium metabisulfite (SMS) for 5 min delayed the browning on the cut surface and inhibited disease infection. The chemical was found in the trimmed mesocarp but not inside the shell (water and meat). The chemical was found in the water and meat if trimmed fruit was dipped in SMS higher than 5% or longer than 5 min. Furthermore, the chemical was found in the edible parts, and if fruit younger than 6 months or the mesocarp thickness at the top less than 1 cm was treated, the chemical could pass through the water and meat through the soft eye (Mohpraman & Siriphanich, 2012). A trimmed fruit was pretreated with hot vapor at least 3 min combined with 0.9% SMS dipping for 3 min and then wrapped with a 9.8-mm polyvinyl chloride film can be kept at 2°C for a month (Luckanatinvong & Sornkeaw, 2011).

9.3 Summary

Tropical fruits deliver exciting, exotic, and luscious sensory experiences into fruit markets around the world. Delivering these experiences depends upon analogous postharvest management practices to those use in other types of fresh produce. Maturity indices, grading, postharvest treatments, packaging, and temperature management all contribute to reliably providing high-quality fruits to market. Each of these aspects needs to be tailored to the particular needs of the individual fruit species and cultivars.

Fruits after harvest are still alive and continue their biological metabolisms changing the texture, color, and flavor. The best eating quality of tropical fruits is short lasting only several days and poses a challenge to maintain the quality after harvest through retail. Full maturation of most fruits gives the best flavor but suitable for the local markets. Consequently, proper harvest maturity could be compromised for the postharvest quality during storage and logistics. Although young coconut is harvested in the immature stage, the meat layer inside the shell continuously develops at postharvest. Mango, durian, and papaya are commercially harvested at 80% maturation for postharvest handling and management. Nevertheless, late harvesting of mangosteen fruit induces the red calyx, which reduces the retail price. Tropical fruits typically contain high phytochemical metabolites that carotenoids predominating in ripe durian, mango, and papaya flesh are a good source of antioxidants. Interestingly, aroma volatiles produced in fruits can be used as an indicator for fruit quality (2-AP in aromatic coconut) or even fruit maturity (ethyl esters in ripe papaya and durian). Furthermore, the anatomical structures of fruits are physiologically responsible for the quality. The edible part of durian and mangosteen is the aril, whereas the rinds independently develop and are responsible for physiological changes of the aril. When hypoxia of the flesh induced by thick peel and increasing cuticle during fruit ripening in durian and mango affects the aroma production, the condition changes the aril texture in mangosteen. For postharvest applications, MA storage or 1-MCP treatment inhibits the production of ester volatiles, whereas low temperature induces fibrous tissue in mangosteen aril. Finally, one needs to recognize that consumers have varied preferences for fruit quality attributes in different countries. Cultivars, field practices, harvest index, and postharvest applications should be earnestly considered to produce an optimal quality of fruit for the ultimate consumer.

References

Allwood, J. W., Cheung, W., Xu, Y., Mumm, R., De Vos, R. C. H., Deborde, C., . . . Goodacre, R. (2014). Metabolomics in melon: A new opportunity for aroma analysis. *Phytochemistry*, *99*, 61−72.

Almeida, F. T. D., Bernardo, S., Sousa, E. F. D., Marin, S. L. D., & Grippa, S. (2003). Growth and yield of papaya under irrigation. *Scientia Agricola*, *60*, 419−424.

Amornputti, S., Ketsa, S., & van Doorn, W. G. (2016). 1-Methylcyclopropene (1-MCP) inhibits ethylene production of durian fruit which is correlated with a decrease in ACC oxidase activity in the peel. *Postharvest Biology and Technology*, *114*, 69−75.

An, M.-R., Keum, Y.-S., & Lee, S.-Y. (2015). Comparative analysis of volatile flavor compounds in Taiwan Apple mango and Philippines Carabao mango. *Korean Journal of Food Science and Technology*, *47*, 191−197.

Anon. (2021). Consumer preference and marketing competition of durian in China: Agriculture section, the Consulate General at Guangzhou. *Kehakaset Journal*. Available from https://www.kehakaset.com/articles_details.php?view_item = 953, Accessed 06.02.21.

Arancibia-Avila, P., Toledo, F., Psrk, Y.-S., Jung, S.-T., Kang, S.-G., Heo, B. G., . . . Gorinstein, S. (2008). Antioxidant properties of durian fruit as influenced by ripening. *LWT—Food Science and Technology*, *41*, 2118−2125.

Arceo, A. J. (2008). *Integrated pest and disease management of durian*. Diliman, Quezon City: Knowledge Products Management Division Agricultural Training Institute.

Aschariyaphotha,, W., Wongs-Aree, C., Bodhipadma, K., & Noichinda, S. (2021). Fruit volatile fingerprints characterized among Four commercial cultivars of Thai durian (*Durio zibethinus*). *Food Quality*, 1383927. Available from https://doi.org/10.1155/2021/1383927.

Belgis, M., Wijaya, C. H., Apriyantono, A., Kusbiantoro, B., & Yuliana, N. D. (2017). Volatiles and aroma characterization of several lai (*Durio kutejensis*) and durian (*Durio zibethinus*) cultivars grown in Indonesia. *Scientia Horticulturae*, *220*, 291−298.

Boonthanakorn, J., Daud, W., Aontee, A., & Wongs-Aree, C. (2020). Quality preservation of fresh-cut durian cv. 'Monthong' using microperforated PET/PE films. *Food Packaging and Shelf Life*, *23*, 100452.

Brooncherm, P., & Siriphanich, J. (1991). Postharvest physiology of durian pulp and husk. *Kasetsart Journal (Natural Science)*, *25*, 119–125.

Buanong, M., & Kanlayanarat, S. (2010). Role of methyl jasmonate on changes in changes in carotenoid and beta-carotene contents of mango fruits (*Mangifera indica* Linn.) 'Nam Dok Mai' after harvest. *Agricultural Science Journal*, *41*, 63–66. (in Thai with English abstract).

Bunsiri, A., Ketsa, S., & Paull, R. E. (2003). Phenolics metabolism and lignin synthesis in damaged pericarp of mangosteen fruit after impact. *Postharvest Biology and Technology*, *29*, 61–71.

Chaiprasart, P., & Siriphanich, J. (2000). Enzymes and intermediates in ethylene production in two cultivars of durian fruits. *Agricultural Science Journal*, *31*, 35–42 (in Thai with English abstract).

Chaisrichonlathan, P., & Noomhorm, A. (2011). Effects of harvesting seasons and maturity stages on internal characteristics of the mangosteen having different surface properties. *International Journal of Food Science and Technology*, *46*, 717–723.

Chanchara, Y., Saengnil, K., & Uthaibutra, J. (2006). Changes in activity of phenylalanine ammonia lyase, levels of total phenolic compounds and anthocyanins in 'Mahajanaka' mango fruit skin during fruit development. *Agricultural Science Journal*, *37*, 34–37. (in Thai with English abstract).

Changprasert, S., Noichinda, S., Bodhipadma, K., & Wongs-Aree, C. (2011). Physico-chemical properties of harvested young Thai fragrant coconut (*Cocos nucifera* L.) fruit: An appropriate data for packaging design. *Applied Science*, *10*, 1–6.

Chanwijit, I., Whangchai, K., Saengnil, K., & Uthaibutra, J. (2010). Effects of methyl jasmonate on red color development of Mahajanaka mango fruit exocarp. *Agricultural Science Journal*, *41*, 91–94. (in Thai with English abstract).

Charoenkiatkul, S., Thiyajai, P., & Judprasong, K. (2016). Nutrients and bioactive compounds in popular and indigenous durian (*Durio zibethinus* Murr.). *Food Chemistry*, *193*, 181–186.

Chawengkijwanich, C., Sa-nguanpuag, K., & Tanprasert, K. (2008). Monitoring volatile compounds emitted by durian pulp (*Durio zibethinus* Murr.) at mature and ripe stage using solid phase microextraction (SPME). *Acta Horticulturae*, *804*, 321–326.

Chayprasat, P. (1993). *Enzymes and intermediates in ethylene production of durian fruits* (M.S. thesis). Bangkok: Kasetsart University.

Chonhenchob, V., Kamhangwong, D., Kruenate, J., Khongrat, K., Tangchantra, N., Wichai, U., & Singh, S. P. (2011). Preharvest bagging with wavelength-selective materials enhances development and quality of mango (*Mangifera indica* L.) cv. Nam Dok Mai #4. *Science of Food and Agriculture*, *91*, 664–671.

Chuennakorn, P., Paiboon, P., & Yingjajaval, S. (2011). *Rate of water flow and the occurrence of gamboges and translucent flesh disorders in mangosteen fruit*. Nakhon Pathom: Center for Agricultural Biotechnology, Kasetsart University, Kamphaeng Saen Campus.

Chuntarat, S., na Jom, K., & Tongchitpakdee, S. (2015). Effect of quality and chemical composition of coconut kernel (*Cocos nucifera*). *Acta Horticulturae*, *1088*, 227–230.

Codex Alimentarius Commission (Joint FAO/WHO Food Standards Programme). (2016). *Report of the 48th session of the codex committee on pesticide residues (REP16/PR)*. Chongqing.

Contreras, C., & Beaudry, R. (2013). Lipoxygenase-associated apple volatiles and their relationship with aroma perception during ripening. *Postharvest Biology and Technology*, *82*, 28–38.

Dantes, P. T. G., Maninang, J. S., Elepano, A. R., & Gemma, H. (2013). Analysis of aroma volatile of Philippine durian pulp (*Durio zibethinus* Rumph. ex Murray) using headspace solid phase microextraction (HS-SPME) coupled with GC-MS. In: *Proceeding of the 13th ASEAN food conference* (pp. 1–6), September 9–11, 2013, Singapore.

de Oliveira, J. G., Bressan-Smith, R. E., Campostrini, E., Cunha, M. D., Costa, E. S., Netto, A. T., ... Vitoria, A. P. (2010). Papaya pulp gelling: Is it premature ripening or problems of water accumulation in the apoplast? *Revista Brasileira de Fruticultura*, *32*, 961–969.

de Oliveira, J. G., & Vitória, A. P. (2011). Papaya: Nutritional and pharmacological characterization, and quality loss due to physiological disorders. An overview. *Food Research International*, *44*, 1306–1313.

der Agopian, R. G., Fabi, J. P., & Cordenunsi-Lysenko, B. R. (2020). Metabolome and proteome of ethylene-treated papayas reveal different pathways to volatile compounds biosynthesis. *Food Research International*, *131*, 108975.

Dorly, Tjitrosemito, S., da Silva, J. A. T., Poerwanto, R., Efendi, D., & Barasa. (2011). Calcium spray reduces yellow latex on mangosteen fruits (*Garcinia mangostana* L.). *Fruit and Ornamental Plant Research*, *19*, 51–65.

Dorly, Tjitrosemito, S., Poerwanto, R., & Juliarni (2008). Secretory duct structure and phytochemistry compounds of yellow latex in mangosteen fruit. *HAYATI Journal of Biosciences*, *15*, 99–104.

Engel, K.-H., & Tressl, R. (1983). Studies on the volatile components of two mango varieties. *Agricultural and Food Chemistry*, *31*, 796–801.

Facanha, R. V., Spricigo, P. C., Purgatto, E., & Jacomino, A. P. (2019). Combined application of ethylene and volatile compound production of 'Golden' papaya. *Postharvest Biology and Technology*, *151*, 160–169.

Fuggate, P., Wongs-Aree, C., Noichinda, S., & Kanlayanarat, S. (2010). Quality and volatile attributes of attached and detached 'Puk Mai Lei' papaya during fruit ripening. *Scientia Horticulturae*, *126*, 120–129.

Hau, T. V., & Hieu, T. S. (2017). Off-season production of durian in the Mekong delta, Viet Nam. *Acta Horticulturae*, *1186*, 85–98.

Islam, M. N., Cedo, M. L. O., Namuco, L. O., Borromeo, T. H., & Aguilar, E. A. (2009). Effect of fruit age on endosperm type and embryo germination of Makapuno coconut. *Gene Conserve*, *8*, 708–722.

Jaroonchon, N. (2017). *Fruit Development and Expression of Genes Associated with 2-Acetyl-1-Pyrroline Synthesis in Aromatic Coconut.*, Ph.D. Thesis. Thailand: Kasetsart University.

Jaroonchon, N., Krisanapook, K., & Imsabai, W. (2017). The development of 2-acetyl-1-pyrroline (2-AP) in Thai aromatic coconut. *Songklanakarin Journal of Science and Technology*, *39*, 179–183.

Jirapong, C., Changprasert, S., Kanlayanarat, S., Uthairatanakij, A., Bodhipadma, K., Noichinda, S., & Wongs-Aree, C. (2018). Characterization of the liquid endosperm attributes in young coconut fruit during storage. *International Food Research Journal*, *25*, 2650–2656.

Jirapong, C., Uthairatanakij, A., Noichinda, S., Kanlayanarat, S., & Wongs-Aree, C. (2012). Comparison of volatile compounds between fresh and heat-processed aromatic coconut. *Acta Horticulturae*, *943*, 111–115.

Jirapong, C., Wongs-Aree, C., Noichinda, S., Uthairatanakij, A., & Kanlayanarat, S. (2015). Assessment of volatile and non-volatile organic compounds in the liquid endosperm of young 'Nam Hom' coconut (*Cocos nucifera* L.) at two stages of maturity. *Horticultural Science and Biotechnology*, *90*, 477–482.

Jung, H.-A., Su, B.-N., Keller, W. J., Mehta, R. G., & Kinghorn, A. D. (2006). Anti-oxidant xanthones from the pericarp of *Garcinia mangostana* (mangosteen). *Agricultural and Food Chemistry*, *54*, 2077–2082.

Karanjalker, G., Ravishankar, K. V., Shivashankara, K. S., & Dinesh, M. R. (2018). Influence of bagging on color, anthocyanin and anthocyanin biosynthetic genes in peel of red colored mango cv. 'Lily'. *Erwerbs-Obstbau*, *60*, 281–287. Available from https://doi.org/10.1007/s10341-018-0371-0.

Ketsa, S. (2005). Pericarp hardening of mangosteen fruit after dropped impact. *Journal of the Royal Institute of Thailand*, *30*, 632–639.

Ketsa, S., & Atantee, S. (1998). Phenolics, lignin, peroxidase activity and increased firmness of damaged pericarp of mangosteen fruit after impact. *Postharvest Biology and Technology*, *14*, 117–124.

Ketsa, S., & Pangkool, S. (1994). The effect of humidity on ripening of durians. *Postharvest Biology and Technology*, *4*, 159–165.

Ketsa, S., Wisutiamonkul, A., Palapol, Y., & Paull, R. E. (2020). The durian: Botany, horticulture, and utilization. *Horticultural Reviews*, *4*, 125–211.

Khurnpoon, L., & Siriphanich, J. (2005). Changes in pectin fractions and enzyme activities during husk dehiscence of Monthong durians. *Acta Horticulturae*, *687*, 187–192.

Lado, J., Alós, E., Manzi, M., Cronje, P. J. R., Gómez-Cadenas, A., Rodrigo, M. J., & Zacarías, L. (2019). Light regulation of carotenoid biosynthesis in the peel of mandarin and sweet orange fruits. *Frontiers in Plant Science*, *15*, October 2019. Available from https://doi.org/10.3389/fpls.2019.01288.

Laohakunjit, N., Kerdchoechuen, O., Matta, F. B., Silva, J. L., & Holmes, W. E. (2007). Postharvest survey of volatile compounds in five tropical fruits using headspace-solid phase microextraction (HS-SPME). *HortScience*, *42*, 309–314.

Laohaprasit, N., Ambadipudi, D. S., & Srzednicki, G. (2011). Optimisation of extraction conditions of volatile compounds in 'Nam Dok Mai' mangoes. *International Food Research Journal*, *18*, 1043–1049.

Laohaprasit, N., Kukreja, R. K., & Arunrat, A. (2012). Extraction of volatile compounds from 'Nam Dok Mai' and 'Maha Chanok' mangoes. *International Food Research Journal*, *19*, 1445–1448.

Li, J., Schieberle, P., & Steinhaus, M. (2017). Insights into the key compounds of durian (*Durio zibethinus* L. 'Monthong') pulp odor by odorant quantitation and aroma simulation experiments. *Agricultural and Food Chemistry*, *65*, 639–647.

Li, P., Yang, Z., Tang, B., Zhang, Q., Chen, Z., Zhang, J., ... Yan, J. (2020). Identification of xanthones from the mangosteen pericarp that inhibit the growth of *Ralstonia solanacearum*. *ACS Omega*, *5*, 334–343.

Llorente, B., D'Andrea, L., Ruiz-Sola, M. A., Botterweg, E., Pulido, P., Andilla, J., . . . Rodriguez-Concepcion, M. (2016). Tomato fruit carotenoid biosynthesis is adjusted to actual ripening progression by a light-dependent mechanism. *Plant Journal*, *85*, 107−119.

Luckanatinvong, V., & Sornkeaw, P. (2011). Quality of blanched aromatic young coconut fruits for export. *Agricultural Science Journal*, *42*, 147−150. (In Thai with English Abstract).

Luengwilai, K., Beckles, D. M., Pluemjit, O., & Siriphanich, J. (2014). Postharvest quality and storage life of 'Makapuno' coconut (*Cocos nucifera* L.). *Scientia Horticulturae*, *175*, 105−110.

Macleod, A. J., & Pieris, N. M. (1982). Volatile flavour component of mangosteen, *Garcinia mangostana*. *Phytochemistry*, *21*, 117−119.

Maldonado-Celis, M. E., Yahia, E. M., Bedoya, R., Landázuri, P., Loango, N., Aguillón, J., . . . Ospina, J. C. G. (2019). Chemical composition of mango (*Mangifera indica* L.) fruit: Nutritional and phytochemical compounds. *Frontier in Plant Science*, *10*, 1073. Available from https://doi.org/10.3389/fpls.2019.01073.

Maninang, J. S., Wongs-Aree, C., Kanlayanarat, S., Sugaya, S., & Gemma, H. (2011). Influence of maturity and postharvest treatment on the volatile profile and physiological properties of the durian (*Durio zibethinus* Murray) fruit. *International Food Research Journal*, *18*, 1067−1075.

Market Analysis Report. (2019). *Durian fruit market size and share, global industry report, 2019−2025* (Report ID: GVR-3−68038-511-3) (80p.). <https://www.grandviewresearch.com/industry-analysis/durian-fruit-market> Accessed 12.02.21.

Mohpraman, K., & Siriphanich, J. (2012). Safe use of sodium metabisulfite in young coconuts. *Postharvest Biology and Technology*, *65*, 76−78.

Meethaworn, K., & Siriphanich, J. (2015). Postharvest behavior during storage of young coconut (*Cocos nucifera* L.) at different temperatures. *Acta Horticulturae*, *1091*, 125−131.

Mujer, C. V., Ramirez, D. A., & Mendoza, E. M. T. (1984). Alpha-D-galactosidase deficiency in coconut endosperm—Its possible pleiotropic effects in Makapuno. *Phytochemistry*, *23*, 893−894.

Naef, R., Velluz, A., & Jaquier, A. (2006). The perfume of Carabao mangoes (*Mangifera indica* L.): Identification of uncommon unsaturated fatty acid esters in the SPME of the intact fruit. *European Food Research and Technology*, *222*, 554−558.

Nakasone, H. Y., & Paull, R. E. (1998). Papaya. In: *Tropical fruits* (pp. 239−269). Wallingford, Oxon: CAB International.

Nanthachai, S. (1994). *Durian: Fruit Development, Postharvest Physiology, Handling and Marketing in ASEAN*. Kuala Lumpur: ASEAN Food Handling Bureau.

Noichinda, S. (1992). *Effect of modified atmosphere on quality and storage life of mangosteen (Garcinia mangostana L.) fruit* (M.S. thesis). Bangkok: Department of Horticulture, Kasetsart University.

Noichinda, S., Bodhipadma, K., & Kong-In, S. (2017). Capillary water in pericarp enhances hypoxic condition during on-tree fruit maturation that induces lignification and triggers translucent flesh disorder in mangosteen (*Garcinia mangostana* L.). *Food Quality*, *2017*, ID 7428959.

Noichinda, S., Bodhipadma, K., & Wongs-Aree, C. (2019). Mangosteen. In S. T. de Freitas, & S. Pareek (Eds.), *Postharvest physiological disorders in fruits and vegetables* (pp. 589−614). Boca Raton, FL: CRC Press, Taylor and Francis Group.

Pakcharoen, A., Tisarum, R., & Siriphanich, J. (2013). Factors affecting uneven fruit ripening in 'Mon-Thong' durian. *Acta Horticulturae*, *975*, 329−333.

Pankasemsuk, T., Garner, J. O., Jr., Matta, F. B., & Silva, J. L. (1996). Translucent flesh disorder of mangosteen fruit (*Garcinia mangostana* L.). *HortScience*, *31*, 112−113.

Panpetch, P., & Sirikantaramas, S. (2021). Fruit ripening-associated leucylaminopeptidase with cysteinylglycine dipeptidase activity from durian suggests its involvement in glutathione recycling. *BMC Plant Biology*, *21*. Available from https://doi.org/10.1186/s12870-021-02845-6.

Phakawan, J. (2018). *Study of ethanol vapour in packaging on quality of 'Nam Dok Mai' mango* (M.S. thesis). Bangkok: Division of Postharvest Technology, King Mongkut's University of Technology Thonburi.

Pino, J. A., Almora, K., & Marbot, R. (2003). Volatile components of papaya (*Carica papaya* L., Maradol variety) fruit. *Flavour and Fragrance Journal*, *18*, 492−496.

Piromruen, B., Jirapong, C., Techavuthiporn, C., & Wongs-Aree, C. (2009). Effects of 1-methylcyclopropene and controlled atmosphere on ripening and volatile compounds of 'Keaw Sawoey' mango. *Acta Horticulturae*, *837*, 259−263.

Punnachit, U., Kwangthong, C., & Chandraparnik, S. (1992). Effect of plant growth regulators and fertilizers on leaf flushing and quality of durian. *Acta Horticulturae*, *321*, 343−347.

Ranganath, K. G., Shivashankara, K. S., Roy, T. K., Dinesh, M. R., Geetha, G. A., Pavithra, K. C. G., & Ravishankar, K. V. (2018). Profiling of anthocyanins and carotenoids in fruit peel of different colored mango cultivars. *Food Science and Technology*, *55*, 4566−4577.

Ratanamarno, S., Uthaibutra, J., & Saengnil, K. (1999). Towards some quality attributes of mangosteen (*Garcinia mangostana* L.) fruit during maturation. *Songklanakarin Journal of Science and Technology*, *21*, 9−15.

Samson, J. A. (1986). *Tropical Fruits* (2nd ed.). New York: Longman.

Sangsoy, K., Mongkolporn, O., Imsabai, W., & Luengwilai, K. (2017). Papaya carotenoids increased in Oxisols soils. *Agriculture and Natural Resources*, *51*, 253−261.

Sangwanangkul, P. (2017). Ethephon remaining in treated-durian fruit. Is it harmful? *Kehakaset Journal*, *41*, 192−194. (in Thai).

Schmier, S., Hosoda, N., & Speck, T. (2020). Hierarchical structure of the *Cocos nucifera* (coconut) endocarp: Functional morphology and its influence on fracture toughness. *Molecules (Basel, Switzerland)*, *25*, 223.

Schweiggert, R. M., Steingass, C. B., Heller, A., Esquivel, P., & Carle, R. (2011). Characterization of chromoplasts and carotenoids of red- and yellow-fleshed papaya (*Carica papaya* L.). *Planta*, *234*, 1031−1044.

Sdoodee, S., & Chairawipa, R. (2005). Regulating irrigation during pre-harvest to avoid the incidence of translucent flesh disorder and gamboge disorder of mangosteen fruits. *Songklanakarin Journal of Science and Technology*, *27*, 957−965.

Sirikul, J., Noichinda, S., Bodhippadma, K., & Sangudom, T. (2015). Red coloration in calyx at different maturity stages of mangosteen. In: *Abstract in the Proceeding of the international symposium on durian and other humid tropical fruits* (p. 78), June 2−4, 2015. Maneechan Resort & Hotel, Chanthaburi, Thailand.

Solovchenko, A. E., Avertcheva, O. V., & Merzlyak, M. N. (2006). Elevated sunlight promotes ripening-associated pigment changes in apple fruit. *Postharvest Biology and Technology*, *40*, 183−189.

Somsri, S. (2008). *Thai durians and the breeding: Case study of hybrid cultivars of 'Chanthaburi 1', 'Chanthaburi 2', and 'Chantaburi 3'* (AFACI5/2008). Thailand: Department of Agriculture, Ministry of Agriculture and Cooperatives (in Thai).

Sukatta, U., Takenaka, M., Ono, H., Okadome, H., Sotome, I., Nanayama, K., . . . Isobe, S. (2013). Distribution of major xanthones in the pericarp, aril, and yellow gum of mangosteen (*Garcinia mangostana* Linn.) fruit and their contribution to antioxidative activity. *Bioscience, Biotechnology, and Biochemistry*, *77*, 984−987.

Sundaram, S., & Prabhakaran, J. (2017). Effect of 1-methylcyclopropene (1-MCP) on volatile compound production in papaya (*Carica papaya* L.) fruit. *Pharmaceutical Innovation*, *6*, 532−536.

Suwannachot, J., Kondo, S., & Setha, S. (2016). Effects of bagging and jasmonate application during fruit development on bioactive compounds and postharvest quality of mango (*Mangifera indica* Linn. cv. Mahajanaka). *Agricultural Science Journal*, *47*, 111−114. (in Thai with English abstract).

Terdwongworakul, A., Chaiyapong, S., Jarimopas, B., & Meeklangsean, W. (2009). Physical properties of fresh young Thai coconut for maturity sorting. *Biosystems Engineering*, *103*, 208−216.

Thai Agricultural Standard: TAS 3-2013. (2013). *Durian* (18p.). Thailand: National Bureau of Agricultural Commodity and Food Standards, Ministry of Agriculture and Cooperatives (ICS 67.080.10).

Tharanathan, R., Yashoda, H. M., & Prabha, T. N. (2006). Mango (*Mangifera indica* L.) the King of fruits: An overview. *Food Reviews International*, *22*, 95−123.

Thi-utit, N., Saengnil, K., & Uthaibutra, J. (2006). Effect of postharvest irradiation on pigmentation changes in mango fruit cv. Mahajanaka. *Agricultural Science Journal*, *37*, 120−123. (in Thai with English abstract).

Thongkum, M., Imsabai, W., Burns, P., McAteee, P. A., Schaffer, R. J., Allan, A. C., & Ketsa, S. (2018). The effect of 1-methylcyclopropene (1-MCP) on expression of ethylene receptor genes in durian pulp during ripening. *Plant Physiology and Biochemistry*, *125*, 232−238.

Voon, Y. Y., Hamid, N. S. A., Rusul, G., Osman, A., & Quek, S. Y. (2007). Characterisation of Malaysian durian (*Durio zibethinus* Murr.) cultivars: Relation of physicochemical and flavour properties with sensory properties. *Food Chemistry*, *103*, 1217−1227.

Wall, M. M. (2006). Ascorbic acid, vitamin A, and mineral composition of banana (*Musa* sp.) and papaya (*Carica papaya*) cultivars grown in Hawaii. *Food Composition and Analysis*, *19*, 434−445.

Wijeratnam, R. S. W., Jeyachandran, V., Karunanithy, K., Hewajulige, I. G. N., & Perera, M. G. D. S. (2006). Extending storage of king coconut, *Cocos nucifera* var. *auranta*. *Acta Horticulturae*, *712*, 407−411.

Wisutiamonkul, A., Ampomah-Dwamena, C., Allan, A. C., & Ketsa, S. (2017). Carotenoid accumulation in durian (*Durio zibethinus*) fruit is affected by ethylene via modulation of carotenoid pathway gene expression. *Plant Physiology and Biochemistry*, *115*, 308–319.

Wisutiamonkul, A., Promdang, S., Ketsa, S., & van Doorn, W. (2015). Carotenoids in durian fruit pulp during growth and postharvest ripening. *Food Chemistry*, *180*, 301–305.

Wongs-Aree, C., & Noichinda, S. (2014). Postharvest physiology and quality maintenance of tropical fruits. In W. J. Florkowski, R. L. Shewfelt, B. Brueckner, & S. E. Prussia (Eds.), *Postharvest Handling: A System Approach* (3rd ed., pp. 275–312). Oxford, UK: Elsevier Inc.

Wongs-Aree, C., & Noichinda, S. (2018). Glycolysis fermentative by-products and secondary metabolites involved in plant adaptation under hypoxia during pre- and postharvest. In K. Das, & M. S. Biradar (Eds.), *Hypoxia and Anoxia* (pp. 59–72). London: IntechOpen.

Wongs-Aree, C., Siripirom, P., Satipongchai, A., Bodhipadma, K., & Noichinda, S. (2021). Increasing lignification in translucent disorder aril of mangosteen related to the ROS defensive function. *Food Quality*, *2021*, 6674208.

Zerena, A. S., & Sankar, K. U. (2012). Isolation and identification of pelargonidin-3-glucoside in mangosteen pericarp. *Food Chemistry*, *130*, 665–670.

PART 3

Process

This page intentionally left blank

CHAPTER

10

Value chain management and postharvest handling

Ray Collins and Benjamin Dent

School of Agriculture and Food Sciences, The University of Queensland, Brisbane, QLD, Australia

Abbreviations

SCM supply chain management
VCM value chain management

10.1 Introduction

10.1.1 Firms, competitiveness, and supply chains

The traditional economics view is that a firm's competitiveness is determined by how efficiently and effectively its management is able to organize the firm's internal processes, structures, resources, and people so as to maximize profits. This allows firms to compete against each other for a share of a particular market or market segment based on their ability to keep prices low and/or to differentiate their product from competitors' products (Porter, 1980; Wernerfelt, 1984; Williamson, 1971).

To some extent this model still applies. Firms *do* have to be price competitive; and firms *do* have to differentiate their products and services from those of their competitors. However, the traditional view of how firms become and remain competitive has been challenged by an alternative view that sees a firm as part of a supply chain that links the production of goods and services with the consumers of those goods and services (Fig. 10.1).

In this alternative view, the competitiveness of a firm is influenced by how it interacts with other firms in the supply chains to which it belongs. As noted in Gifford et al. (1997, p. 4) "it is becoming increasingly evident that achievement of the desired market position cannot be achieved solely through the company's own efforts. Because each company is

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00010-5

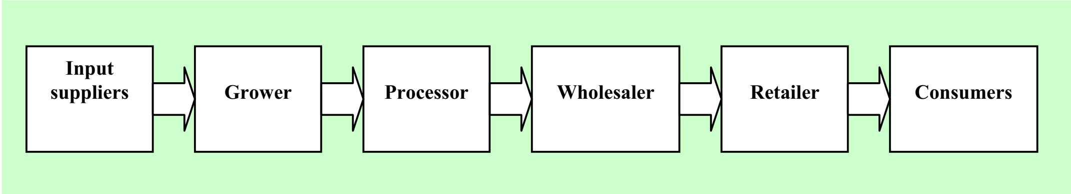


FIGURE 10.1 Simplified supply chain showing flow of product from input suppliers to consumers.

just one link in the production chain, with upstream and downstream links, it has to cooperate. The more effectively it does this, the stronger its competitive position in the market." This statement captures the essence of an alternative view of competitiveness: that cooperation among firms in a supply chain can positively improve their competitiveness. This view is in sharp contrast to the idea of a competitive firm as being independent and internally efficient and effective.

Among traditionally competitive firms, linkages in supply chains are usually at arms-length and adversarial. Typically, firms attempt to buy inputs at the cheapest possible price from their suppliers and sell outputs at the highest possible price to their customers. These transactions are at the expense of the buyers or suppliers in the chain, that is, actions between chain members are self-optimizing and tend to shift costs to other firms in the chain, and ultimately to the consumer. Many authors have pointed to the shortcomings of this approach to business, most noting that it does not necessarily improve the efficiency of the chain, does not lead to the best prices for consumers, and does not make the individual firms more competitive (Bowersox, 1990; Mentzer et al., 2001). Under adversarial conditions, independent, efficient firms do not lead to the most efficient supply chains.

10.1.2 Supply chain management

When firms that belong to a supply chain work together to address interfirm efficiencies and take more notice of what consumers want, a different picture of competitiveness emerges. Here there is an opportunity for collaboration to replace adversarial behavior and for the focus to move away from price and onto customers' needs. This business model, called supply chain management (SCM), is built on the proposition that there are gains from cooperation and coordination between firms in a supply chain that are simply not available to firms that operate independently of each other. In this way, a firm's ability to collaborate becomes intimately linked with its ability to compete, a proposition that is well supported in the literature (Gunasekaran, Patel, & Tirtiroglou, 2001; Halldorsson, Kotzab, Mikkola, & Skjott-Larsen, 2007; O'Keeffe, 1998; van Roekel, 1998).

It has been suggested that the practices of SCM have existed for hundreds of years (Hugos, 2003), but SCM as a modern business strategy has its origins in manufacturing industries in the 1960s (Mentzer et al., 2001). More recently, it has taken hold in agri-food industries, including horticulture (Fearne & Hughes, 1999). Originally, SCM referred to approaches that ensured the logistical and distributional efficiency of flows of materials along a supply chain (Cooper & Ellram, 1990). Over time, however, the focus of SCM became less tactical and less concerned with achieving logistical efficiency alone. It evolved to encompass what Spekman, Spear, and Kamauff (2002, p. 41) called a "competitive reality," where "firms compete as constellations of collaborating partners." More than any other factor, this change in orientation away from just the logistical aspects of the supply chain was driven by the increasing attention being paid to two factors: the importance of relationships in achieving interfirm coordination; and the importance of identifying and satisfying the end consumer as the "target" of the supply chain.

Now, an accepted view is that SCM is "an integrated approach that aims to satisfy the expectations of consumers through continual improvement of processes and relationships that support the efficient development and flow of products and services from the producer to the consumer" (Gifford, Hall, & Collins, 1997, p. 2). The key elements of this definition are:

- the need for integration between firms,
- a focus on consumers,
- the importance of relationships,
- a whole-of-supply-chain perspective.

Integration of business systems and processes between firms is necessary to achieve operational efficiencies and to improve the flow and transparency of information (Kouvelis, Chambers, & Wang, 2006). A focus on consumers acknowledges the need for the supply chain to have information about consumers' needs and wants, including feedback as to how they are being met. Effective relationships drive successful SCM because they are the antecedents of information exchange, conflict resolution, and coinnovation between supply chain partners (Morgan & Hunt, 1994). Finally, supply chains can be viewed as if they are dynamic, complex systems linking input suppliers and producers through to retailers and consumers, reinforcing the idea that the whole is more than an aggregation of parts that can be improved independently of each other, and that performance of the whole system fundamentally depends on the interactions among its parts (Jackson, 2003, 2019; Lambert & Cooper, 2000).

10.2 Value chain management

In spite of appearing to be an all-embracing concept, SCM has been criticized as being too supply oriented, having an upstream focus and not attaching enough importance to the role of consumers in the chain. For example, Mudimigh, Zairi, and Ahmed (2004, p. 309) argue that "SCM does not extend far enough to capture customers' (end user) future needs and how these get addressed and furthermore, it does not encompass the post-delivery, post-evaluation and relationship building aspects." These authors, and others such as Anderson, Britt and Favre (2007), argue that a focus on *value* rather than *supply* is more appropriate. As a result, the term value chain management (VCM) is frequently used in preference to SCM (Martinez & Bititci, 2006), even though the terms are sometimes used interchangeably in the literature.

10.2.1 The concept of value in VCM

In the context of VCM, *value* is defined in terms of the customer (the next firm downstream) or the consumer of the finished goods. Mudimigh et al. (2004, p. 311) list three themes that run through definitions of value:

1. customer value is linked to the use of a product or service;
2. value is perceived by the customer not determined by the seller; and
3. customer value typically involves a trade-off between what the customer wants and what must be given up to acquire and use a product or service.

In agribusiness, sources of value lie in features of products and services such as price, convenience, appearance, nutrition, safety, social and environmental sustainability and reliability. Thus the concept of value is framed by the perspective of the user or consumer looking back to the chain that produced and delivered the product or service. Having a focus on the consumer as the ultimate "target" of the activities of a chain is a distinguishing feature of VCM (Collins, 2006; Zokaei & Simons, 2006). Explanations of VCM such as that given by the Agriculture and Food Council (2002, p. 3) highlight this orientation: "a value chain begins and ends with the MARKET. Interaction with the marketplace provides information to decision makers for every link in the chain."

Fearne (2009) identifies the characteristics of VCM as the pursuit of a shared vision through aligned business structures and processes, based on trust and a commitment to continuous improvement, and which results in mutual benefits from the creation and flow of value. In this way, VCM confers sustainable competitive advantages because partnerships among firms require resources and capabilities that cannot be traded and are hard to imitate because they are socially complex, causally ambiguous and developed through unique histories (Gold, Seuring, & Beske, 2009). Indeed, strong strategic relationships can be harder to imitate than technological or scientific innovation (Gooch, 2012).

VCM incorporates three dimensions: the creation, realization, and distribution of value (Fig. 10.2). The source of value in a value chain (other than credit, subsidies, or aid) comes from consumers when they decide to purchase a product (Collins et al., 2016). Value realization only occurs through exchanges that transform potential benefits into actual ones (Ramsay, 2005). As Moller and Torronen (2003) argue, while core value could be easily assessed against competition, developing suitable partners allows a firm to realize added value. Hence, firms must select customers and through them target those consumers with the most potential to appreciate and so realize as much of the created value as possible (Dent, 2013). Furthermore, to sustain those supplier–customer partnerships, it is essential that having realized value, it is distributed equitably to the chain members responsible for its creation. As explained in the next section, value creation rests on identifying and correctly executing the critical control points of value, and then value distribution is secured through value-based pricing.

10.2.2 Sources and drivers of value

In the context of food in general and horticultural produce in particular, the sources and drivers of value have some special features. Because food is "consumed," attributes associated with provenance, safety, nutrition, well-being, freshness, and the overall

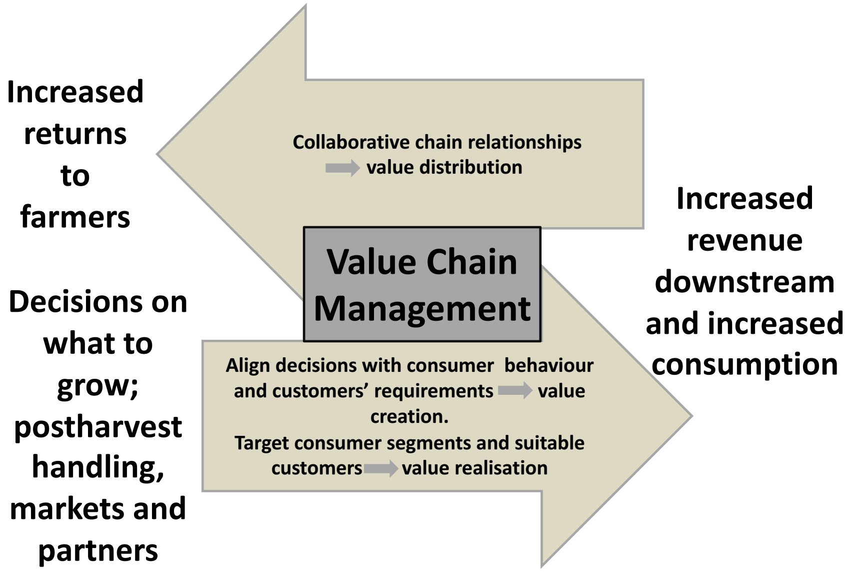


FIGURE 10.2 Value creation, realization, and distribution.

sensory experience of consumption, each play a role in determining how individual consumers attach value to the product as part of their purchase decision making. If these attributes are loosely bundled together under the general banner of "quality" then, as Collins (2006) points out, it is the interaction of price and quality that results in what buyers regard as "value for money." The challenge for the chain is therefore to understand and deliver this value in ways that profitably meet consumers' needs.

The ability of an agri-food chain to deliver consumer value is driven by a combination of its ability to be as efficient as possible and its ability to innovate (Taylor, 2005). Lean manufacturing principles, originally devised by the Toyota Corporation to reduce waste and maximize value-adding activities in car manufacturing, have been adapted to value chains in the food industry (Simons, Francis, & Jones, 2002). A lean agri-food value chain achieves efficiency through operating with minimal waste and a clear focus on only doing those activities that are necessary and that add value in the eyes of consumers and therefore impact their decisions over whether and how much of the product to buy, from whom, and how much to pay for it. The critical control points of value are those inputs and activities along a chain that positively or negatively affect each of the product attributes which most strongly influence consumers' decisions. If chain members are to align themselves with the needs of their target markets, they need a collective commitment to deliver these attributes, and an individual focus on those critical activities for which they are responsible. Identifying critical control points of value can only be achieved through consumer research, then mapping the chain to trace each valued product attribute back to those inputs and activities that create, preserve, and distribute it. The following example is taken from a value chain analysis of domestic garlic value chains undertaken in Northern Mozambique (Matenga, 2017). Table 10.1 highlights that some control points may involve stakeholders outside the direct chain, in this case a research institute.

TABLE 10.1 Critical control points of value: Mozambique garlic value chain.

Product attributes	Valued characteristics	Activities affecting valued characteristics	Chain members responsible for those activities
Taste	Strong acidity and spiciness	Seed variety Farming practices On farm postharvest practices	Research institutes, input dealers, and farmers
Aroma	Strong, spiced aroma	Seed variety Farming practices On farm postharvest practices	Research institutes, input dealers, and farmers
Size of cloves	Larger cloves which are easier to peel	Seed variety Farming practices Sorting and grading	Research institutes, input dealers, farmers, and traders/wholesalers
Shelf life	Up to a month	Seed variety Harvest Postharvest practices Storage and conservation	Research institutes, input dealers, farmers, traders, wholesalers, and retailers
Availability	Year-round	Would require off-season imports, so: Procurement Distribution	Traders, wholesalers, and retailers
Appearance	Color Sorted into single varieties Cleanliness	Seed variety Farming practices Harvest Postharvest practices Sorting and grading	Research institutes, input dealers, farmers, traders, wholesalers, and retailers
Freshness	Not withered, nor too moist, which affects taste	Seed variety Farming practices Harvesting Postharvest practices	Research institutes, input dealers, farmers, traders, wholesalers, and retailers
Convenience	Diversity of garlic on sale Different pack sizes	Procurement	Retailers
Packaging	Supermarket shoppers prefer bags smaller than 10 kg	Pack procurement Packing Weighing Labeling	Package suppliers, traders, wholesalers, and retailers

Value-based pricing is the mechanism by which the value created by the chain is distributed equitably amongst its members. Essentially, once the critical control points of value have been identified, to sustain those practices and attitudes, chain members need to be rewarded explicitly, so the price they receive must reflect the extent to which they contribute to those product attributes that are most important to consumers, and the service standards (consistency, reliability, etc.) that are most important to business customers. For example, paying farmers a flat rate treats their product as an undifferentiated commodity, rewarding mediocrity the same as excellence. In contrast, value-based pricing would require that grading standards and specifications reflect the bundle of attributes that the target market values. For farmers and other chain members, value-based pricing provides signals that encourage and equitably reward the creation and delivery of attributes sought by consumers.

A focus on creating and delivering value can lead to innovation to discover and capture new sources of value, either for the individual firms in a chain or for consumers. Potra, Pugna, Negrea, and Izvercian (2019, p. 207) argue that "products and services need to address customer needs in such a way as to fulfill what they expect but at the same time delight them through unexpected and attractive features." New sources of value are a critical source of competitive advantage in fast changing environments such as the food sector. Firms seek these sources of value through process innovation (new ways to manufacture or deliver products) or product innovation (new product development), and in a value chain this may occur in association with a chain partner (Bonney, Clark, Collins, & Fearne, 2007). The process of pairs or groups of firms innovating with a common purpose is referred to as coinnovation, a concept that has been described as a powerful driver of value in chains (Bonney et al., 2007; Collins, Dunne, & O'Keeffe, 2002).

10.2.3 Value orientation in fresh produce chains

Value chains need to be viewed as systems. Food value chains viewed as systems are driven by the interaction of their technical (production, processing, transport, etc.), economic (profitability), information (communication, information technology), environmental (sustainability, provenance), and governance (human relationships) subsystems. Evaluating their performance is thus a multidisciplinary task that may combine measures drawn from fields as diverse as engineering, biology, economics, strategy, and psychology. A review of literature on the performance of food supply/value chains by Collins (2006) revealed the following indicators of performance:

1. The balance of focus between price and value,
2. The amount and type of information shared,
3. The time orientation of chain participants,
4. The nature of the business to business relationships,
5. The basis of the interactions between chain members,
6. Dependence in the chain,
7. Use of power in the chain,
8. Orientation of chain members to self or chain.

Collins used each of these criteria to evaluate the performance of fresh produce value chains (Table 10.2).

1. The balance of focus between price and value

   On one end of the scale, the members of a fresh produce chain may focus entirely on price. The goal of buyers in the chain is always to achieve the lowest possible price. On the other end of the scale, chain members may focus entirely on value creation through strategies such as product and process innovation, extensive market research, and the adoption of lean manufacturing principles. In chains where some members focus on price while others focus on value, conflict is common because of a fundamental misalignment of business strategies. Note that a value orientation does not mean that price is not important; rather, price is a consequence of value created.

2. The amount and type of information shared

   In traditional, price-oriented chains, individual members can wield power by withholding critical information, such as price signals from buyers, or supply signals

TABLE 10.2 Value chain orientation matrix.

	Characteristics of chain activities least value orientation			
Evaluative criterion	**Least value orientation <**		**> Greatest value orientation**	
Balance between price and value	Always price	Usually price	Usually value	Almost always value
Amount and type of information shared	No significant information shared	Little information shared	Some information shared	Extensive information shared
Time orientation	Short term, transaction to transaction	Short term, periodic	Short-to-medium term	Medium-to-long term
The nature of relationships	Adversarial	Occasionally cooperative	Mostly cooperative	Collaborative
Interactions between chain members	Transaction based	Mostly transaction based	More relationship based	Strongly relationship based
Dependence in the chain	Independence	Occasionally relies on others	Usually relies on others	Interdependence
Power in the chain	The individual has the power	The individual has the power	Some recognition of the consumer	The consumer has the power
Orientation of chain members	Always self-maximizing	Self first, chain second	Chain first, self second	Strongly toward chain optimization

from suppliers. Such information is usually used as a bargaining tool to maximize returns to one chain member at the expense of another, but as noted earlier, this behavior does not result in the greatest value being delivered to the consumer. In contrast, in value-based chains, it is regarded as important by chain members to share information freely so that the needs of chain participants can be fully understood and met, and so that signals from the marketplace can be transmitted undistorted back down the chain to where they are needed so as to evaluate how well the chain is creating value for its consumers.

3. The time orientation

A short-term orientation does not allow chain members to properly understand each other's needs, nor to build stronger relationships. Short-term thinking is associated with an orientation to price rather than value, leading to low levels of innovation.

4. The nature of business to business relationships

Relationships may be adversarial, as in the case of bargaining to get the lowest price, or collaborative, as in the case of trying to achieve a better understanding of chain members' needs. Value chains cannot deliver superior value to consumers in the absence of collaborative relationships among chain members.

5. The basis of the interactions between chain members

Interactions may be on a transaction-by-transaction basis, or on the basis of on-going relationships. Transaction-based interactions are common where relationships are adversarial and the focus is on price.

6. Dependence in the chain

Members of a chain may operate totally independently of each other, typically in a price-based environment, or more interdependently, for example, when collaborating to establish and deliver value to consumers.

7. Use of power in the chain

Power in a chain may lie in the hands of one or a few individuals who use it to their advantage. Alternatively, the chain as a whole may acknowledge that the consumer exercises the ultimate power in the act of making the decision to purchase or not to purchase, and that the chain as a competitive unit can direct its power toward meeting the needs of the consumer. Power asymmetry in chains commonly, but not necessarily, mitigates against collaboration.

8. Orientation of chain members

Chain members may orient themselves toward maximizing gains for themselves at the expense of other chain members, or optimizing returns for the whole chain, in which they share.

Using these eight performance-related criteria, it is possible to map a range of characteristics of a fresh produce chain's orientation, activities, and behavior from the least value-conscious, to the most highly value oriented (Collins, 2006). Such a mapping exercise can profile the "value orientation" of a particular fresh produce chain, as shown in the examples in Tables 10.3–10.5.

TABLE 10.3 Traditional fresh produce chains.

	Characteristics of chain activities			
Evaluative criterion	**Least value orientation <**		**> Greatest value orientation**	
Balance between price and value	Almost always price	Usually price	Usually value	Almost always value
Amount and type of information shared	No significant information shared	Little information shared	Some information shared	Extensive information shared
Time orientation	Short term, transaction to transaction	Short term, periodic	Short-to-medium term	Medium-to-long term
The nature of relationships	Adversarial	Occasionally cooperative	Mostly cooperative	Collaborative
Interactions between chain members	Transaction based	Mostly transaction based	More relationship based	Always relationship based
Dependence in the chain	Independence	Occasionally relies on others	Usually relies on others	Interdependence
Power in the chain	The individual has the power	The individual has the power	Some recognition of the consumer	The consumer has the power
Orientation of chain members	Always self-maximizing	Self first, chain second	Chain first, self second	Always chain optimizing

TABLE 10.4 Contemporary, category-managed fresh produce value chains.

	Characteristics of chain activities			
Evaluative criterion	**Least value orientation <**		**> Greatest value orientation**	
Balance between price and value	Almost always price	Usually price	Usually value	Almost always value
Amount and type of information shared	No significant information shared	Little information shared	Some information shared	Extensive information shared
Time orientation	Short term, transaction to transaction	Short term, periodic	Short-to-medium term	Medium-to-long term
The nature of relationships	Adversarial	Occasionally cooperative	Mostly cooperative	Collaborative
Interactions between chain members	Transaction based	Mostly transaction based	More relationship based	Always relationship based
Dependence in the chain	Independence	Occasionally relies on others	Usually relies on others	Interdependence
Power in the chain	The individual has the power	The individual has the power	Some recognition of the consumer	The consumer has the power
Orientation of chain members	Always self-maximizing	Self first, chain second	Chain first, self second	Always chain optimizing

TABLE 10.5 Best current examples of fresh produce value chains.

	Characteristics of chain activities			
Evaluative criterion	**Least value orientation <**		**> Greatest value orientation**	
Balance between price and value	Almost always price	Usually price	Usually value	Almost always value
Amount and type of information shared	No significant information shared	Little information shared	Some information shared	Extensive information shared
Time orientation	Short term, transaction to transaction	Short term, periodic	Short-to-medium term	Medium-to-long term
The nature of relationships	Adversarial	Occasionally cooperative	Mostly cooperative	Collaborative
Interactions between chain members	Transaction based	Mostly transaction based	More relationship based	Always relationship based
Dependence in the chain	Independence	Occasionally relies on others	Usually relies on others	Interdependence
Power in the chain	The individual has the power	The individual has the power	Some recognition of the consumer	The consumer has the power
Orientation of chain members	Always self-maximizing	Self first, chain second	Chain first, self second	Always chain optimizing

The typical profile of a traditional, price based, adversarial chain where product flows through centralized wholesale marketing channels is shown in Table 10.3. These types of chains are still common, especially in developing countries. Features of this profile are that chain members only cooperate when absolutely necessary, meaning that very occasionally they have to rely on each other, but otherwise the chain is driven by negotiations around price.

A second type of value profile is that of category managed chains. Category management firms bridge between suppliers and retailers such as large supermarket operators. Upstream in the chain, the category manager organizes and manages supply of product to clear specifications that include parameters of quality, quantity, safety, delivery and price. Downstream they manage supply of product to retailers, may plan marketing strategies with them, or may undertake market research upon which to base these strategies. In fresh produce, category managers typically ameliorate problems faced by retailers as a result of the impacts of seasonality, environmental conditions and wholesale price fluctuations. They are also increasingly involved in innovation related to new product development. They achieve these outcomes through their relationships with both suppliers and retailers, and their ability to focus the chain on reliably delivering value for money, as opposed to price alone. Table 10.4 shows a typical value orientation profile for a "category managed" fresh produce value chain.

There are few examples of best practice VCM in fresh produce, but the trends are positive. A small number of value chains have gone beyond the profile of category managers shown in Table 10.4 and have embraced a strategy of total focus on the consumer, absolute transparency of information, and full collaboration among chain members. Their typical profile is shown in Table 10.5.

It is also possible to compare the performance of the three types of fresh produce chains described earlier using the criteria that are associated with competitiveness. These criteria, shown in Table 10.6, focus on attributes such as agility (speed and flexibility), the ability to innovate and not easily be copied by competitors, and the ability to guarantee product integrity.

It is interesting to note from Table 10.6 that the overall competitiveness of each of the three models can be high. At their best, each business model is capable of delivering high returns to the managers of the firms involved. However, as the environment in which fresh produce chains are operating continues to change, firms using traditional adversarial business models will come under increasing pressure as they are forced to compete with

TABLE 10.6 Comparison of competitiveness performance of different types of chains.

	Traditional chain	Category managed chain	Best current practice value chain
Speed of response	High	Medium	Medium
Flexibility	High	High	High
Innovation potential	Low	Medium	High
Ease of copying by competitors	Easy	Moderate	Difficult
Traceability of product	Low	High	High
Overall competitiveness	Can be high	Can be high	Can be high

more closely aligned value chains with the capacity to innovate and whose primary focus is on meeting consumers' needs. This pressure could become disabling for traditional operators in fresh produce retail environments where the demand is for a combination of abilities such as innovation, traceability, differentiation and responsiveness.

10.3 VCM and postharvest chains

10.3.1 The changing environment of VCM in the food industry

To understand how VCM and postharvest horticulture are interrelated, it is necessary first to examine the factors that have driven the adoption of more collaborative whole-of-chain business models. Three broad forces are at work here: the forces of globalization, technology, and consumerism, and how they are shaping the macro environment, the competitive environment, and the internal business environment of every horticultural firm.

10.3.1.1 Globalization

Over the last few decades the barriers to trade in food between most countries in the world have gradually fallen away, spearheaded by the efforts of the World Trade Organization to achieve freer global trade. Under these initiatives, many governments have agreed to reduce tariffs that had been used mainly to protect their domestic food producers. At the same time, new technologies for storage and transport have allowed food products to access distant markets. The physical location of food production and processing facilities is no longer a guarantee of market access and many food companies, including some dealing in fresh produce, see the world as their marketplace, as they have both the access and the technology to reach distant markets.

Global competition means that firms are no longer competing against other local firms for a share of their own domestic market. Many are competing in distant markets against firms from other countries who are also not "locals" to that market, or they are competing in their own domestic markets against firms from overseas. While this global marketplace for food has quite understandably attracted the biggest processors (e.g., Nestlé) and retailers (e.g., Wal-Mart), small firms have not been shut out. There are many examples of small food companies that have identified profitable opportunities in distant markets. It has been shown that the ability of a firm to profit from globalization of markets is not a function of its size, but of how well the firm understands that it is the "total competitiveness along the value chain which determines whether they can export successfully" (Instate Pty Ltd., 2000, p. 3).

The opening of global markets has also resulted in increasing the concentration of supermarket and food service operators. A small number of large food retailers have expanded operations across the globe and they have been especially active in countries where they can introduce more highly developed retail systems that streamline logistics and distribution, widen the choice of products to consumers, and provide new shopping experiences (Regmi & Gehlhar, 2005).

In extending their reach to new and distant markets, one of the biggest challenges for global food retailers has been to take their supply chains with them so that they can guarantee a supply of products that reliably meet quality specifications at competitive prices. What was already a complex and at times difficult process in their own domestic markets becomes far more complex and difficult in markets that are far away and whose consumers are not as well understood. Retailers have realized that sourcing the right products and having a supply chain that is capable of delivering those products, often from one hemisphere to another, is a major challenge in the global marketplace for food.

10.3.1.2 Technological advances

Advances in science and technology have radically re-shaped the food business environment at every stage from production through to processing, storage, transport, and retail. Hewett (2006, p. 39) refers to genetic technology, nanotechnology, and information technology as a "triad of technologies driving change in supply chains world wide." These technologies have spawned innovations in products (genetically modified products, bioactives) as well as processes (radio frequency identification, real time satellite tracking, drone technology, active packaging). At the same time, the technology that allows firms to gather, store, manipulate, verify and communicate information continues to develop rapidly.

In combination, technological advances of all kinds have opened up new possibilities for firms to deliver new food products, more efficiently, more safely, and to more distant consumers and to send and receive information in real time along the complete chain from production to consumption. Not surprisingly, a food industry firm's ability to capture and use newly emerging technologies is closely associated with its ability to compete (Hewett, 2006).

10.3.1.3 Consumerism—the power of consumers

Consumers have more power than ever before, and they are prepared to exercise that power. As many more suppliers achieve the capacity to target many more markets, some markets become "saturated," giving retailers and consumers the ability to exert considerable power in discerning among the many offers from would-be suppliers. The food industry is quoted as one example where markets are saturated with product offers and suppliers are having to become more and more sophisticated in developing new products to attract and retain customers, a process that has been described as "mass individualization" (Linnemann, Benner, Verkerk, & van Roekel, 2006).

Broadly speaking, consumers of food products exert their influence in two different ways. On the one hand, they influence the outputs of food production systems (the kind of food produced); on the other hand, they influence the chains themselves (how food is produced, delivered, and its provenance guaranteed).

Food and lifestyle are inextricably linked. Consumers want food that is nutritious, safe and healthy, but they also want it in a convenient form, they want variety and new experiences, and they want to be able to find food that fits all these needs without having to work too hard to find it. Milstein (2007) identified the megatrends that consumers are responding to as including products and services made "just for me," a growing interest in health and well-being, and an increasing belief that quality is better than quantity.

Milstein also notes that debate will continue to revolve around issues such as obesity, nutrition labeling, absolute traceability along the food chain, and the role of "authenticity" in food production. Consumers are expressing a deepening understanding of the relationships between food and quality of life in their consumption habits and buying behavior.

How food is produced is an increasing concern for consumers world-wide. Of particular interest is how food production affects the environment. Here, too, consumers are expressing their concerns through their purchasing decisions. For example, this has given rise to food certified as being produced in environmentally responsible ways, food that has been produced by systems with a low carbon footprint, or food that has traveled a low number of "food miles." Companies are responding to these consumer-driven concerns by adopting more sustainable business practices such as sourcing products locally, using less water or power in production, producing less waste, or reducing unnecessary packaging. In the developed world, every food company, whether they be farmers, packers, processors, transport operators, or wholesalers, could point to some part if its business that is a direct response to increasing consumer concern for the impact of food production on the environment.

In an increasingly crowded global marketplace for food products, the ability of firms to make profits by responding to what consumers need is related to their ability to differentiate themselves from one another. Differentiation is virtually impossible unless firms play an active role as members of chains that create and deliver what consumers need. In a global marketplace, independent firms, even with the world's best new product development ideas and technologies, simply cannot guarantee consumers that their products are safe, healthy, environmentally responsible, available all year round and represent value for money unless they collaborate with the other firms that make up the chain from production to consumption of those products.

10.3.2 VCM as a setting for postharvest horticulture

Understanding VCM as a model for being competitive in the rapidly changing agri-food business environment provides the background for exploring how VCM and postharvest horticulture are linked. This section argues that postharvest practices are value-creating activities; thus VCM can enhance a firm's ability to profitably deliver postharvest processes, outcomes, and outputs to those parts of the chain where they represent value. For example, downstream in the chain where postharvest practices may create value for a retailer, incentive is generated, often in the form of continuing orders and better prices or payment terms, to continue these practices. Upstream, when a primary producer sees value in the postharvest performance of a potential customer, there is incentive for the primary producer to seek to become a preferred supplier to that customer.

10.3.2.1 Why horticultural firms become involved in VCM

Boehlje, Schrader, and Akridge (1998) note that firms collaborate to form value chains for three reasons: to be able to respond better to consumers, to improve efficiency and to reduce risks.

As mentioned above, consumers are becoming more discerning about the food they consume and they tend to direct their business toward those chains that can anticipate and service these needs. The value created through postharvest activities such as grading, processing, packaging, storage, and transport is targeted at meeting-specific consumer requirements. The more precisely, reliably, and economically those requirements are met, the more value is created. When a chain of collaborating firms is able to create value in this way, it not only strengthens the relationships among the collaborating firms but also builds relationships between the chain and its consumers. This is VCM at work, and chains of firms operating in this way become extremely difficult for competitors to emulate because those competitors have to compete against not only the technical value-creating abilities of the whole chain, but also against the strength of the relationships that have been formed through collaborating to meet consumers' needs.

The second motivator behind value chain formation relates to efficiency. Chains must deliver food products to particular specifications, including conformance with mandatory requirements such as food safety standards. Collaboration among firms in a value chain not only ensures that specifications have been met at every point in the chain but also allows efficiencies and cost savings to be identified within firms as well as between firms. Examples include the ability to hold less inventory through made-to-order chains, sharing of infrastructure such as storage and transport between firms, integrating IT systems between firms, and the adoption of technologies and systems that are unavailable or uneconomic for single firms. The ability to reduce costs through improved efficiency represents value created through collaboration. This value may be retained by the firm(s) responsible, or passed along the chain so that it becomes value for other chain members, and ultimately the consumer.

Finally, firms form value chains to reduce risks. Individual firms can lower their exposure to influences such as the unavailability or rising prices of inputs, the impact of seasonal variation on product quality and availability, or the need to ensure that a whole chain can guarantee food safety through the adoption of a certified food safety management system. On their own, most firms would be far more exposed to these risks and could make few guarantees beyond their own boundaries.

All three examples demonstrate how postharvest chains and practices can create value for collaborating firms along a chain. Put another way, those same postharvest chains and practices in the hands of independent horticultural firms aiming to maximize their individual profitability are far less able to:

1. monitor, respond to, and influence consumer needs;
2. ensure that product is delivered to the retailer as cost efficiently as possible; and
3. guarantee the safety of the product delivered to consumers.

10.3.2.2 How horticultural firms become involved in VCM

The most common pathway to VCM begins when two firms decide to collaborate, then based on positive results they extend their reach to other chain members. A value chain is formed when firms involved in a collaborative relationship share a common objective of targeting a specific market or market segment. The more successful they are, the more difficult it becomes for competitors to copy their value chain, as shown in the example next.

An example (based on an actual case): a large vegetable grower successfully negotiates with a processor to supply higher quality inputs at a slightly higher price. Customers of the processor respond to the higher quality output and business expands until more inputs are required than can be supplied by the original grower. With the support of the processor, the original grower invites a small group of new growers to become high-quality suppliers to the processor. These new growers are in different regions and they can extend supply over a much longer season. Growing across more regions also spreads environmental risks. These growers are trained to meet the same higher standards and they prove to be reliable and committed. Business continues to expand. Now the supplier group goes looking for genetics as a source of even higher quality, and they form an alliance with a supplier of superior genetics. The genetics supplier sees enough business, and has enough trust, to give exclusive rights to the grower alliance for certain of its seed products. The seed supplier's company name also appears on the packaged product that consumers buy. Business continues to expand; retailers are happy with the results and ask for a wider range of products. This represents an opportunity for both the growers and the processor to diversify and spread their risks. Collaboratively, a small number of new products are identified for which high-quality genetics are available, and that require only minimal investment in new processing and growing capacity. These products are also successful and a small portfolio of products under a common brand becomes established. The genetics—grower—processor value chain adopts a strategy of reinvesting a share of each partner's returns into consumer research. The objective is to stay in touch with how consumers are responding to their products so the value chain can assist retailers to promote and merchandize their brand. Over time, and based on consumer feedback, the group is able to incorporate world class environmental standards into its production and processing systems. At this point, with exclusive genetics, dedicated and capable growers across a number of regions, an innovative processor and satisfied retailers and consumers, the value chain has put itself in a position where competitors are struggling to keep up.

It is important to note from the previous example that it is not necessary for every firm in a value chain to collaborate. Retailers and wholesalers, for example, may not be directly involved but may be willing to cooperate as customers of the main value chain partners. In fact, in practice it is rare to find a value chain that is able to achieve high levels of collaboration and value creation that involve *every* member of the chain (Bollen, 2004; Collins et al., 2002). What is always needed, however, is a chain champion who initiates value chain formation and takes oversight of the early stages of formation. These principles, and those illustrated in the example earlier, have been discussed by van Roekel, Kopicki, Broekmans, and Boselie (2002).

In horticulture, as individual producers are small scale in relation to their ability to service a market segment, it is common for producers to form alliances among themselves, sometimes referred to as horizontal alliances (Agriculture & Food Council, 2002). Through their involvement with downstream chain members, these alliances may initiate the formation of value chains in horticultural industries. Collins (2004) describes the kind of activities that firms become capable of through alliance and value chain formation. They include:

- coinvesting in research to better understand consumers' needs;
- actively influencing consumer behavior;
- exploring for new products, technologies or markets; and
- providing proof of authenticity such as country of origin or environmental credentials.

These kinds of activities confer competitive advantage on a whole value chain because each of them is difficult to achieve by individual producers or other chain members acting alone.

10.3.3 Postharvest horticulture as a value creation domain

10.3.3.1 Defining the domain

Postharvest horticulture can be defined at various scales and in various ways. At its widest scale, it begins when the product is separated from the plant or growing medium and ends with consumption by the final consumer. More narrowly, it might be defined as extending from harvest until the product is in the form in which it will be retailed. By any definition, postharvest horticulture involves transformation of a product from its state at harvest to its ready-to-consume state. This may be a simple transformation, for example, for a fresh whole lettuce that will be retailed within a few days, or a complex transformation, for example, for a potato processed into frozen French fries sold many months later in another country. The chain along which the product flows may be very short and may involve no or few other firms, for example, product sold at the farm gate; or it may be long and may involve many other firms, for example, potatoes in the frozen French fries example given previously. Regardless of their scale or complexity, postharvest activities have two features in common: they add value and they involve members of the chain.

The ways in which postharvest activities can involve other chain members have been addressed earlier in this chapter. At sophisticated levels of involvement, these activities are elements of a business model known as VCM. At minimal levels of involvement, they may simply represent the various stages at which product changes hands from one firm to another along a traditional supply chain, for example, from a grower to a packer, a packer to a wholesaler or a wholesaler to a retailer. This chapter concentrates on the higher levels of involvement that are associated with VCM because they have been shown to improve the competitiveness of businesses at all stages of the horticultural supply chain.

10.3.3.2 Adding value through postharvest science and technology

Postharvest horticulture has been defined as having the potential to add value through four interconnected areas of activity. They are food safety, traceability, information systems and consumer response to quality (Bollen, 2004). Each is discussed in the following.

10.3.3.2.1 Food safety

The need for food safety is beyond question. Almost two decades ago, research showed that general consumer confidence in the motives of food producers and retailers had decreased (Frewer, 2003; Stewart-Knox, 2013), fueled by publicity surrounding outbreaks such as BSE, *Escherichia coli*, bird flu, and foot and mouth disease. At the time, horticulture was not immune from public concern about its systems and their outputs. Recent research shows that horticulture's contribution to foodborne disease outbreaks in the United States increased to 9.7% in the period from 2011 to 2015, while in Europe in 2010 more than 20% of foodborne illnesses were from foods of nonanimal origin (Machado-Moreira, Richards, Brennan, Abram, & Burgess, 2019).

Hurst (2004), reporting that the incidence of human foodborne illnesses related to horticultural produce is low but increasing, suggested that this may be because of better microbial detection methods, higher per capita consumption of fruit and vegetables, global sourcing, and the evolution of more virulent strains of pathogens. Hurst argued that every horticultural supply chain needs a food safety plan, and in many countries this is now a mandatory requirement.

Postharvest practices that ensure food safety add value through the consumer confidence they instill. When consumers believe that a horticultural product is "risky" they engage in the following behaviors, all of which directly impact the profitability of the chains that delivered the product to the consumer (Frewer, 2003):

- they move to another product category, for example, from fresh cut product to fresh whole product;
- they change to another brand or origin of the product, for example, away from product produced in a particular country;
- they move to another retailer or type of retailer, for example, away from supermarkets, or away from local markets;
- they move toward product produced in a particular way, for example, toward low chemical usage produce; or
- they reduce consumption altogether, for example, they stop consuming products in that broad category.

In summary, one objective of postharvest horticulture is to create value based on its ability to ensure food safety. Ultimately this is achieved through building trust with consumers that a particular product, brand, retailer, and production method is safe, time after time. From a technical point of view, food safety means avoiding microbiological contamination that exceeds defined limits. From a management point of view, it means implementing and enforcing food safety standards and management systems that deliver value 100% of the time. While individual firms can, and must, carry responsibility for their part of the chain, integrated value chains can give much higher level food safety assurances to consumers because the whole chain is managed as a system whose responsibility is to deliver food safety. Despite occasional scares, consumers take food safety for granted in developed countries, but the situation is very different in developing countries where research has shown willingness to pay, even among the poorest consumers, for better food safety (Macharia & Collins, 2011).

10.3.3.2.2 Traceability

The aim of traceability is to ensure that supply chains deliver product as intended, and if not, to be able to identify and address failures. Bollen (2004) lists four functions of traceability in a supply chain. They are:

- so that product can be traced back as part of a food safety system;
- to allow tracking of product from farm to market to give evidence of good agricultural practice or good manufacturing practice;
- to be able to track and trace shipments by air or sea; and
- to improve segregation of product so that specific market segments may be targeted.

Each of these functions involves postharvest activities and technologies, and each adds value for one or more members of a value chain. As all of them rely on documentation produced as part of a codified management system, it is therefore impossible to achieve traceability without at least some cooperation from every chain member. At one end of the spectrum is the minimum acceptable functional level of traceability, or base-level traceability. At the other end of the spectrum, when chain members make a collective decision to invest in traceability systems as part of a VCM business strategy, very high levels of performance become possible. This may be because of improved inventory management, higher levels of security, guaranteed best practice, or more highly differentiated offers to consumers. In each of these cases, postharvest chains and technologies have a critical role to play in adding value.

10.3.3.2.3 Information systems

The globalization of horticultural markets has brought with it a manifold increase in logistical complexity. Because of the perishability of horticultural products, supply chains have time-critical dimensions; thus any improvements to the ability to store and transport horticultural products have significant commercial value. At the same time, the storage and transport of products is meaningless without information exchange, and the timing and quality of information exchanged often determines the value that can be created by the storage and transport functions themselves.

Information systems may not always be thought of as part of the postharvest chain, yet without them the flow of product within and between firms is impossible. Information is needed to capture the quantity and quality characteristics of the product, its location in the value chain at any time, the state of the processes that transform the product, and the value of the product at each stage of the chain. Postharvest activities not only directly add value to the product along the chain, but they also create information that is needed to inform decisions about the product as it flows along the chain. The integration of postharvest technologies with information management systems has received relatively little research attention. However, in the VCM business model, the value added by improved postharvest technologies is only translated into profits when information about that value is communicated to those to whom it is commercially significant. Bollen (2004, p. 48) has suggested that information systems are “the major opportunity for the logistics supply chain to progress to become a value chain.”

10.3.3.2.4 Consumers and quality

The role of postharvest research and development in assuring that consumers get the quality they demand has been the central orientation of the discipline. A review by the author of 180 published papers in the field of postharvest science since 2003 revealed 155 that made direct reference to consumer satisfaction or meeting the needs of markets as the rationale for the research. The significance of this orientation is captured by Shewfelt (2006, p. 31) in stating "the success or failure of any food is determined by the consumer."

In defining quality using simple and practical terms, Prussia (2004) defined low quality as not meeting consumer expectations; acceptable quality as satisfying consumer expectations; and high quality as exceeding consumer expectations. This definition is consistent with Shewfelt's (2006) view of the primacy of the consumer in determining what constitutes quality. Prussia (2004) also separated purchase quality from consumption quality. Purchase quality related to those attributes that could be assessed at the time of purchase, such as size, color, blemish, firmness, and aroma. Consumption quality related to attributes that could only be assessed destructively, such as flavor, texture, flesh color, juiciness, and mouth-feel. Another distinction that can be drawn is between tangible and credence attributes. Tangible attributes are those properties that can be experienced by the consumer, whereas credence attributes are those that consumers cannot validate personally and are often connected with production conditions, such as low pesticide use, fair trade, environmental responsibility, or provenance.

Understanding what constitutes quality of a product as defined by the consumer and being able to deliver that quality is the main business of a horticultural value chain. The ability to deliver purchase quality attracts consumers to make purchases, but being able to deliver consumption quality drives repeat purchases and builds consumer loyalty—and these form the basis of sustained profitability for a value chain.

While some quality attributes are determined by preharvest operations, many are determined after harvest. Ripening and storage conditions after harvest, for example, have direct effects on quality attributes such as flavor, texture, color, blemish, and perceptions of freshness. For processed horticultural products, every aspect of postharvest chains creates value in the finished product, for example, by grading, slicing, mixing ingredients, sanitation treatments, packaging, and labeling. Collectively, these activities create value through flavor, color and texture profiles, portion or pack size, and attractiveness for the consumer.

The goal of VCM is to deliver value to consumers at an acceptable price, that is, to deliver value for money. Quality as perceived by the consumer is central in determining what represents value for money. The orientation of postharvest R&D toward quality for the consumer is in fact an orientation toward value creation, which is the basis of VCM.

10.4 The future

The future for VCM and its interaction with postharvest horticultural chains will be shaped by the three forces of change discussed earlier: globalization, technology, and consumerism.

Globalization will continue to give access to new markets and will bring more competition to domestic markets. Both large players and small will stand to benefit, but whatever the scale, the ability to capture new markets will be determined by the performance of the value chain as a whole, not the performance of any individual firm. At the same time, food security will be a counterbalancing force. Nations will not want to become wholly reliant on imported foods, and local production to ensure food security will be a strategic issue for many nations. Horticultural industries will figure prominently in these strategies for their ability to produce and distribute to local communities, large volumes of fresh, nutritious food, quickly, and flexibly.

Advances in postharvest technologies will be used to create new food products, new processes, and new ways of generating and managing information. Only those that represent value, either to members of value chains or to consumers, will survive. New technologies associated with the intersection of food production, health, and well-being will be especially valued, along with those that help to ensure the security of supply chains.

Consumers in the future will be even more discerning than they are now. The ability to anticipate, understand, and influence consumers will confer competitive advantage on value chains, the members of which will invest more and more in consumer research. Shewfelt and Henderson (2003) list six consumer trends related to horticultural produce that are relevant to this chapter. They are:

1. More emphasis on quality: fruits and vegetables will become more of a high value speciality item; safety may be associated with total absence of pesticides.
2. More emphasis on local production: more incentive to produce horticultural food locally to avoid dependence on imported produce.
3. Less emphasis on shelf life and more emphasis on consumption quality: long shelf life will be considered a negative attribute; a true appreciation of flavor will supersede the importance of purchase quality attributes such as size and color.
4. Less concern about price and more emphasis on value: consumers will pay higher prices for fruit and vegetables as a speciality item; consumers will be less forgiving of unreliability of quality and will demand more information.
5. More emphasis on technological solutions: campaigns against technologies such as irradiation and genetic modification will be less effective; technologies that can deliver consumption quality, especially those that maximize flavor, will be accepted.
6. More emphasis on sustainable production: governments will require accounting for environmental impacts; inputs such as power and water will become more expensive; higher costs will be passed on to the consumer.

Broadly speaking, the forces of globalization, changing technology, and consumerism will exert their influence on postharvest horticulture in two ways. They will define what constitutes consumer value; and they will therefore influence R&D priorities in the domain of postharvest R&D. Perhaps most importantly, more firms will adopt VCM strategies that are based on delivering value to consumers based on these R&D outputs.

References

Agriculture and Food Council. (2002). *Value chain handbook*. Alberta: Alberta Agriculture, Food and Rural Development.

Anderson, D., Britt, F., & Favre, D. (2007). The 7 principles of supply chain management. *Supply Chain Management Review*, *11*, 41–46.

Boehlje, M., Schrader, L., & Akridge, J. (1998). Observations on the formation of chains. In G. Ziggers, G. Trienekens, & J. Zuurbier (Eds.), *Proceedings of the third international conference on chain management in agribusiness and the food industry* (pp. 393–403). The Netherlands: Wageningen Agricultural University.

Bollen, F. (2004). Logistics in supply chains for fresh produce. In: *Proceedings of the APEC symposium on quality management in postharvest systems* (pp. 47–56). Thailand: King Mongkut's University of Technology.

Bonney, L., Clark, R., Collins, R., & Fearne, A. (2007). From serendipity to sustainable competitive advantage: Insights from Houston's farm and their journey of co-innovation. *Supply Chain Management: An International Journal*, *12*, 395–399.

Bowersox, D. (1990). The strategic benefits of logistics alliances. *Harvard Business Review*, *68*, 36–43.

Collins, R. (2004). Whole-of-chain quality management: An emerging perspective for postharvest science. In: *Proceedings of the APEC symposium on quality management in postharvest systems* (pp. 15–23). Thailand: King Mongkut's University of Technology.

Collins, R. (2006). The functions and consequences of alternative fresh produce supply chain models. *Acta Horticulturae*, *712*, 67–73.

Collins, R., Dunne, A., & O'Keeffe, M. (2002). The locus of value: A hallmark of chains that learn. *Supply Chain Management an International Journal*, *7*, 318–321.

Cooper, M., & Ellram, L. (1990). Supply chain management, partnerships, and the shipper-third party relationship. *International Journal of Logistics Management*, *1*, 1–10.

Dent, B. (2013). *Managing the uncertainties of climate change mitigation – A real options approach* (Ph.D. dissertation). The University of Queensland.

Fearne, A. (2009). *Sustainable food and wine value chains*. Adelaide: Department of the Premier and Cabinet, Government of South Australia.

Fearne, A., & Hughes, D. (1999). Success factors in the fresh produce supply chain: Insights from the UK. *Supply Chain Management*, *4*, 120–128.

Frewer, L. (2003). Quality in chains: Consumers and risk. *Acta Horticulturae*, *604*, 233–237.

Gifford, D., Hall, E., & Collins, R. (Eds.), (1997). *Competitive Performance*. Canberra: Australian Government Publishing Service.

Gold, S., Seuring, S., & Beske, P. (2009). Sustainable supply chain management and inter-organizational resources: A literature review. *Corporate Social Responsibility and Environmental Management*, *17*, 230–245.

Gooch, M. (2012). *Motivating and enabling value chain innovation in Canada's agri-food industry*. Guelph, ON: Value Chain Management Centre, George Morris Centre.

Gunasekaran, A., Patel, C., & Tirtiroglou, E. (2001). Performance measures and metrics in a supply chain environment. *International Journal of Operations and Production Management*, *21*, 71–87.

Halldorsson, A., Kotzab, H., Mikkola, J., & Skjott-Larsen, T. (2007). Complementary theories to supply chain management. *Supply Chain Management*, *12*, 284–296.

Hewett, E. (2006). Progressive challenges in horticultural supply chains: Some future challenges. *Acta Horticulturae*, *712*, 39–49.

Hugos, M. (2003). *Essentials of supply chain management*. Hoboken New Jersey: John Wiley & Sons Ltd.

Hurst, W. (2004). GAPs/GMPs/HACCP: Food safety systems for handling fresh produce. In: *Proceedings of the APEC symposium on quality management in postharvest systems* (pp. 129–136). Thailand: King Mongkut's University of Technology.

Instate Pty Ltd. (2000). *Exporting Australian processed foods: Are we competitive?* Canberra: Agriculture, Fisheries and Forestry Australia.

Jackson, M. (2003). *Systems thinking. Creative holism for managers*. West Sussex, England: John Wiley & Sons Ltd.

Jackson, M. (2019). *Critical systems thinking and the management of complexity*. West Sussex, England: John Wiley & Sons Ltd.

Stewart-Knox, B. (2013). Consumer perception and understanding of risk from food. *British Medical Bulletin*, *56*, 97–109.

Kouvelis, P., Chambers, C., & Wang, H. (2006). Supply chain management research and production and operations management: Review, trends, and opportunities. *Production & Operations Management*, *15*, 449–469.

Lambert, D., & Cooper, M. (2000). Issues in supply chain management. *Industrial Marketing Management*, *29*, 65–83.

Linnemann, A., Benner, M., Verkerk, R., & van Roekel, M. (2006). Consumer driven food product development. *Trends in Food Science and Technology*, *17*, 184–190.

Machado-Moreira, B., Richards, K., Brennan, F., Abram, F., & Burgess, C. (2019). Microbial contamination of fresh produce: What, where and how? *Comprehensive Reviews in Food Science and Food Safety*, *18*(6), 1727–1750.

Macharia, J., & Collins, R. (2011). Consumer value preferences: A pre-requisite for sustainable performance improvement in agri-food supply chains. In: *Proceedings of the fifth international consumer science research conference*. Germany: University of Bonn.

Martinez, V., & Bititci, U. (2006). Aligning value propositions in supply chains. *International Journal of Value Chain Management*, *1*, 6–18.

Matenga, A. (2017). *Developing garlic value chains in Northern Mozambique*. Australia: The University of Queensland. Available online: https://icte.uq.edu.au/project/developing-garlic-value-chains-northern-mozambique.

Mentzer, J., DeWitt, W., Keebler, J., Min, S., Nix, N., Smith, C., & Zacharia, Z. (2001). Defining supply chain management. *Journal of Business Logistics*, *22*, 1–25.

Milstein, D. (2007). *What's hot in food?* (6th ed.). Brisbane: Update, David Milstein and Associates.

Moller, K. E., & Torronen, P. (2003). Business suppliers' value creation potential – A capability-based analysis. *Industrial Marketing Management*, *32*, 109–118.

Morgan, R., & Hunt, S. (1994). The Commitment-Trust theory of relationship marketing. *Journal of Marketing*, *58*, 41–55.

Mudimigh, A., Zairi, M., & Ahmed, A. (2004). Extending the concept of supply chain: The effective management of value chains. *International Journal of Production Economics*, *87*, 309–320.

O'Keeffe, M. (1998). Establishing supply chain partnerships. *Supply Chain Management*, *3*, 5–9.

Porter, M. (1980). *Competitive strategy*. New York: The Free Press.

Potra, S., Pugna, A., Negrea, R., & Izvercian, M. (2019). Customer perspective of value for innovative products and services. *Procedia – Social and Behavioural Sciences*, *238*, 207–213.

Prussia, S. (2004). Systems thinking for improving modern quality management systems. In: *Proceedings of the APEC symposium on quality management in postharvest systems* (pp. 39–46). Thailand: King Mongkut's University of Technology.

Ramsay, J. (2005). The real meaning of value in trading relationships. *International Journal of Operations & Production Management*, *25*, 549–565.

Regmi, A., & Gehlhar, M. (Eds.). (2005). *New directions in global food markets* (Information Bulletin No. 794, USDA).

Shewfelt, R., & Henderson, J. (2003). The future of quality. *Acta Horticulturae*, *604*, 49–59.

Shewfelt, R. L. (2006). Definign and meeting consumer requirements. *Acta Horticulturae*, *712*, 31–38.

Simons, D., Francis, M., & Jones, D. (2002). Food value chain analysis. In G. Doukidis, & A. Vrechopolous (Eds.), *Consumer driven electronic transformation* (pp. 179–192). Berlin: Springer.

Spekman, R., Spear, J., & Kamauff, J. (2002). Supply chain competency: Learning as a key component. *Supply Chain Management*, *7*, 41–55.

Taylor, D. (2005). Supply Chain Analysis: An approach to value chain improvement in agri-food chains. *The International Journal of Physical Distribution and Logistics Management*, *35*, 744–761.

van Roekel, J., Kopicki, C., Broekmans, C., & Boselie, D. (2002). *Building agri supply chains: Issues and guidelines*. Washington, DC: World Bank.

Wernerfelt, B. (1984). The resource-based view of the firm. *Strategic Management Journal*, *14*, 415–423.

Williamson, O. (1971). The integration of production: Market failure considerations. *American Economic Review*, *23*, 335–345.

Zokaei, A., & Simons, D. (2006). Value chain analysis in consumer focus improvement. *International Journal of Logistics*, *17*(2), 141–162.

This page intentionally left blank

CHAPTER

11

Plant to plate—achieving effective traceability in the digital age

Arthur Frank Bollen and Matt Adkins

Zespri International Limited, Mount Maunganui, New Zealand

Abbreviations

Alphanumeric ID	alphanumeric identification
QR code	quick response code
RFID	radio-frequency identification

11.1 Introduction

Tracking and tracing has been an expected attribute of modern horticulture value chains for over 20 years. When working effectively, traceability is a well-coordinated and well-documented movement of product and documented activities associated with the product, from producer, through a network of intermediaries, to the final consumer. Traceability is not only a fundamental tool for global trade but, when used well, is a mechanism for reduced food safety risks, minimizing food wastage, improved sustainability, increased brand recognition, enhanced brand value, and greater profitability.

When first published, this chapter discussed the various technologies that enable a traceability system and emphasized how the components of postharvest value chains interacted and the impacts of these interactions on other businesses. While the building blocks for high-performing traceability systems exist, the implementation of anything past relatively basic systems has been slow. To navigate the complexity associated with traceability in modern horticulture value chains, this chapter will consider not only the advances in traceability technology over the past decade but also identify barriers to implementation of effective value chain traceability and describe that the strategies horticulture value chain managers should be considering to achieve the best application of these technologies.

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00011-7

11.2 Successful implementation of traceability

11.2.1 Step 1—make sure everyone is on the same page

The terminology used to describe tracing and tracking of product within food value chains is mostly commonly referred to as "traceability." However, there is no exact, single definition of traceability. It has a wide number of different meanings, depending on both the industry sector within a system, and the perspectives of the suppliers and users of the information. Bosona and Gebresenbet (2013) noted this lack of consistency when considering the definition of traceability in food value chains within the scientific literature. However, their research did identify three main components commonly associated with traceability:

1. Tracing—backward follow-up of products.
2. Tracking—forward follow-up of products.
3. History—information associated with the product movement within a system.

But, while these appear to be the three main components, only about 30% of the literature included all three at once when referring to or describing traceability (Bosona & Gebresenbet, 2013). Adding further to the complexity and confusion that exists with traceability the Karlsen, Dreyer, Olsen, and Elvevoll (2013) literature review of traceability found differences between what the information technology (IT) sector and the food industry sector define as traceability. Their review concluded that a successful implementation of traceability requires an interdisciplinary research approach across both natural and social sciences. However, the lack of a common understanding of traceability as a concept between disciplines is to the extent where the authors suggest that it is currently not possible to create a theoretical framework for the implementation of food traceability.

These papers help emphasize the first, and commonly overlooked, barrier to implementing effective traceability; everyone needs to be "on the same page." While these papers demonstrate differences between stakeholders within a postharvest business or research discipline associated with traceability, it is important to recognize that even within an organization, that is, a single stakeholder within a value chain or postharvest business, different views on what is "traceability" will and do exist. Often the differences are due to the mixture of disciplines contained within the many different business groups that make up an organization, that is, the silo effect. To this end Spink (2019a) has suggested a "taskforce" approach within any organization when tackling food risk (which would include traceability) to transcend and avoid the confusion associated with organizational silos.

11.2.2 Definition of traceability

The complexities of postharvest value chains for perishable products mean that a succinct definition of traceability is difficult. ISO 9001:2015—quality management systems (ISO, 2015) define traceability within a business entity as the ability to trace the history, application or location of an object. When considering a product, traceability can relate to:

- The origins of materials and parts,
- The processing history, and
- The distribution and location of the product after delivery.

In the context of a food manufacturing system, Moe (1998) defined traceability as "...the ability to track a product batch and its history through the whole, or part, of a production chain from harvest through transport, storage, processing, distribution and sales" which was defined as *chain traceability*. Moe further defined *internal traceability* as all product batches and activities within one-step of the chain. Moe's work built on the work of Kim, Fox, and Gruninger (1995) who had stated that: "... the fundamental and necessary core in an ideal traceability system is the ability to face both products and activities."

Bodria (2002) observes the obligation of traceability is unique in that the responsibility to provide traceability is shared by all businesses involved in a particular value chain. Therefore, traceability requires the unique identification of products and processes coupled with information systems that are able to deliver relevant information to meet trace forward (track) or trace back (trace) requirements. The meeting of requirements must occur across several business boundaries.

To avoid confusion and ambiguity around the terminology "traceability" and to ensure that all aspects of effective monitoring and decision-making associated with the delivery of horticulture product from plant to plate are considered, we offer the following definition of traceability:

> *Effective traceability should provide an ability for any stakeholder within a value chain to know* ***the precise location*** *of a product consignment and* ***access to necessary information*** *to make the most appropriate decisions for that product throughout its journey. This includes the ability to* ***trace*** *back along the value chain to know its full history (custody, food safety, value chain conditions), and the ability to* ***track*** *its forward journey. The* ***greater transparency*** *and* ***ease of information sharing*** *between the various stakeholders within the value chain, whether tracing or tracking, the better the outcomes* (also see Fig. 11.1).

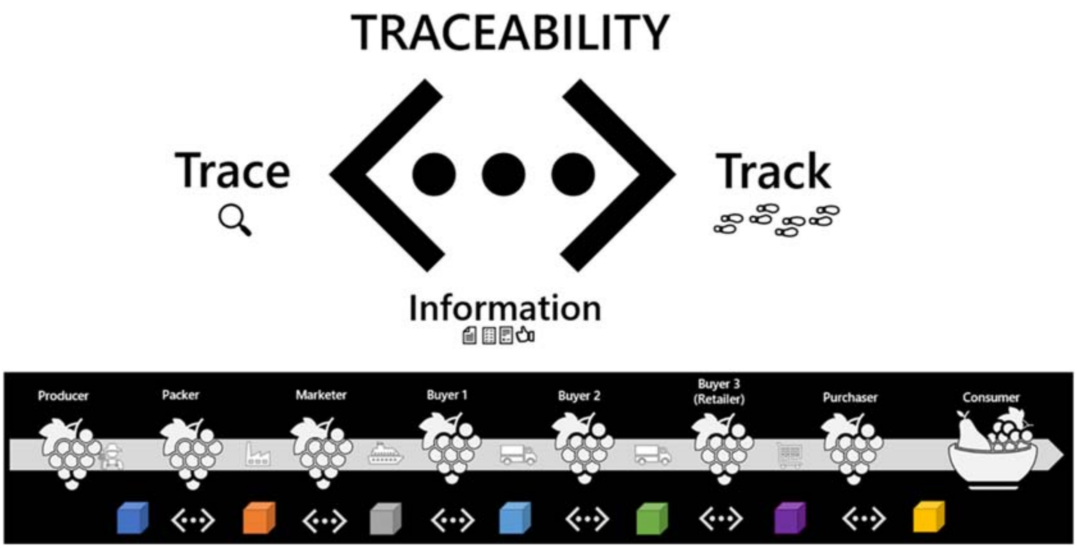


FIGURE 11.1 The traceability system (linear sequence applied for the simplicity of the concept presentation, but in reality this is generally a network of linkages).

11.3 Strategic considerations—understand your needs

11.3.1 Do not let the tail wag the dog

Traceability technologies are an essential necessity within the modern postharvest value chains for their ability to facilitate trade. Over the past decade, food safety has become an increasingly important component of global trade contributing to the increased complexity of postharvest value chains. Along with this complexity, the abundance of technology "solutions" and the degree with which they are marketed as "complete" solutions make it crucial businesses apply a strategic approach to ensure the successful application of traceability systems. Without assessment and understanding how traceability technologies meet a defined business goal, significant gaps in the integrity of a value chain can occur, including fundamental areas such as food risk. To ensure the "the tail does not wag the dog" (Fig. 11.2), it is crucial that horticulture value chains managers understand and define the *drivers of food risk* within their system. Spink (2007) has developed the concept of the food risk matrix that breaks "risk" down into four major components (food safety, food quality, food fraud, and food defense) as discussed in the following section.

11.3.2 Focus on "the why"

Management of all four food risk components (safety, quality, fraud, and defense) is reliant on, and improved by, track and trace systems. However, each component of food risk has its own unique drivers and characteristics that need to be understood and appreciated when selecting track and trace technologies. Spink and Moyer (2011) break down the risks for each of the four components (safety, quality, fraud, and defense) based on three factors: (1) the type of harm it causes, (2) the motivation of the parties involved, and (3) if an incident was accidental or intentional. To that end the four components of the food risk matrix are summarized by Spink and Moyer (2011) and Spink, Chen, Zhang, and Speier-Pero (2019) as follows:

- Food safety: Unintentional acts that cause public health harm.
- Food quality: Unintentional acts that do not cause public health harm (but can and will have large economic consequences).

FIGURE 11.2 Differentiating the drivers for traceability (food risk—safety, quality, fraud, and defense) from the enablers of traceability (technology solutions).

- Food defense: Intentional act with the intention of causing public health, terror, or economic harm.
- Food fraud: Intentional deception for economic gain. Human health harm may be an unintentional by-product of the deception.

Understanding of each of the four food risk components is critical when selecting and implementing the correct track and trace technologies but is beyond the scope of this chapter. However, it is important to highlight how complex, and therefore considered, the thinking must be to design a strong strategy. Accordingly, we have chosen to highlight food fraud and food quality as examples. These two components were chosen because:

- food fraud risk is the most complex of the four areas and reinforces the degree of understanding necessary when considering a track and trace solution;
- traceability of food quality is a yet-to-be optimized opportunity; if implemented correctly, it can prevent significant volumes of fruit loss within a postharvest system leading to increased profitability and improved sustainability credentials.

Traceability effectiveness for food safety and food defense is analogous; speed of trace back to the source issue. Historically, both areas have shown a similar pattern of detection and response (Fig. 11.3).

In that regard, without downplaying the significant impacts associated with safety and defense factors, nor the difficulty in achieving it, effective traceability for food safety and food defense is predominantly about *speed and accuracy of traceback* within a value chain.

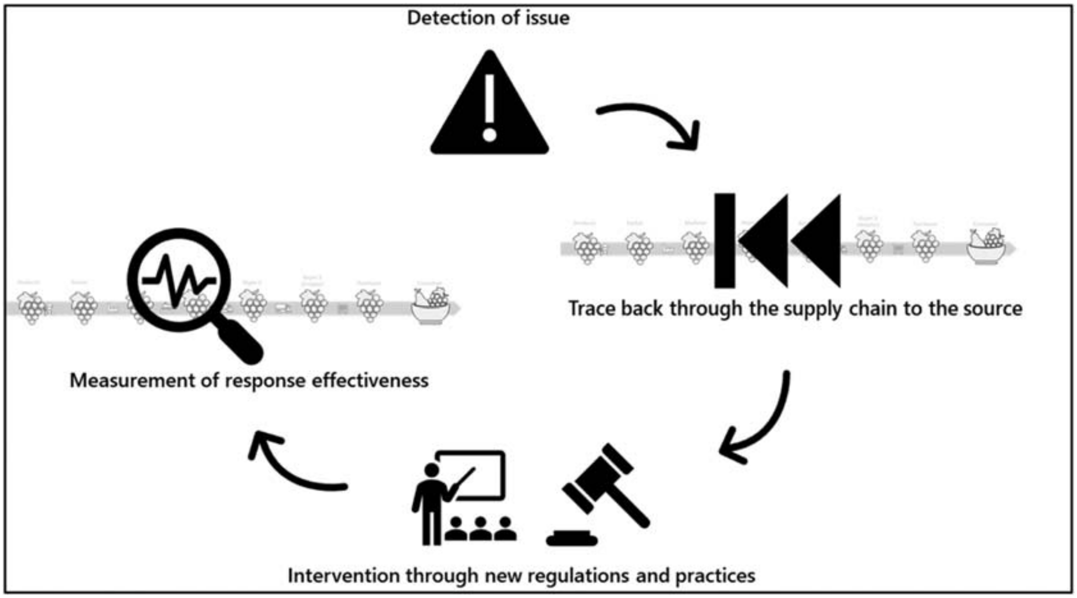


FIGURE 11.3 Food safety and traceability effectiveness.

11.3.3 Reduce food fraud vulnerability through traceability: prevent negative spillover

Reducing vulnerability to food fraud is heavily reliant on proactive rather than reactive strategies. Food fraud perpetrators are opportunistic and sit outside, or on the periphery, of existing value chains or businesses, making it a significant challenge to detect and intervene (Spink, 2011). Although legitimate stakeholders within postharvest businesses and value chains make significant effort to preserve the quality and safety of their products, counterfeiters do not necessarily adhere to the same standard (Spink, 2011). The lack of integrity associated with counterfeit product, and its presence in a value chain, represents significant food quality and safety risk. Food fraud can have devastating effects within a value chain; individual businesses and brands can suffer irrevocable reputational damage on the back of viral social and mainstream media "outbreaks." In worst case scenarios, this can lead to business failure. Consequences can extend beyond individual businesses; associated products and value chains can be "tarred with the same brush" and suffer loss of confidence from regulators and consumers alike (van Ruth, Luning, Silvis, Yang, & Huisman, 2018).

There are many instances of food safety issues that have created negative consumer perception and loss of sales on other brands within a category and other closely related product types. Recent events include:

- 2018 Australia: *Listeria* outbreak in rock melons caused $60M in lost sales including loss of export markets (Sanda, 2018).
- 2018 Arizona, USA: *Escherichia coli* outbreak in Romaine lettuce in Arizona (USA) saw sales of the lettuce reduced by about 50% as well as loss of sales for other lettuce types not associated with the outbreak.

Cuite's et al. (2009) survey of the public's response to the *Salmonella* Saintpaul outbreak of 2008 provides evidence that consumers are often confused by communications associated with food safety warnings. Confusion such as this can lead to misperception and a brand or industry not directly associated with a food safety incident can be seen as unsafe and suffer reputational and economic loss as a result. This is known as "negative spillover." Strategically, proactively disassociating from a brand impacted by a food safety incident has been shown to be an effective approach to negative spillover, rather than remaining invisible (Zhang & Lim, 2021).

Effective traceability systems within a value chain can have enormous benefit in preventing or minimizing system vulnerability to product harm associated with food fraud and negative spillover. The ability for a company, brand, industry, or country to quickly and definitively differentiate itself from a food quality or food safety issue can be the difference between being dragged under or being unaffected. Therefore the ability of traceability solutions to provide resilience to food quality and safety events by providing assurance that any issue is not associated with their product is critical. Being able to demonstrate this in a proactive manner, that is, before an incident occurs, can help build brand confidence and provide further resilience when and if food quality or safety issues occur because of fraud within a value chain. The key aim of proactively "advertising" value chains traceability credentials is demonstrating clearly how the traceability system provides the outcomes consumers expect; any doubt or confusion increases the chance of negative spillover.

Determining the food fraud vulnerability of a postharvest value chain by identifying the weakest link is a logical and critical step when determining where best to focus efforts (Spink, 2019b). This approach logically applies to traceability While "silver bullet" solutions to traceability are often touted, the reality is "no one size fits all." Identifying the weakest link/s within a chain, and what makes it/them vulnerable, is important for implementing effective traceability. Yan, Erasmus, Toro, Huang, and van Ruth (2020) provide a good example of how to conduct this through their work in the extra virgin olive oil value chain. Their research was able to pinpoint the weaker points in the chain on a country-by-country basis as well as stakeholders within the chains (i.e., retailers and business-to-business companies were found to be most vulnerable) and the specific factors (i.e., opportunities, motivation, or control measures) that made each area vulnerable to food fraud.

11.3.4 Food quality and traceability—getting more out of the traceability investment

Food loss and waste within agricultural value chains is an ongoing issue requiring tools and interventions to reduce its impact. Approximately 14% of food produced globally is lost from postharvest up to, but not including, the retail level (Food and Agriculture Organisation of the United Nation, 2019). The estimated total amount of land occupied to produce this unconsumed food is 1.4 billion hectares (Food and Agriculture Organisation of the United Nation, 2019). Such loss or waste of food within global food value chains reduces not only the profitability of all stakeholders within the chain (estimated to be US $750 billion based on producer prices (Food and Agriculture Organisation of the United Nation, 2015) but is also a major contributor to human influenced climate change. If food loss and waste were a country, it would be the third biggest source of greenhouse gas emissions (United Nations Environment Programme, 2021).

Choosing traceability technologies that lead to better decision-making processes resulting in improved product movement efficiency (through accuracy of location), visibility of postharvest conditions (particularly identification of suboptimal conditions), and tracking of fruit or vegetable quality will all help to reduce loss and waste within a chain. Moreover, a traceability system that can demonstrate this improvement and/or provide transparency of the value chain journey to consumers will be important in addressing societal concerns around sustainable management practices. In the past, consumers were once satisfied to know their produce was associated with a particular country, region, or brand portraying a sense of "clean and green." However, the growing urgency around climate change action is seeing the degree of resolution applied to business activities and their impact on the environment increase dramatically. Correspondingly, implementing appropriate traceability systems will also be a critical component of the future as regulators and customers will seek to identify and enforce sustainable practices throughout the breadth of chains in response to societal concerns.

Generating more data through traceability systems does not necessarily guarantee reduced wastage and loss within a food value chain. This is because often the perceived value of a traceability system is its ability to accumulate greater quantities of data. However, focusing on only the quantity, and not the attributes (quality) of the data collected within a postharvest chain, makes it potentially ineffective. Extrapolating from

Redman (2001) "A Database is Like a Lake," a glass of potable water is of more value to someone who is thirsty than a polluted lake; similarly, unless data collected within a chain meet the needs of decision makers, then more do not equal better. This glut of data can in fact confound and distract decision makers from achieving improved value chain outcomes. A traceability system that allows for the collection and sharing of high-quality data associated with perishable products for a particular horticultural product value chain journey will be enormously beneficial to decision makers; from postharvest operators, wholesalers, transporters, and extending as far back to primary producers. But the true value will be in the quality and usefulness of the data. It cannot be overstated how important it is for value chain managers to commit time and effort toward understanding the types of data that will lead to reduced waste and loss within a food value chain.

Implementing a traceability system that allows for identification of when and where loss occurs is critical to overall improvement of postharvest chain performance. Success will only occur via the development of sound data collection methodologies and collaboration with chain partners to gather the data that are relevant. Determining this allows the development/sourcing of appropriate digital tools (including traceability technologies) to aid the ease of data collection and collation. The development of a coherent strategy to reduce food loss/waste within a value chain, starting with the data required, then identifying the techniques required to generate the data and finally choosing the most appropriate data capture systems, will also help overcome the barriers to change brought about by this desire to improve (see also Chapter 1: Postharvest Systems – Some Introductory Thoughts, and Chapter 11: Tracking Products from Field to Consumer).

In summary, it is unlikely a particular technology or system will meet the needs of all four components associated with food risk. Knowing this and identifying where gaps exist within each area are crucial to successful track and trace outcomes to minimize disruption and risk of value chain failure.

11.4 Implementing effective traceability technology within a postharvest chain

11.4.1 Getting the parts to work as a whole

Moe (1998) identified that the future trend for value chain traceability would be a "desire for the integration of more and more information in food production management and the increasing demands for information along the food processing chain will set higher requirements for well-structured traceability systems in the future." What could not be predicted was the extent of this desire nor the ability of the digital revolution to feed the appetite for information. As a result, the challenge of achieving well-structured traceability systems is significant and grows more and more difficult with our increasing capacity to accumulate data. This is compounded by the advances in the type of technology capable of being deployed to trace products within a value chain. Kok et al. (2012) cite not just conventional labeling and batch management but also genetic traceability (the ability to identify biological products based on their unique DNA fingerprints) and geographic or point of origin traceability through analysis of unique isotope and trace elements ratios relating links to where the product was grown.

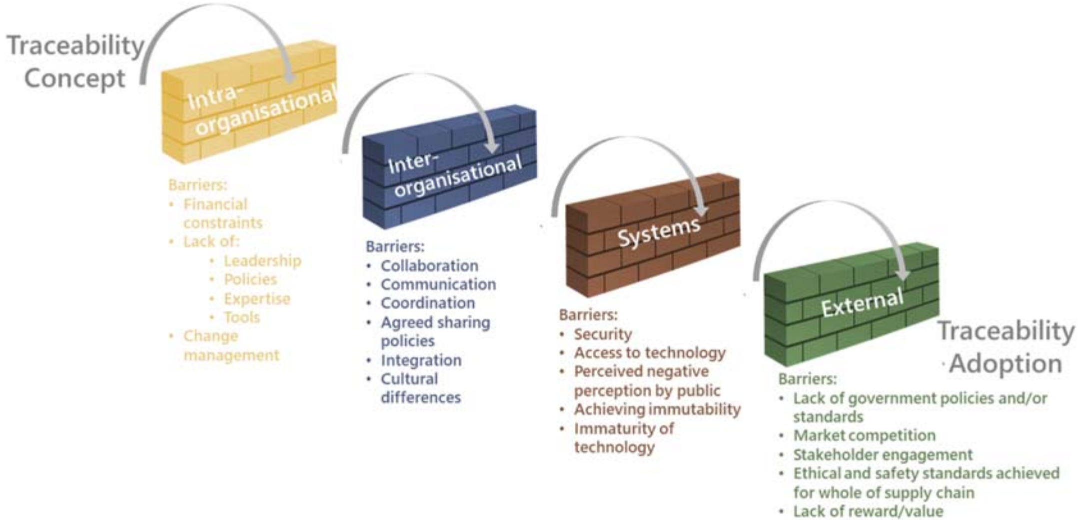


FIGURE 11.4 Barriers to implementation of new technologies into a value chain or system. Source*: Adapted with permission from Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable chain management.* International Journal of Production Research*, 57(7), 2117–2135.*

To achieve the mark of "well-structured" or "effective" traceability, value chain information systems must be able to provide timely information regarding the provenance of the food product with adequate security measures to provide confidence and trust in those who utilize the information (Saberi, Kouhizadeh, Sarkis, & Shen, 2019). But this is complex; the number of stakeholders utilizing information associated with traceability technologies within a postharvest chain is immense. While Saberi et al. (2019) described the challenges of implementing blockchain technology into value chains to achieve sustainability, the barriers to adoption they identified are true for any technology. The four main barriers relate to (1) intraorganizational or internal traceability; (2)) interorganizational or chain traceability; (3) system/technology; (4) external barriers. The specifics associated with each barrier are detailed in Fig. 11.4.

11.4.2 Interoperability

Interoperability (*the ability of computer systems or software to exchange and make use of information)* is seen as one of the biggest challenges to effective traceability with modern food value chains. Once again, while many see the solution to this issue as employing a single system, to date there is no single software solution that can meet the needs of effective value chain traceability (nor is there likely to be). But the challenge associated with interoperability extends beyond the digital realm; in many ways human inoperability is an even bigger challenge, that is, the ability of stakeholders within a value chain to exchange and make use of information. It is easy to ask for information from other value chain partners, but often more difficult to make meaningful use of the information.

11.4.2.1 *Success and failure factors*

The success and failure factors for effective value chain management, including partnerships, are considerable. Critical success factors in management were first introduced into the literature over 60 years ago by Daniel's Harvard Review article "Management information crisis" and have been a topic of academic consideration in supply chains for the past 30 years (Ab Talib, Abdul Hamid, & Thoo, 2015). Applying a Pareto analysis the "vital few" and the "useful many" success factors associated with value chain management have been identified (Ab Talib, Abdul Hamid, & Thoo, 2015). From 25 critical success factors 9 were classified as the "vital few." The top three factors were (1) use of IT, (2) top management consideration, and (3) partnership/integration.

In discussing these findings, Ab Talib, Abdul Hamid, and Thoo (2015) concluded that the use of IT and top management consideration represents an internal focus, where organizational goals (driven and communicated by top management) should shape and influence the selection, implementation, and use of technology. They go onto suggest that, if done effectively, this will assist in achieving the third critical success factor that is better integration with partners and stakeholders (Ab Talib, Abdul Hamid, & Thoo, 2015).

A useful, and commonly overlooked, step in successful integration with value chain partners is the use of pilot projects. While van Roekel, Kopicki, Broekmans, and Boselie (2002) talk about the development of pilot projects in the context of the creation and development of chains, it is a useful mechanism for also improving and optimizing existing partnerships. Afterall, the success of value chain partnerships is dependent on interpersonal relationships that require frequent recalibration and realignment to be successful (van Roekel et al., 2002). Development of pilot projects, workshops, etc. that involve greater interaction develops trust, which is one of the most important factors for value chain partnership success (Ab Talib, Abdul Hamid, & Thoo, 2015; van Roekel et al., 2002).

11.5 The digital revolution

11.5.1 The impact of the digital revolution

The digital revolution has impacted every facet of modern life. One of the major drivers of today's value chains is the phenomena of social media. The number of social media platforms and users has grown phenomenally over the past decade—Facebook and YouTube both had about 500 million users that have now grown to over 2 billion for Facebook and 1.9 billion for YouTube. In that time, new platforms have emerged such as WhatsApp, Instagram, WeChat, Twitter, and, most recently, TikTok. Combined those platforms have over 4 billion users (Ortiz-Ospina, 2019).

The implications of the explosion in users of social media are that consumers have never been more empowered and influential in voicing their expectations and concerns around products. From a consumer point of view, this advancement means an expectation of total visibility of the products they purchase from "plant to plate"; from where they were grown, how they were grown (see also Chapter 7: Fresh-cut Products—Implications for Postharvest), the way they were handled postharvest (i.e., genuine and safe), the way employees within postharvest businesses were treated (i.e., ethically), while meeting consumer expectations for quality and consistency (see also Chapter 3: Consumer Eating Habits and Perception of Fresh Produce Quality, Chapter 13: Sorting for Quality, Chapter 14: Non-destructive Evaluation: Detection of External and Internal Attributes Frequently Associated with Quality and Damage, and Chapter 19: Nutritional Quality of Fruits and Vegetables). If a value chain can achieve the desired level of transparency, then social media platforms form the best free advertising a brand, business, or producer can hope to have. Failure to meet any of these expectations and the speed and coverage of negative feedback can have major consequences for short- and long-term profitability. How real the risk of failing to meet consumer expectations is debatable, but what is not debatable is the response regulatory institutes have taken based on this perception of demand for clean and green products. Providing evidence of management processes associated with the growing and supply of horticulture product continues to become more pressing. Thus the need for appropriate track and trace systems to provide the necessary evidence instantly and seamlessly. Providing regulators and consumers with confidence that food risk mitigation processes are in place is an essential part of modern value chain business. Consequently, modern value chains and systems are reliant on the same advancement in digital technology that has enabled the proliferation in social media platforms to provide track and trace processes that meet the needs of the modern consumer and the resultant changes to the regulatory landscape.

11.5.2 Big data that just keeps getting bigger

Advances in technology and communication over the past decade have created significant potential for improved traceability within postharvest chains. It provides managers who believe in the notion of you "can't manage what you can't measure" with the means to collect, collate, and analyze data in ways that were not possible even 10 years ago. In theory, this increased business knowledge, through increased data, should equate to improved decision-making outcomes (McAfee & Brynjolfsson, 2012). However, successful implementation of "data-driven" practices is not a given and is a huge challenge for modern postharvest chains to overcome.

The rate at which data are generated in 2020 and the predictions for the future are ever increasing (Fig. 11.5) (Bulao, 2021). As identified in Section 11.3.4, one of the challenges of our age will be to devise strategies that enable us to identify and implement technology to collect *only* the data that are important in our decision-making processes. In the absence of sound strategy, we run the risk of collecting data for data's sake and, in this modern digital world, that can quickly lead to information inundation creating a situation akin to the irony of someone adrift at sea; thirsty for water but surrounded by an infinite quantity of water, unable to drink. Knowing what data are required for effective traceability within your own business link is essential; otherwise, stakeholders will become swamped with data that they are not able to utilize.

11.5.3 Identification technologies

The basic traceability of product through the postharvest value chains is achieved by being able to identify each "identifiable unit" (Bollen, Riden, & Cox, 2007) with a unique

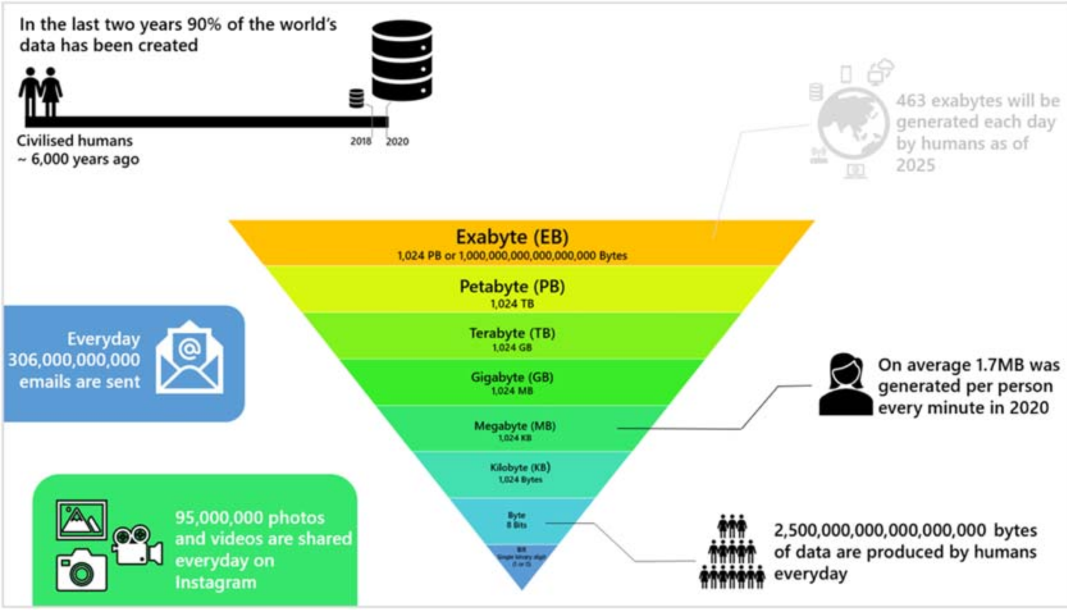


FIGURE 11.5 Growth in data-generated globally. Source*: Information sourced from Bulao, J. (2021). How much data is created everyday in 2021?*. Techjury. *https://techjury.net/blog/how-much-data-is-created-every-day/#gref*.

code. There is a vast array of technology providers seeking to provide machine-readable solutions, which become incrementally more reliable than their predecessors (Bollen, Riden, & Opara, 2006). There are many ways of identifying products:

- *Alphanumeric identification (Alphanumeric ID)* is still a common system in particular sectors of value chains, including farms/orchards, air and sea freight, and retail. Generally, alphanumeric IDs are read by humans and manually recorded into an information system. There is a reasonable chance for errors in this situation and some major international ports use optical character recognition to automatically capture and record the IDs of the produce, for example, shipping containers (Bollen, 2004).
- The *barcode* is the most successful machine-readable ID system. It has been applied worldwide over the last 40 years because it is a very reliable, low-cost system. The system involves printing a label, or a pack, or directly on the product. The code is then able to be read and interpreted using a laser to scan the bars. Modern smart phones are now able to read many barcodes as the codes conform to one of a number of standards (GS1, 2007).
- To meet the ever-increasing demand for more information to be included with the product, the most popular symbology is now the *QR code* (quick response code—where Version 40-L can store over 4000 alphanumeric characters). QR codes are a 2D barcode able to be readily interpreted using any image analysis system, such as a smart phone app. The QR code has become the default standard for consumers to access information about products, particularly as the QR code will often direct the user to a website where the unique ID

embedded in the QR code will link the user to a range of additional traceable information about their product (Kim & Woo, 2016).

- *RFID* (radio-frequency ID) is the most automated technology. The improved automation is the ability to read the ID "tag" more readily without the need to shine a laser or point a reader (e.g., smart phone) directly at the barcode. The RFID technology has two primary components; a tag consists of a small chip with onboard memory, which holds a unique ID (read only tag) or has the ability to have some information written to the tag (read−write tag). The tag also contains a small radio antenna. The second component is the reader that consists of a pair of antennae with an operating and recording system. When the tag is close to the reader, the reader powers the tag through the tag antennae and the tag reports information it contains to the reader. This allows considerably more flexibility operationally while still allowing easy, reliable, communication. There are several different tag technologies, some small enough to be embedded in labels on packaging. Other systems have active tags that are able to transmit over a wider range; these tags often will incorporate other sensors such as temperature, humidity, shock, or light (BT9 − Xsense). The implementation of RFID has, however, been slower than expected due to costs, limitation on reader performance (range and reliability), and lack of global standards that allow for standard equipment across global value chains, which have hampered the expansion of the technology.

Commercial suppliers of these technologies will often promote the capabilities of their particular proprietary solution to solve some specific traceability problem, but as discussed in Section 11.3.3, it is important to determine what the system needs to deliver and not be directed by the technology.

11.5.4 Information systems—is blockchain the solution?

Since the advent of the digital revolution, blockchain is one of the most hyped but least understood technology products to arrive on the market. Most people when looking for an explanation or when asked to provide the benefits of blockchain will no doubt refer to the fact that it is an "immutable digital ledger." However, rarely does a search provide an answer as to how a digital ledger will actually be an improvement over current data tracing systems.

This section explains what blockchain is relative to other types of database systems and discusses the probability of blockchain being a viable solution for data management within a postharvest business. As noted by Behnke and Janssen (2020), successful implementation of blockchain technology will only occur if there is a clear understanding of the business problem it is solving (see also Section 11.3.1).

The most critical elements that differentiate blockchain from other database systems are their improved level of transparency and trust. From a transparency perspective the advantage of a blockchain database system within a horticulture value chain is easy to conceptualize in that it can link information and provide transparency for all stakeholders within a value system (Fig. 11.6) (Simply Explained, 2017). Blockchain is a singular platform shared amongst all participants but not necessarily owned by any of the participants. Participants add data to the transactional process that occurs as product moves along the chain (as depicted by the different color blocks). Within a blockchain system this

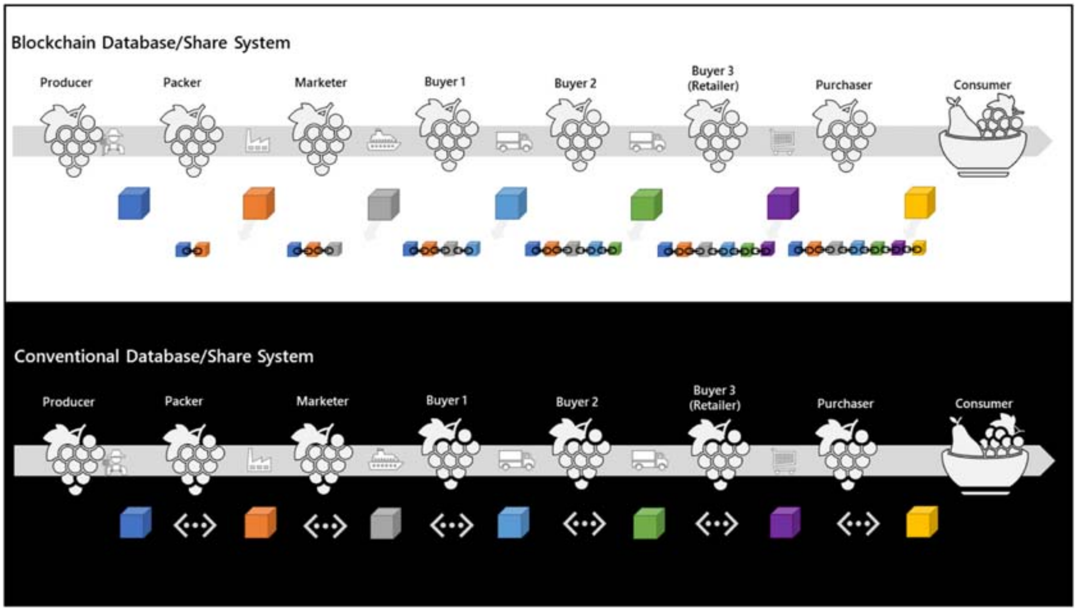


FIGURE 11.6 How a blockchain can describe a horticultural value chain. Source*: Information sourced from Simply Explained (2017)*. How does a blockchain work – Simply explained. *https://www.youtube.com/watch?v = SSo_EIwHSd4*.

information "block" is then linked via the encryption processes that drive blockchain technology. As each transaction occurs, not only does each participant add their relevant information but also they have visibility on all previous links, not just the information provided through their direct relationships (Iansiti & Lakhani, 2017; Kamilaris, Fonts, & Prenafeta-Boldú, 2019; Simply Explained, 2017).

Similarly, new data being added to the chain are not only visible but must also be validated by all previous parties. As such this mechanism provides not only transparency, but also security and reduced opportunity for false information. The system will in theory prevent counterfeit product entering into the chain. This feature of blockchain gives it a degree of immutability that is not possible in other traceability systems. Hence, the greater level of trust is attributed to blockchains (Simply Explained, 2017) (Fig. 11.7).

Traditional digital databases work off a centralized concept where many players access the one database to update and make changes. The inherent risk with such systems is that a single incorrect entry or deletion (whether accidental or malicious) can occur as undetected inconsistency within the system. The encryption processes that drive blockchain technology provide a database system that is far more adept at reducing inconsistencies within a data set used by a large number of individual stakeholders. Rather than providing a centralized database that all participants have access to and the ability to change or potentially corrupt, blockchain, through its encryption process, allows all participants to contribute information and view but not changes preexisting data (Iansiti & Lakhani, 2017; Kamilaris et al., 2019; Simply Explained, 2017). This potentially provides a far higher level of security as any participant contributing data to the chain cannot have their data

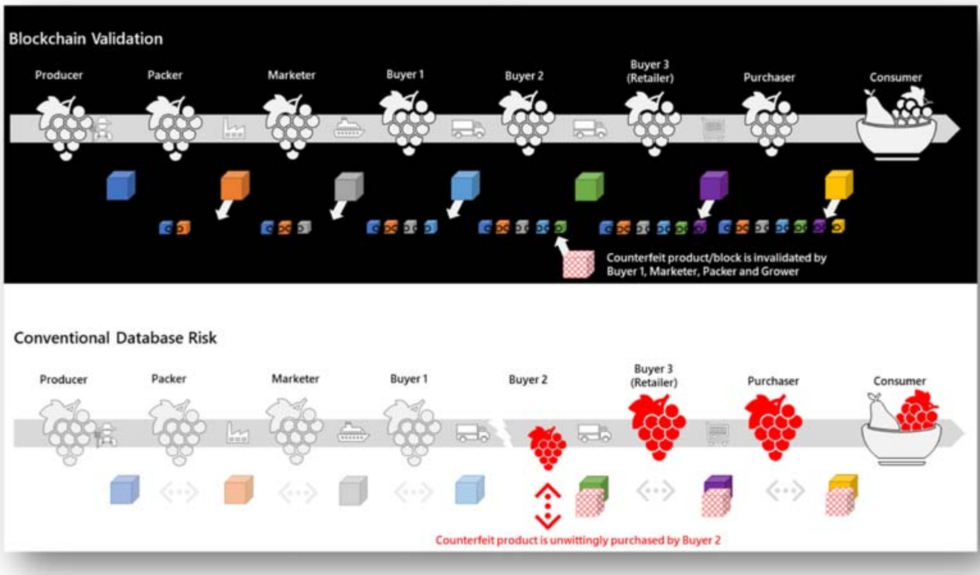


FIGURE 11.7 How blockchain prevents counterfeit product entering a value chain compared to conventional value chain database systems. Source: *Information sourced from Information sourced from Simply Explained (2017).* How does a blockchain work – Simply explained. *https://www.youtube.com/watch?v=SSo_EIwHSd4.*

changed by any other participant. It is an incorruptible mechanism that improves the confidence and trustworthiness of the data within a system. So, if data corruption, or risk of data corruption, is the biggest issue that occurs within a value chain, then the implementation of blockchain technology should be a priority.

Given the seemingly improved transparency and immutability benefits associated with blockchain, it is interesting that, despite a growing number of scientific publications, there is considerable absence within the literature of real case studies of blockchain application in agricultural value chains (Mirabelli & Solina, 2020). Recently, Stranieri, Riccardi, Meuwissen, and Soregaroli (2021) completed an explorative study with a large European retailer keen to understand the potential and limitations of blockchain within their organization. Their work considered three agri-food value chains associated with the retailer; poultry, lemons, and oranges. From an interview process with stakeholders within the value chain, the work sought to understand whether blockchain impacted on the stakeholders across a variety of themes, including efficiency, flexibility, responsiveness, food quality, transparency, governance, and resources and capabilities. In summary, their (Stranieri et al., 2021) results showed the following:

- no impact on production or distribution costs;
- a decrease in product loss through better management (but only for the lemon value chain, presumably because the blockchain implementation process highlighted existing weaknesses);

- no improvement in data accuracy;
- improved data accessibility/availability and information sharing as well as data flow compared to the current situation;
- improved collaboration through a paradigm shift in how the participants viewed data ownership, that is, stakeholders are no longer "owners of information" but contributors to a partnership;
- an ability to reduce unfair practices because of greater value chain visibility;
- increased customer satisfaction through increased visibility and understanding of the product quality and origin.

To this last point the retailer, in seeking to implement a blockchain solution, saw one of the key benefits of the technology as a marketing tool that allowed them the opportunity to connect with their consumers, which the results of the study have seemingly validated.

While Stranieri et al. (2021) demonstrated potential benefit for horticultural value chains using a blockchain traceability technology, implementation will have its challenges. But due to its relative immaturity in application, many are yet to be defined (Saberi et al., 2019). For instance, one consideration is the use of a public or private blockchain; the greatest success of blockchain application to date has been in financial blockchains (including Bitcoin) that operate as public blockchains. However, it is expected that postharvest businesses will generally function as private, exclusive networks, with limited players requiring permission to join (Saberi et al., 2019). In achieving this, Saberi et al. (2019) also identified other challenges, including the need for new or greater engagement with entities such as registrars, standard organizations, and certifiers, as well as the "common" stakeholders within a postharvest chain (producers, processors, marketers, distributors, consumers, and regulatory agents).

It seems clear to these authors that it is not necessary to understand what blockchain is, rather what it offers, that makes it of such interest to postharvest businesses. Blockchain at its heart provides greater transparency and trust that is fundamental to any successful value chain or system. However, superseding a conventional database with a blockchain database is not easy, and for its potential to be fully realized it means all the stakeholders in the chain must be willing to participate. But a willingness to participate will be based on understanding what blockchain is. Kamilaris et al. (2019) identified that currently there is a general lack of awareness and skills associated with blockchain technology within the agriculture and food value chain sector and that the development of user-friendly software, which many start-ups are working on, will be required for value chain adoption. As it currently stands within most value chains, it is the reluctance to share data that are probably the most challenging aspect, but not because of the risk of corruption. It is likely a more fundamental barrier; a sense of protecting key intellectual property that prevents data sharing, not the concerns around technology. As such this is the likely reason why blockchain adoption within postharvest businesses has not been significant to date; it is a solution to a future problem that will only become relevant when other barriers associated with data sharing and relationship development are overcome. More broadly though, Iansiti and Lakhani (2017) believe blockchain transformation is still many years away as it (blockchain) is a foundation technology, not just disruptive. This being a true adoption of blockchain is more likely to occur slowly, but surely, over decades rather than as a rapid, short-term event (Iansiti & Lakhani, 2017).

In many ways the barriers for blockchain implementation are similar to the constraints that prevent optimal traceability, and indeed, postharvest value chain efficiency in general. van Roekel's et al. (2002) assessment of the reasons for failed value chain alliances suggested that issues such as lack of senior management support, lack of trust, fuzzy goals, lack of commitment, and lack of control are just as big barriers to effective relationships within value chains today as they always have been.

11.6 Conclusion

The main challenges that modern postharvest value chain strategy needs to consider to successfully deliver product consignments and derive maximum value for stakeholders are:

- tracing and tracking perishable product and making optimal decisions regarding their management through increasingly more and more complex postharvest value chains;
- the demand by society and regulators for transparency regarding their food products and assurance that it is genuine, safe, and ethical; and
- consumers ability to amplify concerns and awareness regarding food safety/quality incidents via social media.

At the heart of overcoming these obstacles is the use of digital traceability systems. Digital technology has delivered the potential for traceability systems to instantaneously track and trace product accurately within a chain while providing data and insights to improve the decision-making processes of postharvest value chain stakeholders. The main challenges to successful implementation are:

- Converting the prolific amount of data that can be collected throughout the postharvest value chains into decision-making processes that improve outcomes, for example, increase profitability, less environmental harm, less food waste.
- Understanding and assessing the vulnerability of the food risks associated with a product within value chains and/or channels to best know what traceability systems to implement, that is, right tool for the job.
- The interoperability of selected traceability systems with other stakeholders within the postharvest value chains.
- The development of trusted relationships with value chain partners to facilitate the sharing and flow of information throughout chains to allow for effective decision-making within each link.

References

Ab Talib, M. S., Abdul Hamid, A. B., & Thoo, A. C. (2015). Critical success factors of supply chain management: A literature survey and Pareto analysis. *EuroMed Journal of Business*, *10*, 234–263.
Behnke, K., & Janssen, M. (2020). Boundary conditions for traceability in food supply chains using blockchain technology. *International Journal of Information Management*, *52*, 1–10.

Bodria, L. (2002). 'System integration and certification. The market demand for clarity and transparency – Part 2', Presented at the Club Bologna meeting, 16 November 2002, Bologna, Italy, Overview Paper. *Agricultural Engineering International: CIGR Ejournal*, *4*, 1–6.

Bollen, A. F. (2004). Traceability in fresh produce supply chains. In *Proceedings of the international conference – post-harvest unlimited downunder 2004. Acta Horticulturae*, 687, 279–288.

Bollen, A. F., Riden, C. P., & Cox, N. R. (2007). Agricultural supply system traceability – Part I: Role of packhouses and effects of fruit mixing. *Biosystems Engineering*, *98*(4), 391–400.

Bollen, A. F., Riden, C. P., & Opara, L. U. (2006). Traceability in postharvest quality management. *International Journal of Postharvest Technology and Innovation*, *1*(1), 93–105.

Bosona, T., & Gebresenbet, G. (2013). Food traceability as an integral part of logistics in food and agricultural supply chain. *Food Control*, *33*, 32–48.

BT9 – Xsense. *BT9 intelligent supply chain solutions and the Xsense System* http://www.bt9-tech.com/.

Bulao, J. (2021). How much data is created everyday in 2021?. *Techjury*. https://techjury.net/blog/how-much-data-is-created-every-day/#gref.

Cuite, C. L., Schefske, S. D., Randolph, E. M., Hooker, N. H., Nucci, M. L., & Hallman, W. K. (2009). *Public response to the* Salmonella *Saintpaul outbreak of 2008*. New Brunswick, NJ: Rutgers, the State University of New Jersey, Food Policy Institute. (Publication number RR-1208-017).

Food and Agriculture Organisation of the United Nations (2019). *The state of food and agriculture 2019. Moving forward on food loss and waste reduction*. Rome. Licence: CC BY-NC-SA 3.0 IGO. Also Available at http://www.fao.org/3/ca6030en/ca6030en.pdf.

Food and Agriculture Organisation of the United Nations. (2015). *Global initiative on food loss and waste reduction*. Rome: FAO (also available at. Available from http://www.fao.org/3/a-i4068e.pdf.

GS1 (2007). *Barcode types*. http://www.gs1.org/productssolutions/barcodes/technical/bar_code_types.html Accessed 24.09.07.

Iansiti, M., & Lakhani, K. R. (2017). The truth about blockchain. *Harvard Business Review*, *95*(1), 118–127.

ISO (International Standards Organization) (2015). *ISO 9001:2015 Quality management systems – Fundamentals and vocabulary*. International Standards Association.

Kamilaris, A., Fonts, A., & Prenafeta-Boldú, F. X. (2019). The rise of blockchain technology in agriculture and food supply chains. *Trends in Food Science and Technology*, *91*, 640–652.

Karlsen, K. M., Dreyer, B., Olsen, P., & Elvevoll, E. (2013). Literature review: Does a common theoretical framework to implement food traceability exist? *Food Control*, *32*, 409–417.

Kim, H. M., Fox, M. S., & Gruninger, M. (1995). Ontology of quality for enterprise modelling. In *Proceedings of the IEEE international workshops enabling technologies: Infrastructure for collaborative enterprises WET-ICE* (pp. 105–116).

Kim, Y. G., & Woo, E. (2016). Consumer acceptance of a quick response (QR) code for the food traceability system: Application of an extended technology acceptance model (TAM). *Food Research International*, *85*, 266–272.

Kok, E., van der Spiegel, M., Prins, T., Manti, V., Groot, M., Bremer, M., … van Ruth, S. (2012). Traceability. *Chemical Analysis of Food Techniques and Applications*, *14*, 465–498.

McAfee, A., & Brynjolfsson, E. (2012). Big Data: The management revolution. *Harvard Business Review*, 60–69, October 2012 edition.

Mirabelli, G., & Solina, V. (2020). Blockchain and agricultural supply chain traceability: Research trends and future challenges. *Procedia Manufacturing*, *42*, 414–421.

Moe, T. (1998). Perspectives on traceability in food manufacture. *Trends in Food Science and Technology*, *9*, 211–214.

Ortiz-Ospina, E. (2019). *The rise of social media*. https://ourworldindata.org/rise-of-social-media.

Redman, T. C. (2001). A database is like a lake. *Data quality: The field guide*. Digital Press: An Imprint of Butterworth-Heinemann. (Chapter 10) in.

Saberi, S., Kouhizadeh, M., Sarkis, J., & Shen, L. (2019). Blockchain technology and its relationships to sustainable chain management. *International Journal of Production Research*, *57*(7), 2117–2135.

Sanda, D. (2018). https://www.goodfruitandvegetables.com.au/story/5535517/boost-for-melons-after-listeria-outbreak/.

Simply Explained (2017). *How does a blockchain work – Simply explained*. https://www.youtube.com/watch?v=SSo_EIwHSd4.

Spink, J. (2007). *Global counterfeit and beverage packaging impacts on food safety*. Paper presented at the Association of Food and Drug Officials (AFDO), annual conference. Available from http://www.afdo.org/afdo/Conferences/upload/070619-Food-1600%20-%20Final.pdf Accessed 22.02.11.

Spink, J. (2011). The challenge of intellectual property enforcement for agriculture technology transfers, additives, raw materials, and finished goods against product fraud and counterfeiters. *Journal of Intellect Property Rights*, *16*(2), 183–193.

Spink, J., & Moyer, D. C. (2011). Defining the public health threat of food fraud. *Journal of Food Science*, *76*(9), 157–163.

Spink, J., Chen, W., Zhang, G., & Speier-Pero, C. (2019). Introducing the Food Fraud Prevention Cycle (FFPC): A dynamic information management and strategic roadmap. *Food Control*, *105*, 233–241.

Spink, J. W. (2019a). Food fraud prevention overview (Part 2 of 3): The approach. *Food fraud prevention*. New York: Springer Food Microbiology and Food Safety. Available from https://doi.org/10.1007/978-1-4939–9621-6_4.

Spink, J. W. (2019b). Risk analysis (Part 1 of 3): Basic fundamentals. *Food fraud prevention*. New York: Springer Food Microbiology and Food Safety. Available from https://doi.org/10.1007/978-1-4939–9621-6_15.

Stranieri, S., Riccardi, F., Meuwissen, M. P. M., & Soregaroli, C. (2021). Exploring the impact of blockchain on the performance of agri-food supply chains. *Food Control*, *119*, 107495.

United Nations Environment Programme (2021). *Food waste index report 2021*. Nairobi.

van Roekel, J., Kopicki, R., Broekmans, C., & Boselie, D. (2002). *Building agri supply chains: Issues and guidelines*. World Bank Document.

van Ruth, S. M., Luning, P. A., Silvis, I. C. J., Yang, Y., & Huisman, W. (2018). Differences in fraud vulnerability in various food supply chains and their tiers. *Food Control*, *84*, 375–381.

Yan, J., Erasmus, S. W., Toro, M. A., Huang, H., & van Ruth, S. M. (2020). 'Food fraud: Assessing fraud vulnerability in the extra virgin olive oil supply chain. *Food Control*, *111*, 107081.

Zhang, J., & Lim, J. S. (2021). Mitigating negative spill over effects in a product-harm crisis: Strategies for market leaders vs market challengers. *Journal of Brand Management*, *28*, 77–98.

This page intentionally left blank

CHAPTER

12

Managing product flow through postharvest systems

Jean-Pierre Emond

The Illuminate Group, Tampa, FL, United States

Abbreviations

DC distribution center
ULD unit load device

12.1 Introduction

The fresh produce segment has seen a constant increase, as people are more conscious about their health (see also Chapters 19 and 21). Consumers expect year-round availability of fresh produce, which requires bringing produce all around the world. More than 40% of all imports in the United States, the United Kingdom, and Europe are fresh produce (Cuellar, 2003). Fresh produce value chains are very different from any other value chain. It is a very complex system that deals with constant changes due to short shelf life, customer demand, transportation disruption, weather, and many other factors, such as the recent pandemic (see also Chapters 8, 11, and 16). It is not easy to understand this complexity due to the significant number of handling points between the farms and the consumers.

A typical fresh produce value chain will involve about 12 different parties until produce reaches consumers (Pelletier, Nascimento Nunes, & Emond, 2005; Villeneuve, Vezina, & Emond, 2002). It is not surprising that such complexity can lead to loss of quality resulting in waste (see also Chapter 2). There is a lack of understanding and information between players in this industry, which leads to much finger-pointing and lack of cooperation when quality issues arise further down the chain (see also Chapters 3, 5, 6, and 18). This chapter aims to bring knowledge and explain the roles and challenges for each step involved in the flow of fresh produce from farm to fork.

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00012-9

12.2 Local distribution

Growers who are selling in the same country do not have as many restrictions as if they were selling their produce across borders (see also Chapters 3 and 18). The movement of their products is very often more flexible and diverse. Many options are available for these growers. Small growers will sell most of their produce to farmers markets, and they are responsible for the transportation. In some cases, smaller growers will rely on food distributors to bring their products to a larger market, such as retail stores. Food distributors collect products from small farmers and transport them to retailer's distribution centers (DCs) or food service companies. This way, they can bring together goods from many different growers to be sold in bulk. Food distributors have their own fleet of refrigerated trucks to collect and distribute fresh produce.

For large growers usually, they are selling directly to retailers and food service companies. It is the responsibility of the buyers to provide transportation from the grower to the DCs. Very often, growers are preparing the orders and will receive a notice from the buyer regarding transportation. Most retailers will use an interactive bidding system where transportation companies will provide a price and a window of potential equipment near the collection point. Retailers may require certain transportation equipment features but will not know precisely the type and condition of the equipment selected. This may sometimes lead to inadequate equipment for specific produce (underperforming refrigeration, poor air distribution). At the moment of pickup, the grower's staff will inspect the refrigerated equipment to assure it is already at the right temperature and that the equipment is suitably clean before loading the produce.

The main difference between retailers and food service companies is how the produce is packed. Retailers will require individual portions, while foodservice companies will require larger packaged quantities dedicated to restaurants and institutions. Packinghouses are essential for both national and international shipments. They separate out debris and uneatable items, sort batches into desired grades, package and precool the shipment, and provide other required services. Fresh produce that is packed in the field also proceeds through a packinghouse for cooling, quality control, and other preparations for shipment (see also Chapter 14).

12.3 International distribution

Growers who are selling internationally usually export their products through the care of third-party logisticians called forwarders. Forwarders do not physically move the products but rather supervise the logistic. As an example, forwarders will organize to have the produce moved by truck to the airport, arrange for refrigeration while at the airport, book the space on the plane, fly to destination, clear custom, coordinate for quarantine treatment if necessary, and deliver the products to the customer's facility. In many cases, buyers will request that each pallet has a temperature logger.

Once the products are at the importer's facility, the produce's distribution follows the same process as the local distribution covered before in this chapter.

12.3.1 Airport and port operations

One of the unknown areas where fresh produce is handled is at the airport or the port. The main reason is that these areas have restricted access, and only the handling staffs are allowed after a thorough background check.

In airport operations, fresh produce loads are temporary stored at the airport's perishable center or the airline storage area. Perishable centers can accommodate most of the products with their required storage temperature. Airline facilities have minimal refrigerated storage space. Once received, products are first inspected and passed through an X-ray machine for screening requirements. Later, pallets of produce are prepared and placed on a unit load device (ULD). Most of the time, ULDs consist of a simple aluminum sheet that can carry six pallets at a time.

Depending on the customer's requirements, a protective cover will be placed on the load. The cover can be a plastic sheet, a "fruit-fly" net, or an insulated cover. The types of cover play an essential role in keeping fresh produce quality. Transparent plastic sheets used as cover will usually damage the products much more as they will prevent oxygen from reaching the produce and significantly increase the temperature if exposed to direct sun (Badia-Melis, Emond, Ruiz-Garcia, & Robla Villalba, 2016). The same issues can be observed when using metalized bubble wrap sheets, as it will prevent air exchanges with the load. More innovative is breathable reflective cover such as the Tyvek cargo cover (Dupont, 2016). Fig. 12.1 shows the temperature benefits of pallets of asparagus with a reflective covers compared with clear plastic covers.

Once the load is secured with a net on the ULD, the ULD is brought to the location of the airplane on the apron. Usually, for an international flight, the ULD must be on the apron 2 h before departure. At this moment, the load is exposed to the environment

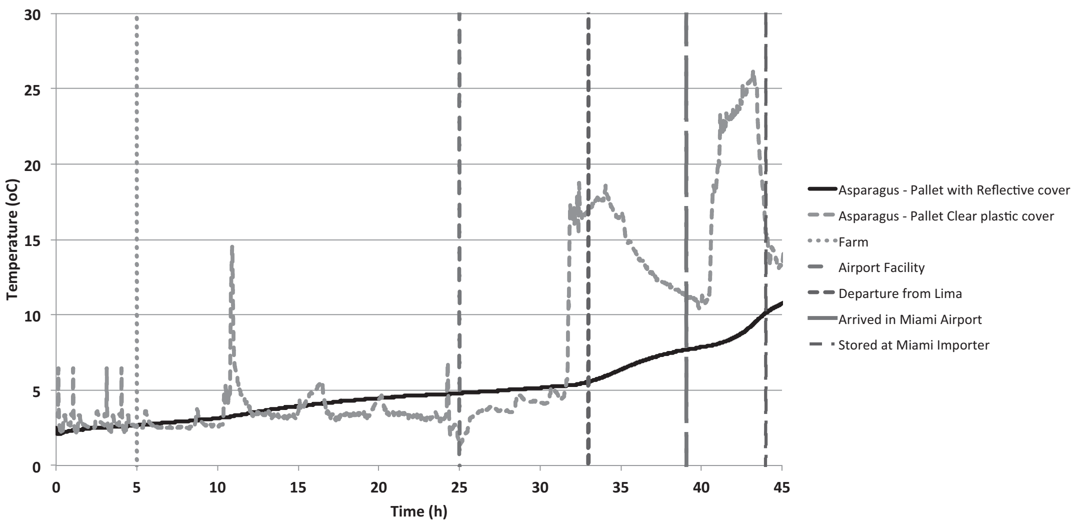


FIGURE 12.1 Temperature of pallets of asparagus using a reflective cover and a clear plastic cover during an air shipment from Peru to Miami, the United States (Emond & Germain, 2014).

regardless of the weather. Once the plane is ready to be loaded, an airport handling company is responsible for the loading by following the loadmaster's instructions. The loadmaster will determine based on weight, how the plane should be loaded, and the exact location of each ULD. Depending on the weather and wind, it may be decided not to load some of the ULD at the last minute. In that case, these ULDs will be brought back to the airport facility and temporarily stored (not necessary in a temperature-controlled area) until the next available flight (Villeneuve, Mercier, Pelletier, Ngadi, & Emond, 2000).

Ocean transportation differs significantly from air transportation. Fresh produce is transported in refrigerated ships or by refrigerated sea containers, usually called a "reefer." In refrigerated ships, the pallets are directly placed inside the refrigerated compartments in the ship. However, the vast majority of fresh produce is placed in reefer containers. These containers' logistics originate at the grower's facility, where pallets of produce are placed directly inside these containers (see also Chapter 18). Temperature is set to the requirements, and the containers are delivered to the port facility. The refrigeration system of these containers requires electric power. During ground transportation, a diesel generator called "Genset" provides electric power. These generators can provide electricity to the container for up to 5 days without refilling fuel.

Once received at the port facility, each container is allocated a space where electricity can be provided. At this point, third-party cargo handlers called "stevedore" load containers on the ship. From the moment the container is unplugged, it is loaded by a crane on the ship and placed to its specific slot. This operation may take between 2 and 12 h before the container is plugged again using the ship's electric power. It is a critical part where quality can be lost (see also Chapter 5). Fig. 12.2 shows how fast the air inside a reefer container can increase while unplugged.

During the trip, each container is monitored for temperature, and in case of an equipment failure, a team can repair the equipment. However, it may take as long as 24 h to have the refrigeration unit rerun. These days, most containers are equipped with a satellite device for "real-time" tracking (see also Chapter 12).

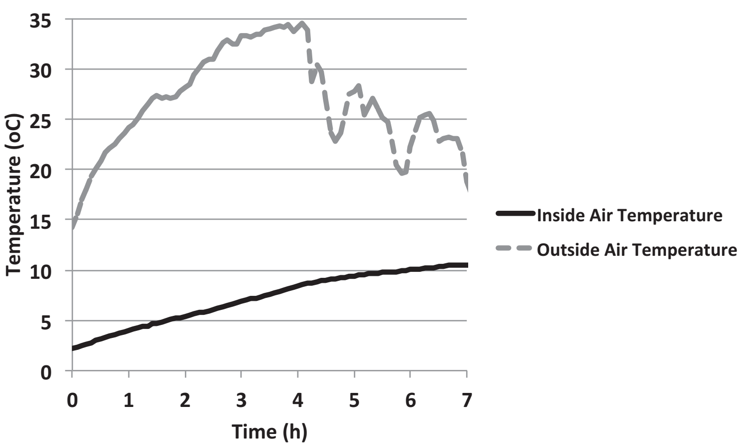


FIGURE 12.2 Evolution of air temperature inside a refrigerated sea container (reefer) containing 20 pallets of orange when the power is interrupted during unloading from the ship (Emond, Vezina, & Khalil, 2010).

Depending on quarantine requirements, some buyers require a cold treatment to be performed in the reefer container during the trip. Most treatments will last between 14 and 21 days using a temperature below 1.1°C.

Once arrived at the destination port, containers will be unloaded and placed temporarily in a receiving area where power will be provided. Again, the containers may be without power for 2−12 h and sometimes as long as 24 h if space is not available. The loading and unloading process is the most critical part where produce can be exposed to unfavorable conditions and loses quality.

12.4 Transportation

The flow of fresh produce from farm to fork requires multiple types of transportation. Understanding the specificity of each of them can help to avoid situations where quality can be lost.

12.4.1 Air transportation (airlines)

For most highly perishable produce such as berries and asparagus, a fast transit time from origin to destination is required. In these cases, air transportation is the only viable option. Even though the "flying time" can be short (6−14 h), the total duration of typical air transportation will last about three days, but it can take as much as a week in some cases. About 60% of all the shipments transported by air are onboard passenger flights (Emond, 2005; Villeneuve et al., 2002). This means that there will always be an uncertainty about the schedule and what can be loaded in the cargo compartment due to weight restrictions. As seen recently, the pandemic had created an immense lack of air transportation capacity when most passenger airlines halted their international flights. Only full cargo planes (freighters) were available to move fresh produce when freighters' demand became very high due to other needs such as transportation of the personal protective equipment.

Most of cargo planes time will be spent on the ground at origin and destination for fresh produce shipments due to the multiple entities involved in the shipping. Inspection and preparation of the load for the plane usually take an entire day. All the information about the load, such as weight and dimensions, must be communicated to the airlines a day before departure, so the loadmaster can prepare the loading pattern. Depending on location in the plane, the height of the load can be limited. For shipments placed in the lower deck (belly cargo compartment), a maximum height of 1.2 m is allowed (Fig. 12.3), while for shipments placed on the main deck (main floor), a maximum height of 2 m can be accommodated (Fig. 12.4).

Contrary to the common belief that cargo compartments are freezing during a flight, all compartments on board a plane are maintained at a temperature of 15°C−18°C (Pelletier, 2010). However, there is an exception about temperature control onboard cargo compartments. Most plane air conditioning systems can only provide cold air when engines are running at 50%, which is impossible before takeoff. For jam-packed airports, this waiting time can significantly increase the temperature in the cargo compartment. It was observed that in some locations like Miami, a temperature of 35°C could occur (Emond, Mercier, & Nunes, 1999).

FIGURE 12.3 Pallets of fresh produce wrapped in the reflective cover waiting to be loaded in a passenger airplane.

FIGURE 12.4 Inside the main deck of a full cargo airplane (freighter).

Once arrived at the destination, loads must be brought to the airport facility and removed from the ULD and wait to be cleared by custom and sanitary agencies. Depending on their origins, some loads will be required to go through a fumigation process. Fumigation providers will usually be located near or at the airport to fumigate the loads. In many cases, the fumigation is performed outside under tarps. The products are required to be warmed up to about 15°C−25°C (Emond & Germain, 2014). It can take a full day for the whole fumigation process. Once the agencies clear the products, customers can come and pick up their shipments (Emond, 2014).

12.4.2 Ocean transportation (steamship companies)

Ocean transportation is the backbone of international transportation for the produce industry. Bananas, citrus, and grapes are the primary produce shipped by ocean. This transportation mode has already been covered earlier in this chapter, but it is crucial to understand the technologies used in this mode of transportation (Emond, 2007a, 2007b). Two systems are used for ocean transportation: refrigerated vessels and refrigerated containers (reefer).

Refrigerated vessels are pretty much a vast cold room that covers most of the cargo hold. It is mostly used for produce like bananas and other tropical crops. It requires special cranes for the loading process and will expose the products to the surroundings for a specific time. Ethylene must be well controlled in this system, as a large amount of produce is stored together.

The intermodal way for ocean transportation is the use of refrigerated containers. Most of them are coming with a standard length of 40 ft, but some containers are available in the 20 ft version. The refrigeration unit of these containers is very powerful and can provide excellent temperature control. Contrarily to the typical refrigerated truck, the cold air is delivered through a vented floor. Some versions can also provide a controlled atmosphere, which can help to extend produce shelf life. Most carriers provide satellite-tracking services. As explained previously, the critical parts of the whole journey are during the loading and unloading of the containers when no power is provided.

12.4.3 Air/Ocean (mixed modes)

For the last 20 years, a new approach to international transportation has gained much popularity. It is using a mix of ocean and air transportation. The idea is to use airline destinations that do not have a lot of cargo business. It is mainly seen in vacation destinations where large planes fly empty in their cargo compartments. Shippers came with an innovative system where they build loads of fresh produce on an airplane ULD and place it inside a refrigerated sea container. The container is moved by ocean to a location where air cargo capacity is high. Once at the intermediate location, the container is transported to the airport facility. Each ULD is taken out of the container and staged, and ready to be loaded on the next flight available. This mixed-mode can save as much as 40% compared to an entire air shipment and allow reaching destinations not possible before.

12.4.4 Ground transportation systems

For any movement of fresh produce, there is always a segment that will use ground transportation. This mode of transportation is widely used and can cover local and international shipments. Because it is widely used, many variations and features can be found. A basic principle is a refrigeration unit placed at the front of the cargo section of a truck or trailer (see also Chapter 16). The refrigeration unit in the front blows cold air out the top to the back of the trailer. The air flows through the packages on its return to the bottom of the unit in the front (Brecht, Sargent, Brecht, Saenz, & Rodowick, 2019).

This refrigeration system may lead to bypasses (shortcuts) if the loads are blocking airflow. It is important to mention that the refrigeration unit is designed to maintain the produce temperature and will never be able to cool down if the produce is not at the right temperature at the beginning. Most of the new systems use an air delivery chute that goes from the refrigeration unit outlet to about three-fourth length of the truck or trailer (Fig. 12.5). Any good refrigerated ground transportation equipment should have an air delivery chute (Emond, 2007a, 2007b).

FIGURE 12.5 Refrigerated trailer with an air delivery chute.

12.5 Importers/buyers/food distributors

Importers/buyers provide services as food distributors, and they connect growers to those who sell produce. They gather produce from farmers abroad, store them in warehouses, and offer specific services to clients.

From the moment they receive the produce (air, ocean, or ground), they store them at their appropriate temperature and inspect them for quality control. Some of them will also offer a repacking service. Many produce shipments arrive in bulk and need to be prepared for specific customers, usually using their house brand. Produce is sorted for a specific color, size, and quantity. This service is also beneficial when parts of a load have decay or physical injuries. Rather than throwing away the whole load, a repacking service will save the healthy produce. Repackers have played an essential role during the recent pandemic as food service companies moved from delivering produce to restaurants and institutions to retailers. Packages for food service are much larger and usually do not have all the labeling required for retail sales.

Produce can stay as long as a few months at these locations, depending on shelf life and demands.

12.6 Retailers

Retailers are playing an essential role in bringing fresh produce to consumers. Globalization has one of its most prominent exponents in food value chains; it has become a standard to find avocados from Peru all over the European Union or mangos from the

Philippines in the United States. Consumers want all kinds of fruit and vegetables all year round, so retailers have an essential role in providing out-of-season and seasonal fresh fruit and vegetables on demand in an affordable manner (see also Chapters 3, 11, 19, and 21).

12.6.1 Transportation to distribution center

As mentioned earlier, most transportation carriers selected to pick up an order from growers or an importer/buyer are chosen at the last minute depending on the closest carrier, price, and equipment available. Depending on the produce's perishability, the transportation service selected can use a single or double driver, as it will determine the time it takes to reach the destination. The retailer will request a specific temperature for each load and sometimes consolidate the shipment with multiple produce types. Appendix II in Brecht et al. (2019) provides lists groups of fruits and vegetables that are compatible in mixed loads.

12.6.2 Unloading and quality evaluation

Due to the high traffic at retailer DCs, each shipment (trucks) is assigned arrival times and loading dock number. In many cases, trucks can be waiting between a few hours to a full day before being called for unloading. Most very perishable produce items are given priority so that potatoes will go last.

Once the truck is docked, DC staff will look at the temperature at arrival by measuring the produce temperature physically or/and download temperature loggers (if any). Quality control inspectors will randomly pick produce in the load and assess their quality. If problems are observed, more inspection can be required. In the case the retailer staff find quality issues and need a second opinion, a third party can be requested for a second inspection. Once the retailer accepts the load, they usually have to live with any subsequent losses.

A typical DC will receive most of the produce in the first part of the day, as they will use the same docking area for shipments going out to the stores during the evening.

12.6.3 Storage (distribution center)

Once the quality control team accepts produce, they are brought to the specific cold storage room for their temperature requirement. Most DCs will have rooms set at 12°C−15°C (wet and dry), 2°C−4°C (wet and dry), and sometimes an area where they have ripening rooms. Potassium permanganate pouches or ozone generators are used to control the ethylene concentration in each room (Nunes, Emond, Dea, Yagiza, 2011a; Nunes, Dea, Emond, 2011b).

12.6.4 Order preparation and transportation to stores

Depending on the stores' proximity, the closest stores will receive orders multiple times a week, while the farthest stores will receive once or twice a week. The store's produce manager sends the day before delivery the list of produce and their quantity. DC staff will build the order on a pallet by starting with heavy produce like potatoes and will finish with delicate produce like berries. Since bananas are a trendy item, it is usual to have a full pallet load for each store. There is no segregation by temperature in these orders as all orders are usually shipped in a refrigerated truck with only one set temperature, which is usually about 7°C. Due to some produce's perishability, the DC manager may decide to ship more produce than ordered to the stores so they will not perish at the center (Emond & Germain, 2013).

Some DCs manage their inventory by First In First Out, while others will manage by using a First Expire First Out based on temperature history and shelf life prediction (Brecht et al., 2014; Nunes, Nicometo, Emond, Melis, & Uysal, 2014; Jedermann, Emond, & Lang, 2007; see also Chapter 5).

Once the orders are ready to ship, they are loaded in refrigerated trucks for delivery. A typical truckload will serve between four to eight stores. For long-distance delivery (10−18 h), mixed loads of frozen and refrigerated products are placed in two separated compartments. Produce very susceptible to chilling injury like bananas are placed away from the separation wall (frozen and refrigerated).

The reception of the loads at the stores differs widely even in the same retail chain. Some stores have a cold room for temporary storage of shipments, but most of them will try to place the produce in the store displays directly (Nunes, Emond, Rauth, Dea, & Chau, 2008). The cold room located in the reception area is usually set at 4°C, and all the chilling sensitive produce are stored at room temperature in the same area (Nunes, Emond, Dea, Yagiza, 2011a; Nunes, Dea, Emond, 2011b).

12.7 Home delivery

12.7.1 Meal-kits

One of the most innovative businesses over the past 5 years is the meal-kit home delivery industry. This business has been even trendier recently as consumers stay home due to Covid-19 restrictions, lockdowns, and limited restaurant offerings. In this era of social media and lifestyle, these meal-kit services reach working consumers looking for healthy foods and convenience. It is expected that this business segment to reach more than $12 billion per year. The grocery business still outranks this new business, but it is a new trend that cannot be ignored (Team Linchpin, 2021).

Most meal-kit companies offer dinners that need to be prepared at home. All the ingredients (proteins, produce, sauce, etc.) are provided with the right amount of each recipe. The fresh produce included need to be cut while making the recipe (Fig. 12.6).

Meal kits are shipped in an insulated box using ice packs as a cold bank. Since the proteins have to be kept below 4°C, most of the cold bank is used for them, while fresh produce has minimal temperature protection. This lack of protection significantly affects the quality of the fresh produce during summer and winter. Fig. 12.7 shows the lack of temperature control for the fresh produce compared to the proteins.

FIGURE 12.6 Typical meal-kit box.

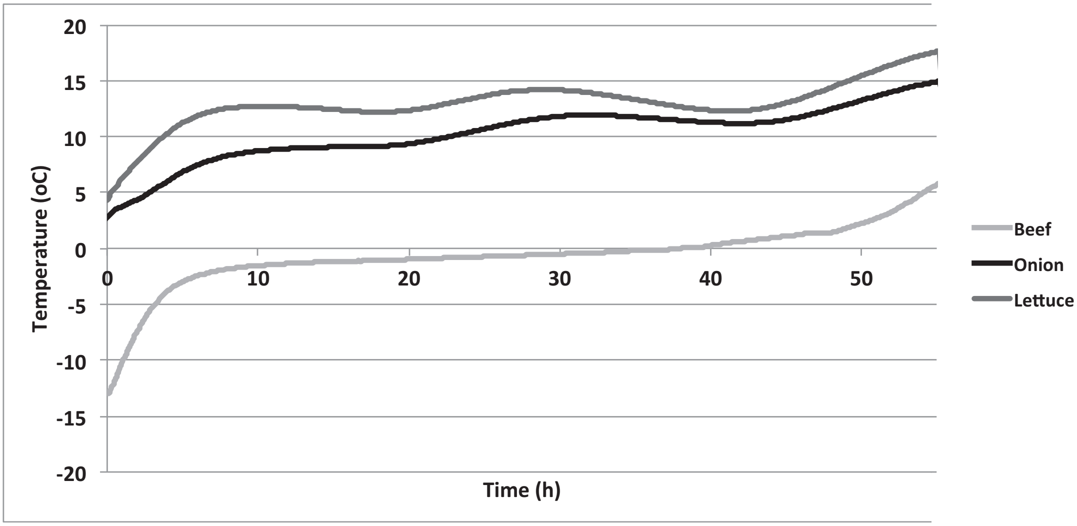


FIGURE 12.7 Temperature inside a meal-kit box during shipment (Germain, 2020).

12.7.2 Imperfect produce home delivery

Every year a significant amount of fresh produce is rejected by retailers due to their imperfections like shape, size, or color. A new business was created to address this issue and reduce food waste (see also Chapters 2 and 19). Customers order every week a mix of imperfect vegetables or fruits that are shipped to their homes by courier (at a reduced price). During summer, fresh produce is shipped in an insulated box with a small amount of ice packs.

12.7.3 Grocery home delivery

During the Covid-19 pandemic, retailers have teamed up with companies that operate a grocery pick-up and delivery service. Services are offered via a website and mobile application that allow customers to order groceries from participating retailers. It is like having a personal shopper. Depending on the company or retailer, fresh produce is delivered at the house doorstep in a regular paper bag or insulated pouches. Just in the United States, more than 100 million home deliveries were made in 2020.

12.8 Conclusion

As seen in this chapter, fresh produce value chains involve multiple parties until produce reaches consumers. It is a very complex operation that very often leads to loss of quality resulting in waste. Quality issues that arise further down the chain will still happen until knowledge and information are transparently shared between players in this industry. New tracking technologies such as "real-time" temperature and position tracking may reduce losses along the chain. The recent pandemic has highlighted the fragility of the flow of fresh produce around the world. This tragic event should be an opportunity to rethink the current system and look at robust contingency plans.

References

Badia-Melis, R., Emond, J. P., Ruiz-Garcia, L., & Robla Villalba, J. I. (2016). *Explorative study of using infrared imaging for temperature measurement of pallet of fresh produce*. Available from https://doi.org/10.1016/j.foodcont.2016.12.008.

Brecht, J. K., Nunes, M. C. N., Emond, J. P., Uysal, I., Wells, J., & Saenz, J. (2014). Reducing strawberry waste and losses in the postharvest supply chain via intelligent distribution management. In *29th International horticultural congress*. Brisbane, Australia.

Brecht, J. K., Sargent, S. A., Brecht, P. E., Saenz, J., & Rodowick, L. (2019). *Protecting perishable foods during transport by truck and rail*. University of Florida, Institute of Food and Agricultural Sciences. Available from https://doi.org/10.9752/TS230.04-2019.

Cuellar, S. (2003). Marketing fresh fruit and vegetable imports in the United States: Status. *Challenges and opportunities*. Dept. of Applied Economics and Management, Cornell University.

Dupont. (2016). *Tyvek® cargo covers: The science behind the covers*. <http://www.dupont.com/products-and-services/fabrics-fibers-nonwovens/covers/articles/air-cargo-covers-science-behind.html>.

Emond, J. P., & Germain, M. (2013). *Thermal behavior of a pallet of fresh produce during distribution*. Sarasota, FL: Florida State Horticultural Society, May 2013.

Emond, J. P., & Germain, M. (2014). Air transportation of asparagus between Peru and the United States. *The illuminate group test report* (pp. 23). Tampa, FL.

Emond, J. P. (2005). *IATA perishables cargo manual* (5th ed., p. 187)Montreal, QC: International Air Transport Association.

Emond, J. P. (2007a). Ocean transportation for cold chain products. In *Paper presented at the IQPC cold chain distribution*. Philadelphia, PA.

Emond, J. P. (2007b). Temperature mapping for aikir, sea and land transportation. In *Paper presented at the IQPC cold chain distribution*. Philadelphia, PA.

Emond, J. P. (2014). Interaction of the custom and border protection, quarantine treatments and APHIS requirements, and food safety modernization act in international shipping. In *Workshop: Nuts and bolts of postharvest shipping around the world, paper presented at the American Society for Horticultural Science (ASHS)*. Orlando, FL.

Emond, J. P., Mercier, F., & Nunes, M. C. N. (1999). In-flight temperature conditions in the holds of a widebody aircraft. # 281. In *Paper presented at the proceedings of the 20th international congress of refrigeration*. Sydney, IIR, Australia.

Emond, J. P., Vezina, J., & Khalil, C. (2010). Temperature mapping of refrigerated sea container during power shutdown. *Technical report* (pp. 14). Plant City, FL: Blueye LLC.

Germain, M. (2020). Field study of temperature behavior of meal-kits during distribution. *The illuminate group 2020 report* (pp. 45). Tampa, FL.

Jedermann, R., Emond, J. P., & Lang, W. (2007). *Shelf life prediction by intelligent RFID*. *International dynamics in logistics*. *SFB637-B6-07-021-IC* (pp. 1−5).

Nunes, C. N., Emond, J. P., Dea, S., & Yagiza, Y. (2011a). Distribution center and retail conditions affect the sensory and compositional quality of bulk and packaged slicing cucumbers. *Postharvest Biology and Technology*, *59*, 280−288.

Nunes, C. N., Emond, J. P., Rauth, M., Dea, S., & Chau, K. V. (2008). Environmental conditions encountered during typical consumer retail display affect fruit and vegetable quality and waste. *Postharvest Biology and Technology*, *51*, 232−241.

Nunes, M. C. N., Dea, S., & Emond, J. P. (2011b). Visual and compositional quality of bulk and packed yellow summer squashes displayed under simulated retail conditions. *HortScience: A Publication of the American Society for Horticultural Science*, *46*(9), S334−S335.

Nunes, M. C. N., Nicometo, M., Emond, J. P., Melis, R. B., & Uysal, I. (2014). Quality improvement in fresh fruit and vegetable logistics: Berry logistics field studies. In *Transactions of the Royal Society A, theme issue: Intelligent food logistics*, vol. 372, 20130307.

Pelletier, W. (2010). *Air transport of horticultural produce: A thermal analysis* (Ph.D. dissertation no. 3436418) (pp. 248). University of Florida.

Pelletier, W. D., Nascimento Nunes, C., & Emond, J. (2005). Air transportation of fruits and vegetables: an update. *Air Transportation of Fruits and Vegetables: An Update*, *1*, 1−7. <http://www.stewartpostharvest.com/June_2005/Emond.pdf>.

Team Linchpin. (2021). *Trends shaping the meal kit industry outlook in 2021*. <https://linchpinseo.com/trends-shaping-the-meal-kit-industry>.

Villeneuve, S., Mercier, F., Pelletier, W., Ngadi, M. O., & Emond, J. P. (2000). Effect of environmental conditions on air shipment of perishables during ground operations. *Paper no. 006058*. ASAE, 2950 Niles Road, St. Joseph, MI.

Villeneuve, S., Vezina, J., & Emond, J. P. (2002). La logistique du froid dans le transport aérien des denrées périssables. *Revue Générale du Froid*, *1029*, 32−38.

This page intentionally left blank

CHAPTER

13

Sorting for defects

Arthur Frank Bollen[1] *and Stanley E. Prussia*[2]

[1]Zespri International Limited, Mount Maunganui, New Zealand [2]University of Georgia, College of Engineering, Athens, GA, United States

13.1 Background

13.1.1 Reasons for sorting

Modern industrialized value chains and supply systems have many established quality criteria, and for producers to be competitive, they must meet the specified requirements. Buyers will pay premium prices for fruit and vegetables of uniform size and color. In general, items should not be misshapen or bruised and should be free of blemishes, diseases, and mechanical damage. For exporters, many international and national quarantine regulations must also be met for insects and diseases. Product that will be stored for a length of time prior to marketing must also meet criteria for maturity, firmness, and damage to ensure storability. These quality specifications have been established primarily to protect members of value chains and ensure a saleable product arrives to the consumer.

Consumer perception of quality is highly variable and changes for many reasons, for example, time of year, supply of product, supply of other products, and end use. Although initial product quality is determined by the producer, the dynamics of price and quality requirements are established largely by the retailer and consumer.

To assist both the seller and the buyer, many public agencies and marketing organizations have developed standards for the grades of most horticultural crops. The documents commonly are called "grade standards" and include one or more sets of specifications and tolerances. Compliance with a specific set of requirements in the grade standard enables the lot to be sold as a shipment labeled with the specified grade, for example, US Extra Fancy, Fancy, No. 1, or Utility. When required, a third-party inspector evaluates samples from each lot shipped by a seller before certifying that the lot complies with the grade standard specified.

The application of grade standards in value chains is essential to codify the quality attributes of a product that are acceptable: (1) to meet some value chain requirement, such as storage or transport performance, or (2) that are considered acceptable to the consumer or

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00013-0

buyer. Many such attributes have not been tested specifically with consumers but more often change over time based on experience and the expert opinion of marketers and others involved in each value chain. Kusabs, Trigg, Bollen, and Holmes (2006) investigated the relationship between sorters of mushrooms and consumer's ratings of the same product. There was little relationship between the two. The sorters were applying a set of attributes to sort against which differed from the visual attributes applied by the consumers. Jahns, Moller-Nielsen, and Paul (2001) attempted to use mapping of fuzzy image analysis attributes to predict consumer assessments of quality and used this approach as a technique to grade product that directly met consumer expectations.

The sorting operation must be viewed in the context of overall postharvest value chains. It is important to understand how cultural practices and uncontrolled inputs such as weather cause variation of quality of products that enter the packinghouse. Likewise, at the time of shipping, it is important to be able to predict the quality of shipments as they progress through the rest of a postharvest value chain (see also Chapter 18). A major function of a packinghouse is to transform the highly variable product received from the harvesting operation into uniform lots of product for shipments that comply with the requirements of the buyer. The importance of the sorting operation cannot be overstated, since variations in this operation will affect returns for most other links in postharvest value chains.

13.1.2 Sorting terminology

The following terminology is applied in this chapter. *Separation* is the removal of nonusable materials from usable product. An early operation in packinghouses is the separation of debris and inedible items from the flow of marketable product. Separations are generally made with mechanical devices such as sizers, blowers, and washers.

Sorting is the segregation of edible or marketable products into distinct quality categories. Sorting of the marketable items is accomplished by both mechanical equipment (sizers or color sorters) and by human means (visual or tactical). The equipment used for sorting is referred to as a *sorting line*. People who perform sorting operations are referred to as *sorters*. *Graders* are the third-party inspectors who evaluate whether or not the packed lot complies with requirements of a grade standard for a predetermined grade classification. *Inspection* of samples for quality control processes is more precise than, and differs from, the dynamic inspection of product necessary for sorting.

13.2 Design and operation of manual sorting equipment

Basic manual sorting operations have developed over a long period of time. Most design and operating conditions have been determined by trial and error for parameters such as table width, table speed, number of sorters, and speed of product rotation. Different products place different requirements on the system. Most sorting operations are still performed by human visual inspection of the product and manual removal of items with defects. Humans have unique abilities for identifying defects and for determining if they exceed prescribed threshold criteria.

A typical sorting operation consists of a continuous flow of product passing in front of one or more stationary sorters (Fig. 13.1). Normally, the task of the sorter is to remove items that do not meet the specifications for the lot being shipped. Nonconforming items are placed into a discard flow, and items meeting other specifications are placed on separate conveyers that may flow to packing areas for lesser quality markets. The design of sorting equipment has considerable effect on efficiency of the sorter in detecting and removing defective items.

The interrelationship between physical design characteristics, the productivity and accuracy of the sorters, and the quality of the product are only partially understood (Prussia & Meyers, 1989), yet the result of the sorting operation has significant effect on postharvest value chains.

A sorting table for manual sorting should be designed at a height and width that is comfortable for the sorter to reach product on both sides of the table, and it should be easy to deposit rejects on the appropriate belt or in the appropriate chute. The design philosophy is to minimize hand movements to enable rapid location and removal of defective items. Also, hand movements should occur within a comfortable envelope of space. An ergonomics handbook (Tilley & Dreyfuss, 2002) provides some basic ergonomic information indicating that the sorters should be positioned so that an angle of 45 degrees is measured between the center of the table and the shoulder.

A recent *Human Factors and Ergonomics Design Handbook* (Tillman, Fitts, Woodson, Rose-Sundholm, & Tillman, 2016) suggests ways to expand opportunities for global economic and ergonomic development by "delineating the crucial role that standards and guidelines play in facilitating the design of advantageous working conditions to enhance individual performance"

FIGURE 13.1 Typical sorting operation—well lit, with narrow tables and number of tables and sorters used matched to fruit flow and defect levels.

(Karwowski, Szopa, & Soares, 2021). Other books with relevant details for designing sorting tables include Tillman et al. (2016) and Chaffin, Andersson, and Martin (1999).

The most efficient sorting operations require two sorters per table for a line carrying products with low levels of defects. A good design allows accommodation of additional sorters in the event of high defect rates for the incoming product. Sorting productivity is reduced if the sorters stand directly opposite one another, since they tend to compete for the same product and do not use the full width of the table properly. Research with kiwifruit on a table 0.8-m wide showed that the proportion of the defective fruit removed was 96% when the sorters were staggered and fell to 68% when the sorters were standing directly opposite each other (Bollen, 1986).

Research with simulated fruit (Meyers, Prussia, Thai, Sadosky, & Campbell, 1990) showed a 23% improvement in defect detection for sorters positioned at the end of an inspection conveyor compared with sorters positioned at the sides. Approximately two-thirds of the improvement was shown to result from the ability to see more of the surface area when at the end than when at the side.

Translation speed is the velocity at which products pass the sorter. If the feed rate for incoming items is constant, then changes in translation speed will vary the amount of product on the table at a given time (Prussia, 1985). Changing the translation speed must be done with caution since it is unsettling for sorters if speed is adjusted frequently. However, human sorters have the ability to adapt to a wide range of steady speeds. The limiting factors appear to be overflowing the table with product when operating at a low speed, and rotating the fruit too fast at a high translation speed. Most researchers suggest speeds of 6.5–9.0 m/min.

The quantity of product is often described in terms of product density on the table (kg/m^2 or fruit/m^2) or in terms of number of fruits per row. Loading can be regulated by adjusting the translation speed or the product feed rate. Loading should be regulated to insure the capability of the sorters to maintain a desired accuracy and to ensure that sufficient product can be handled when incoming quality has a high reject level. Product loading is generally between three and five fruits per row, irrespective of table width.

To achieve effective sorting, the product must be rotated in front of the sorter. It is desirable to rotate the fruit completely at least twice within the immediate field of view. The maximum rotational speed at which sorters can operate effectively is determined partly by the size and types of defects being removed but, in general, rotational speeds above 50 rev/min are detrimental.

13.2.1 Lighting

Correct lighting is critical for an efficient sorting operation (Guyer, Brown, Timm, Brook, & Marshall, 1994). Proper illumination improves defect detectability and reduces eye strain. Low intensity light makes a perception of contrasts difficult. A study on lighting for fruit sorting by Nicholson (1985) recommended a uniform light level of at least 1000 lx at the sorting table. A large number of illumination requirements for specific tasks are listed by Tillman et al. (2016). The preferred illumination level for "fine work detail" is 1075 lx [100 fc (foot-candle)]. The minimum level is 810 lx (75 fc).

Fluorescent tubes are used most commonly. If they are mounted 1.5 m above the table, there is minimum glare and the whole area is well lit. When it is necessary to mount lights at or below eye level to avoid shadowing, the lights should be fitted with deflectors and diffusers to direct a diffuse light onto the table where it is required, and not into the eyes of sorters. Both Guyer et al. (1994) and Nicholson (1985) also suggest that the surroundings should be well lit. When sorters look up from the table, their eyes adjust to the light intensity of the background. Background light of a similar intensity helps reduce eye strain. Neutral-colored walls help reflect diffuse light back to the table. Sorting products on white belts can produce glare or high reflectivity of the incident light. Dark, dull belts can ease eye strain and improve visibility of the product.

If determining product color is important, then it is necessary to use lights that produce a spectrum similar to that of daylight. In the extreme case, green light falling on a red surface will make the surface appear dark to the eye, since most of the light at these wavelengths will be absorbed by the surface. Making accurate decisions based on dark images is difficult. Unfortunately, "cool white" fluorescent tubes have a high intensity but a blue bias, which makes products appear excessively green.

13.2.2 Defect type

The types of defects have significant effects on the optimum operating parameters. Some simulated products could be sorted at very high throughput rates of 5.3 fruits/s (Meyers, Prussia, & Karwoski, 1990) and 7.0–11.6 fruits/s (Hunter & Yaeger, 1970). These simulated defects tended to be limited to one or two types and usually were all of similar size. A real sorting operation encounters a large range of defect types; sorters must make decisions on the severity of each. This additional decision process results in a significant slowing in the potential product throughput. Typical throughput rates with real product are reported as 2.0 fruit/s (Pasternak, Lidror, & Engel, 1989), 1.0 fruit/s (Stevens & Gale, 1970), and 1.6 fruit/s (Bollen, 1986).

13.2.3 Visual perception

The ability of humans to perceive a visual image depends on both physical and cognitive factors (Prussia, 1991). Changes in the color and intensity of light change the image received by the eye. The method of presenting the product to the sorters also has an important effect on perception. If product speed (either translation or rotation) is too fast, it is not possible to fixate properly on a defect; hence, it is not possible to reach a decision about whether or not the item should be rejected.

Any vision difficulties adversely influence the detection of defects. Both visual acuity and visual processing ability decline as people age (Ip, 2011). Visual acuity typically declines 26% by age 60. Significantly more light is required with increasing age. A 40-year-old person needs twice the light of a 20-year-old one and a 60-year-old person needs five to six times as much light. An ergonomics handbook (Tillman et al., 2016) indicates that workers between 25 and 65 years old need twice the illumination as workers less than 25 years old and workers over 65 years old need four times as much illumination as those less than 25. Older workers also need more time to achieve accuracy. Compared with a 20-year-old worker: a 40-year-old worker requires 120% as much time; a 50-year-old worker requires 160% as much time; and a 60-year-old worker requires 270% as much time.

Vision examinations for sorters are useful for determining problems with visual acuity, peripheral vision, and color blindness. Also, the inability to concentrate for long periods of time results in a relaxing of vigilance, which is an important factor of visual perception. These human factors can lead to highly variable performance between sorters and also variable performance of an individual sorter over time.

13.3 Automated sorting

While most sorting operations worldwide are still manual, they are now increasingly being supplemented with automated sorting based on computer vision (see also Chapter 15). These systems are often implemented to perform presorting operations to reduce the number and range of defects that human (manual) sorters need to work with. A typical system is shown in Fig. 13.2. Fruit is received after the bin dump and cleaning brushes and carried on a singulator conveyor under a hood where the fruit is rotated and a camera, or a set of cameras, captures a number of images of the fruit. The images are then rapidly processed and defects or quality attributes identified (see Chapter 15). The fruits are dropped from the conveyor at an appropriate position based on the decision reached by the image analysis (Kondo, 2010).

The technology offers significant advantages over human sorters as it is generally fast, often more consistent, not prone to fatigue, more objective, and becoming progressively lower in cost (Blasco, Munera, Aleixos, Cubero, & Molto, 2017; Cubero, Lee, Aleixos, Albert, & Blasco, 2016; Wu & Sun, 2013; Zhang et al., 2018).

Early work in this area (Miller & Delwiche, 1989; Shearer & Payne, 1990; Yang, 1992) focused on techniques for identifying the fruit and descriptions of shape and color. Shape is particularly important as a grading parameter in fruits that have variable shapes but need to be marketed with a consistent shape (Blasco et al., 2017; Cubero, Aleixos, Molto, Gomez-Sanchez, & Blasco, 2011) and also for the estimation of the volume of fresh products where combined with weight can be used as an internal defect detection method (Phate, Malmathanraj, & Palanisamy, 2019; Ruiz-Altisent et al., 2010). Achieving acceptable accuracy at high speeds is still difficult to achieve for many products (Blasco et al., 2017; Moreda, Ortiz-Canavate, Garcia-Ramos, & Ruiz-Altisent, 2009).

The early work on shape and color has led on to development of very specific algorithms and analyses for much more complex quality traits and the identification of specific defects (Blasco et al., 2017; Zhang et al., 2019). The analysis techniques are beyond the scope of this chapter but a range of approaches that have been successfully implemented for fruit and vegetables are described by Graves and Batchelor (2003), Ngan, Penman, and Bowman (2003), Du and Sun (2006), Zheng, Sun, and Zheng (2006), Lopez-Garcia, Andreu-Garcia, Blasco, Aleixos, and Valiente (2010), Ruiz-Altisent et al. (2010), Li et al. (2019), Iraji (2019), and Azarmdel, Jahanbakhshi, Mohtasebi, and Muñoz (2020).

The bulk of the reported research relates to apples and citrus. Apples have particularly difficult issues associated with the stem and calyx ends of the fruit (Blasco et al., 2017; Leemans & Destain, 2004; Leemans, Destain, & Magein, 2000; Zhang et al., 2017; Zhu, Jiang, & Tao, 2007) that limit the accuracy of detection for russetting, scab, and physical damage. More sophisticated lighting and filtering using multispectral imaging have also been used, in particular to assist with the detection of bruising (Kleynen,

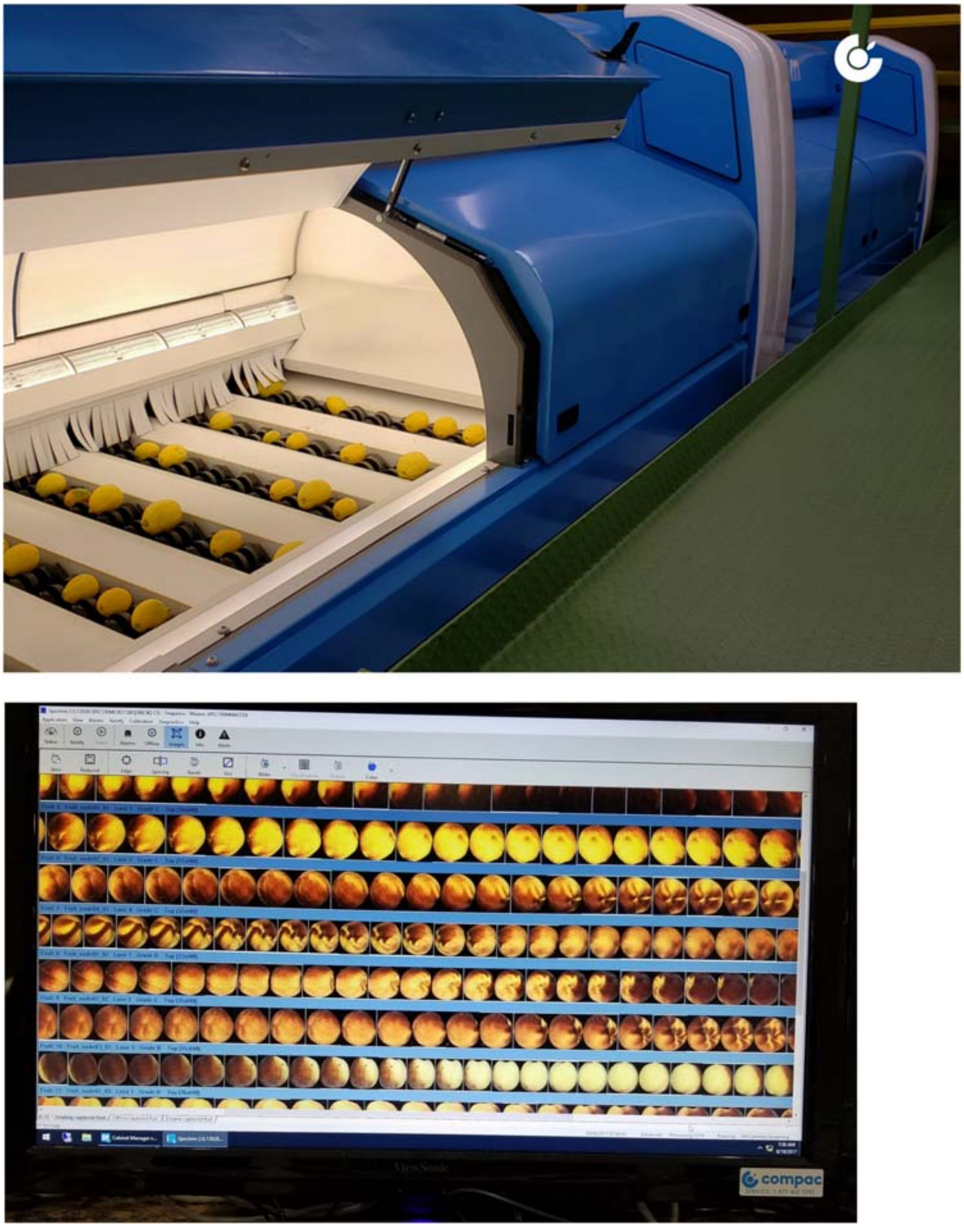


FIGURE 13.2 Automated sorting systems—Compac Spectrim.

Leemans, & Destain, 2005; Xing & De Baerdemaeker, 2005; Zhang et al., 2018). Other applications that have been achieved include surface defects on citrus (Aleixos, Blasco, Navarron, & Molto, 2002; Cubero et al., 2011; Lopez-Garcia et al., 2010; Miller & Drouillard, 2001; Cubero et al., 2017) and shape and defects on cherries (Rosenberger, Emile, & Laurent, 2004).

TABLE 13.1 Examples of manufacturers offering automated visual defect detection systems.

Equipment supplier	Manufacture	Main crops[a]	URL
Aweta	The Netherlands	A, D, E	https://www.aweta.com/en
BBC—Tomra	New Zealand	B	https://bbctechnologies.com/
China Colour Sort—Taiho	China	A, B, C, D	http://www.chinacolorsort.com/default.asp
Compac—Tomra	New Zealand	A, B	https://www.compacsort.com/
Elisam	Italy	A, B, C, D, E	https://www.elisamgrading.com/
Ellips	The Netherlands	A, B, C, D	https://ellips.com/about-us/
FruitTek	United States	B	https://www.fruittek.com/multiscan/
Futura	Italy	A, B, C, D	https://www.futura-grading.com/
GP Graders	Australia	B	https://www.gpgraders.com/
Greefa	The Netherlands	A, D, E	https://www.greefa.com/solutions/grading-machines/
MAF-RODA	France	A, B, C, D	https://www.maf-roda.com/en/
Protec	Italy	A, B, C	https://www.protec-italy.com/en/
Reemoon	China	A	https://www.reemoon.com/en
Ser-Mac Quadra	Italy	A, B, C, D	https://www.quadramachinery.com/index.html
Unitec	Italy	A, B, D, E	https://en.unitec-group.com/

[a]*Target crops: (A) mid-range fruit and vegetables (30–250 g), for example, apples, citrus, stone fruit, potatoes; (B) small fruit (5–65 g), for example, cherries, blueberries, cherry tomatoes; (C) large fruit (200 g +), for example, melons; (D) elongated vegetables, for example, cucumbers, carrots; and (E) others.*

The technology has reached a level of maturity where all the major international fruit-grading manufacturers offer commercial systems (Table 13.1). These are available for sorting for color, shape, surface defects, and even some internal defects for a range of fruit and vegetables, including apples, pears, kiwifruit, tomatoes, potatoes, onions, melons, peaches, nectarines, cherries, blueberries, citrus, avocados, and mangoes.

The accuracies, of automated sorting algorithms, where reported, for most of these techniques range from 80% to 99%. Misclassification is, however, generally not reported (it is often not even measured). This is unfortunate as, for a commercial operation, this can have significant effects as discussed in Section 13.4, if a large quantity of "good" product is being discarded at the expense of the accuracy of identification of the defect. The automated sorting process using other nondestructive technologies is further discussed in Chapter 15.

13.4 Analysis of sorting operations

To analyze a sorting operation, it is necessary to establish parameters, such as efficiency or accuracy that may be useful for comparing performance under different conditions. When analyzing an automated or manual sorting operation, the information directly available includes the throughput, the defect removal rate of product, the proportion of defects removed, and the proportion of good fruit removed with the rejects. Sometimes a breakdown by defect type is also possible. This information has been used by various investigators to predict the performance of operations, to provide sorting system design information, and to provide operational information and management tools.

When using a systems approach to postharvest handling, it is useful to be able to predict how a particular operation might function under various conditions. It may be necessary, for example, to predict productivity and staffing levels for various throughput or quality conditions. Many attempts have been made to analyze and describe the sorting operation mathematically; some of these models can be useful in a systems analysis.

13.4.1 Signal detection theory

Signal detection theory (SDT) was developed in the 1940s to quantify the effectiveness of systems used for detecting communication signals from background noise [reviewed by Egan (1975)]. When attempting to detect a signal, there are two possibilities: a *signal-plus-noise stimulus (SN)* and a *noise-with-no-signal stimulus (N)*. The two possible responses to a stimulus, "yes" and "no," indicate the observer's belief (or in the case of automated sorting, the algorithm estimate) that the signal is present or absent. That either response may be in error is always a possibility also. SDT continues to be adapted for applications such as wireless communication systems (Chavali, 2012). Aipour and Ayat (2012) detected primary from secondary radio signals.

Outside of its original applications in the communications field, an early adaptation of SDT was in psychology experiments to determine human ability to distinguish a visual signal from background visual noise (Tanner & Swets, 1954). Subsequent researchers retained much of the original communications terminology (Green & Swets, 1966). A chapter on the basics of SDT is in a book on *Quantitative Sensory Analysis* (Lawless, 2013). He states "SDT represented a great leap forward in the thinking about sensory phenomena and how to measure them" (Lawless, 2013).

SDT has numerous applications to visual and other sensory perceptions for various research, commercial, and industrial tasks. The ability of people to detect audio signals from background noise was evaluated by Mao, Vosoughi, and Carneya (2013). Jaraiedi, Toth, Aghazadeh, and Herrin (1986) modeled decision-making behavior of inspectors. Goh and Wiegmann (2006) evaluated vigilance during airport baggage screening. An SDT study was conducted to evaluate interactions between the sensitivity of consumers to different concentrations of salt and their decisions strategies based on different payoff levels (Martín-Guerrero, Ramos-Álvarez, & Rosas, 2016). The payoff affected the tasters' decisions but did not affect their sensitivity to basic tastes. Even the process of retail customers searching for products has been analyzed using SDT (Liu, Chen, Melara, & Massara, 2008).

A series of publications, many in the journal *Food Quality and Preference*, describe the development of improvements for SDT applied to consumer products and foods. Examples from 2015 to 2020 are Kim, Yoon, and Lee (2015), Shin, Hautus, and Lee (2016), Kim, Hopkinson, Van Hout, and Lee (2017), Kim, Van Hout, and Lee (2018), Mun, Kim, Sim, and Lee (2019), Hautus, Van Hout, Lee, Stocks, and Shepherd (2020), and Lee (2020).

SDT is especially important during dynamic detection processes (Balakrishnan & MacDonald, 2011). Researchers have adapted SDT for evaluating dynamic manual sorting of fruits and vegetables (Meyers, 1988; Meyers et al., 1990a, 1990b; Prussia, 1985; Prussia, 1991; Yaptenco et al., 2013).

13.4.1.1 Adaptations of signal detection theory for sorting fresh produce

For manual sorting operations, a flow of fruits or vegetables passes in front of human sorters. Their task is to remove the defective items while leaving the good product on the conveyor to the packing area. Automated sorting machines pass items under a set of cameras or other sensors. Defective product is directed to a reject drop. The incoming mixture of both good and defective products is considered SN. The incoming defective product can be considered the signal, *S*. The good product is considered *N*.

The ability of the sorter (or algorithm) to make "yes" and "no" decisions correctly is influenced by the physical parameters of the operation; for example, speed, rotation, fruit density, number of defective fruit, types of defects, and lighting. Decisions for manual sorting have further complications as they are also influenced by psychophysical factors such as sorter sensitivity to perceptual stimulus (visual acuity, color perception), sorter alertness, and sorter motivation to give one response or the other. A major contribution of SDT is the ability to separate the physical conditions from the psychological influences. It is suggested that the same will be true for automated systems where SDT should be able to separate physical and algorithm performance. There is little independent data published by the commercial systems (Table 13.1) to validate such separate performance.

The conditional probability of responding "yes" when a signal is present is termed the Hit rate, p(Hit) or $p(H)$, and is calculated by dividing the number of rejected items by the total number of defective items in the batch sorted. The conditional probability of responding "yes" when a signal is *not* present is termed the False Alarm rate, p(False Alarm) or $p(FA)$, and is calculated by dividing the number of good items that were removed by the total number of good items sorted.

A third possibility is the conditional probability of responding "no" when a signal is present, which is called a p(Miss) or $p(M)$, and is calculated by dividing the number of defective items incorrectly packed by the number of defective items in the batch sorted. The last conditional probability is that of responding "no" when a signal is not present, which is called p(Correct Acceptance) or $p(CA)$, and is calculated by dividing the number of good items packed by the total number of good items sorted.

There are a number of similar classifications used in different areas of science and industry. The relationships between the different systems are summarized in the following confusion matrix:

Miss False negative Type II error	Hit True positive	Sensitivity = Σtrue positive/Σ(true positive + false negative)
Correct Acceptance True negative	False Alarm False positive Type I error	Specificity = Σtrue negative/Σ(true negative + false positive)

The quadrants in Fig. 13.3 are defined by the distribution of signals from *Bad items above* the bold horizontal line and the distribution of signals from *Good items below* the line. The bold vertical line separates the items on the *left* that are *packed* and the ones on the *right* that are *removed*. *Above* the horizontal line, the *Missed* items are Bad items that get *packed* and *Hits* are *Bad* items that are *removed*. *Below* the line, the *Correct Acceptance* items are *Good* items that are *packed* and the *False Alarms* are *Good* items that are *removed*.

Since the probabilities are conditional, all four possibilities can be described using only two probabilities, because the pairs are complementary, with $p(M) = 1.0 - p(H)$ and $p(FA) = 1.0 - p(CA)$. Conventional SDT techniques assume that probabilities are distributed normally and are of equal variance as shown in Fig. 13.3. Note that the curves are frequency distributions for the *intensity* of the signal. They are not a histogram for the *number* of Bad or Good items.

The z-values are the standard deviation for a normal variate. Statistical tables, calculators, or computer algorithms give z-values for selected probability values. The statistical tab on Microsoft Excel spread sheets has an option for "NORM.S.INV(probability)" that is the inverse of a normal standard deviation. For example, the z-value for the Miss rate of

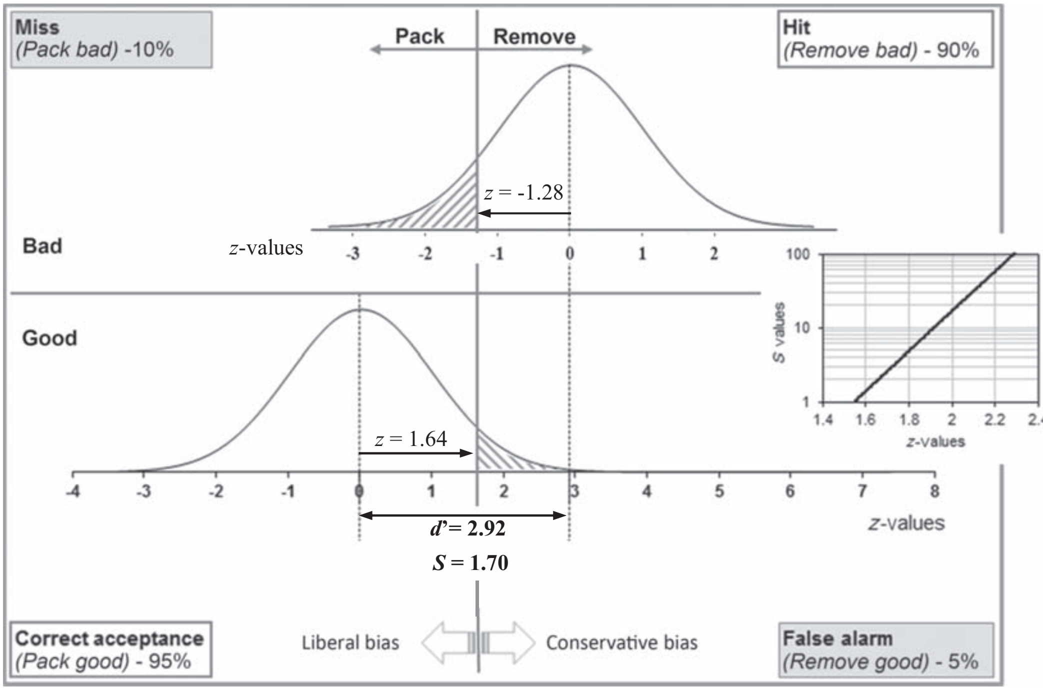


FIGURE 13.3 Probability distributions for signal intensity of "Noise-with-no-signal" (N or Good) and "Signal-plus-noise" (SN or Bad). The four possible outcomes (Hit, Miss, False Alarm, Correct Acceptance) are shown, as are representations for detectability, d', and set point, S. The shaded area under the bad normal distribution is the percent of the total number of bad items misses. The shaded area under the good curve is the percent of the total number of good items removed. Misses and false alarms are not the percent of the total number of items in the batch. As the sorter becomes more conservative, S moves to the right in the figure, and if more liberal S moves to the left. The insert shows the logarithmic relation of set point values with z-values.

10% shown in Fig. 13.3 is found by entering the decimal probability (0.1) in the Excel function. The result is -1.28, with a negative sign because probabilities less than 50% are negative on the left side of the mean.

13.4.1.2 Detectability

For a particular sorting operation in which the physical and operational parameters and the product characteristics do not change, the Bad and Good distributions do not change, the distance between the normal deviates of the means is described by the parameter d', the detectability (Freeman, 1973). The easier the detection of defects, the further apart the two distributions will be, making d' larger. A sorting process with a high d' indicates that the operation has the potential to reduce both Misses and False Alarms better than those sorting operations with more overlap of the two distributions.

Fig. 13.3 gives a visual aid while writing an equation for calculating d'. The vertical set point line, S (described later), is common to both normal distribution curves. It demarks the boundary between the areas representing Misses and Hits under the upper normal curve and simultaneously separates the areas representing Correct Acceptances and False Alarms under the lower normal curve.

The value for d' on the z-value axes is the distance between the means of the two standard normal distribution curves. Sorting percentages for both miss and False Alarm rates are represented by the shaded areas under the two normal curves. Normal distributions have a maximum height at the mean where the z-value is zero and symmetrical asymptotes on both sides. Negative values for z on the left side of the mean are for percentages less than 50%. Positive values for on the right side of the mean are for values greater than 50%.

The shaded area under the upper normal distribution represents the 10% Miss rate. The distance from the mean to the set point line is the negative z-value for a probability of 0.1. Microsoft Excel gives a z-value of -1.28 units. The distance from the mean to the left of the shaded area in the lower distribution represents a Correct Acceptance rate of 95% and has a positive z-value of 1.64 units.

False Alarm rates receive more attention than Correct Acceptance rates during commercial sorting operations because FA rates show the number of rejected items that could have been sold at a full price. If the set point moves to the right, then the area under the curve for CA increases while the probability of FA decreases, according to their complementary relationship $CA\% + FA\% = 100\%$. The z-value of 1.64 units shown in Fig. 13.3 indicates the end of the CA area under the curve that includes both the 50% from the negative side of the mean and the area on the positive side from a z-value of 0 to 1.64 units.

The shaded area under the right side tail of the lower curve represents the 5% False Alarm area. The z-value of 1.64 units is where the CA area ends and FA area starts. The shaded area under the right-hand side of the Good curve can be understood as the total area under the curve minus FA ($100\% - FA\%$) giving $100\% - 5\%$ for the case shown in Fig. 13.3. So, the z-value for FA is $z[p(1.0 - 0.05)] = +1.64$ units on the z-value scale.

The equation for d' is the total separation between the means of the two distributions, which is the sum of the two z-value distances from the set point line to the means of the two distributions. Sorting operations typically have percentages of misses that are much less than 50% that results in negative z-values. Therefore the term for a miss is traditionally subtracted from the term for False Alarms in the equation for d' (Green & Swets, 1966). From Fig. 13.3, it is clear the negative sign between the two terms in Eq. (13.1) is required because the miss and False Alarm rates increase in the opposite directions on the z-value axis. The equation for detectability is found as the sum of the two z-values:

$$d' = z[p(1.0 - FA)] - z[p(M)] \tag{13.1}$$

13.4.1.3 Receiver operating characteristic

The detection performance at a sorting situation may be evaluated visually by using receiver operating characteristic (ROC) plots (Fig. 13.4), on which $p(M)$ is plotted against $p(FA)$. Changing from $p(H)$ to $p(M)$ changes the curves from convex toward the upper left corner to curves convex toward the lower left corner. In manual sorting, points for $p(M)$ and $p(FA)$ on a d' curve can be found by varying the instructions to the sorters or by adopting some incentive payment scheme. In automated sorting the points on an ROC curve can be found by varying algorithms or sensitivity parameters.

By selectively varying $p(M)$ and $p(FA)$, it is possible to generate any number of points on an ROC curve that all have the same value for d'. Since the physical parameters of the system (such as speed or rotation) have been unchanged, this curve is characteristic of that operation. Each sorting system has a curve for each value of $p(M)$ and the corresponding $p(FA)$; resulting in a unique detectability curve for that value of d'. The power of SDT is that it is possible to generate a complete d' curve after an average value has been determined for one pair of $p(M)$ and $p(FA)$.

13.4.1.4 Set point

The second useful descriptor for SDT theory is the criterion likelihood ratio or bias, β, which represents the probability that a decision was based on N stimuli relative to the

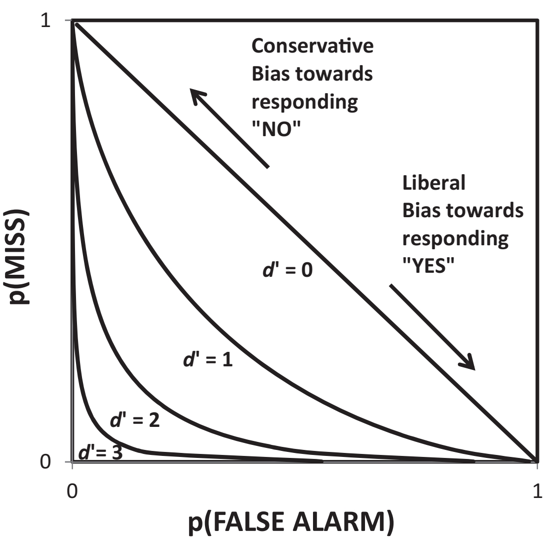


FIGURE 13.4 Typical receiver operating characteristic plot showing relationships between p(MISS) and p(FALSE ALARM) as a family of detectability (d') curves.

probability that the decision was based on SN stimuli. For this chapter, we use the term "set point" (S) to emphasize the purposeful decisions of human sorters and the mechanical or electronic settings established on automated sorting equipment.

An equation for calculating S is given by Harvey (2013), Meyers (1988), and Egan (1975). If the normal density functions are equal and have a standard deviation of 1.0, then a more complex ratio simplifies to

$$S = \frac{e^{0.5\{-z[p(1.0-FA)]\}^2}}{e^{0.5\{-z[p(M)]\}^2}} \tag{13.2}$$

The physical representation of the set point, S, is a description of the cutoff position for an algorithm or that which a sorter sets in his or her own mind. Changes in the set point can be visualized in Fig. 13.3 by considering the changes resulting in the four conditional probabilities as the vertical line is moved to the right or left.

The value for S is 1.0 when the distance from the mean for the Good distribution to the set point is equal to the distance from the mean for the Bad distribution to the set point. At $S = 1.0$ the numerator and denominator in Eq. (13.9) are equal and the shaded area representing the False Alarm rate is equal to the shaded area representing the Miss rate. When $S = 1$ the values for $z(1.0 - FA)$ and $z(M)$ both equal half the value for d'.

As the set point moves to the right the values for S become greater than 1.0 because $z(1.0 - FA)$ increases, making the numerator in Eq. (13.2) larger. Note that the shaded area representing False Alarms decreases, making the z-values larger. Simultaneously, the denominator decreases as the set point moves toward the mean for the Bad distribution. The shaded area in the Good distribution representing Misses increases, making the negative z-values smaller. Likewise, the value for S is less than 1.0 as the set point moves to the left of the point where the FA rate is equal to the Miss rate.

Any stimulus above this set point is called a signal, regardless of whether it is SN or only N. The set point, S, may be varied by the sorter, and a deliberate change in S results in differing Miss and False Alarm rates for an otherwise constant sorting system (no change in d'). A low value for S moves the vertical line to the left and indicates that an increasing amount of N is being accepted as SN, so $p(FA)$ is high and $p(M)$ is low. Such a tendency is termed a liberal criterion or bias. A high S moves the vertical line to the right, giving a low $p(FA)$ and a high $p(M)$ and is called a conservative criterion or bias. The inset in Fig. 13.3 shows the relationship between S and z-values, but is valid only for $d' = 2.92$ as shown.

Each pair of $p(M)$ and $p(FA)$ has a corresponding d' and S. For a particular system, d' is constant and all the values of $p(M)$ and $p(FA)$ will be on a curve for that value of d' (see relevant curves in Fig. 13.5). The position of points on a d' curve for a pair of $p(M)$ and $p(FA)$ values depends on the value of S. The system parameters d' and S thus are separated conveniently. The physical parts are encapsulated by the value of d' and the psychological factors are described by S (Table 13.2).

Analyses using SDT highlight the importance of determining the False Alarm rates in the assessment of any manual or automated sorting operation, which is rarely considered. The resulting detectability and set point values have several useful applications.

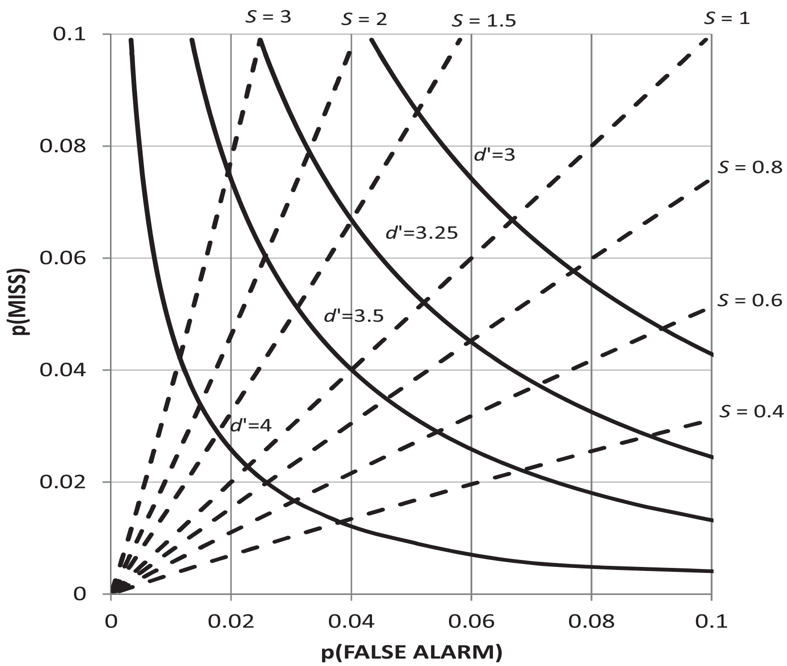


FIGURE 13.5 A section of receiver operating characteristic (ROC) plot with low values for p(FA) and p(H) that are common for sorting operations showing the contour lines for set points, *S*, (dotted curves) superimposed on a family of detectability curves, *d′* (solid curves).

TABLE 13.2 Calculation of *d′* (detectability) and *S* (set point).

Pack *Bad*	Remove *Bad*
Miss % = (5/**50**)100 = 10%	Hit% = (45/**50**)100 = 90%
Miss% shaded area ends at S line.	Miss% + Hit% = 100%
$z[p(0.1)]$ = NORM.S.INV(0.1) = − 1.28 z-units	
Pack *Good*	Remove *Good*
CA% = (190/**200**)100 = 95%	*FA%* = (10/**200**)100 = 5%.
50% on negative side and 45% positive side	*FA%* starts where *CA%* ends at (100% − *FA%*)
CA% + *FA%* = 100%	$z[p(1.0-0.05)]$ = NORM.S.INV(0.95)
CA% = (100% − *FA%*) At the end of *CA*	= +1.64 z-units
From Eq. (13.1): $d' = z[p(1.0-FA)] - z[p(M)] = [1.64] - [-1.28] = 2.92$ z units	
From Eq. (13.2): valid only when $d' = 2.92$ z units: $S = \{e\text{^}0.5(z[p(1.0-FA)])^2\}/\{e\text{^}0.5(z[p(M)])^2\} = \{e\text{^}0.5(1.64)^2\}/\{e\text{^}0.5(-1.28)^2\} = \{e\text{^}0.5(2.71)\}/\{e\text{^}0.5(1.64)\} = \{e\text{^}1.35\}/\{e\text{^}0.82\} = 3.87/2.27 = 1.70$ S units	

For the example data in Fig. 13.3 with a hypothetical sample that has 50 Bad items and 200 Good items. Values for z were calculated by Microsoft Excel using ⟨NORM.S.INV(probability)⟩ by entering the probability (decimal) in the brackets.

13.4.1.5 Physical design and operational parameters

The detectability, d', can be used to compare the design and operating characteristics of different sorting setups without a consideration of sorter bias. For example, *increasing d' is the only way to simultaneously avoid discarding good items and shipping bad items*. Various alterations and modifications of operating conditions or designs for a particular system also can be optimized by using real product to find the highest possible d' values.

The advantage of SDT over the other techniques of evaluating sorting operations, already discussed, is that d' can be determined without concern that a sorter's bias might vary during the trial or when changing to different physical equipment. However, the SDT analysis has some limitations. For example, product quality does have some effect on the sorting behavior as some defects are easier to identify than others.

13.4.1.6 Sorter criterion

By calculating S for a sorter, it is possible to determine whether that sorter has a conservative or liberal approach, which could serve as a useful management tool. A conservative approach prevails when the sorter only removes the worst product.

In a commercial operation, the objective usually is to maintain a consistent quality of the packed product. If the incoming product quality is poor, it is necessary for the Miss rate to be low (high Hit rate), whereas if the quality is good, a higher Miss rate is adequate. The sorters thus are required to vary their own criterion, depending on the incoming quality. Analysis of individual criterion values help determine how effectively each sorter is able to adjust.

13.4.1.7 Performance of automated sorting

There is a direct analog with SDT applications and sorting applications based on manual and automated image processing. Both are based on the ability to analyze a signal described by two nondimensional parameters, d' and β. The first parameter depends on the sensitivity of the sensor and the second represents adjustments that are possible for changing threshold values.

SDT should be useful in the analysis of automated sorting systems. As with manual sorting, it is possible to separate out the different aspects of the system. Detectability, d', is generally a measure of the physical design, including the illumination of the product, product speed and rotation, camera design and resolution, and the number of images captured. The set point, S, is predominantly a measure of the performance of the algorithm. There can be some interaction between the two parameters.

13.4.1.8 Systems analysis

SDT mathematically describes the relationship between Miss and False Alarm rates. The detectability of individual manual sorters can be compared with other sorters to determine if any have a d' lower than average. Remedies could include the following: obtain corrective lenses if visual acuity is low, transfer to other tasks if the sorter is color blind, increase illumination if needed by older sorters, place older sorters at the end of the sorting table where fewer items need sorted per minute, and replace lazy sorters if they are below average for FA rate and at the same time above average for Miss rate.

After a value of d' has been determined experimentally, it may be used in a model of the packinghouse to predict Miss and False Alarm rates. The analyst also has the ability to use S to vary the behavior of the sorters and predict the impacts of such changes on whole value chains. Another possibility is to use benchmarking where an independent evaluator measures d', S, and other conditions at several packinghouses. Anonymous results of analysis would be shared with all participants to enable them to compare their operations with others.

13.5 Economics of sorting operations

In many cases, the ability to predict performance of a sorting operation with SDT is useful for management operations on a daily basis. In addition, the usefulness of the model can be extended if it is possible to predict the economic value of potential changes. Models provide a useful tool during planning and design phases, as well as for managing an operation. Economic models are also necessary to evaluate the impact of different sorting scenarios.

One method of optimizing a sorting operation is using the sorting efficiency defined by Peleg (1985). Peleg's sorting efficiency requires the proportion of defective product to be known or estimated in both the incoming and the sorted product flows, and monetary values to be assigned to the various grades. The calculated efficiency is weighted according to product value and allows a comparison of various scenarios. The total value of sorted product, V, is calculated:

$$V = E_w T v \tag{13.3}$$

where T is the throughput sold (e.g., kg/h, t/season, and so forth), E_w is $p(CA)$, and v is the unit value of the product (e.g., \$/kg, \$/t). The returns, represented by total value, can be used in addition to the costs to evaluate various alternatives or used as part of a wider system model.

For any marketed product, there will be a payout schedule that is a function of the product amount that is defective. Therefore the higher the Hit rate, the better the returns (Fig. 13.6). Higher hit rates also reduce environmental impacts by not adding resources (packaging, cooling, transport, and others) to items that are discarded at the end of the chain. Every "False Alarm" represents a lost item; thus the value of returns decreases with increasing $p(FA)$.

For a predetermined payment schedule, a payout matrix can be established, as represented in Fig. 13.6. The payout must be established for a known incoming fruit quality to specify a Hit rate to produce the desired output quality. For example, for a required output quality of 95% good product, the sorter must maintain a Hit rate of 0.53 if 10% defects are incoming but must have a Hit rate of 0.92 if 40% are defects.

If the relationship between $p(FA)$ and $p(H)$ for a particular system is known, or can be determined, this information can be used to determine the relationships between the sorting operation and the returns for product sold, thus combining economic and operational parameters into the same model. The $p(H) - p(FA)$ relationship may be determined from historical data of sorter performance or it may be predicted using SDT.

For the example shown in Fig. 13.6, managers might want to know the consequences of advising their sorters to "reduce the number of good fruit in the reject bin" (reduce False Alarms) or "reduce the number of defects in the outgoing product"

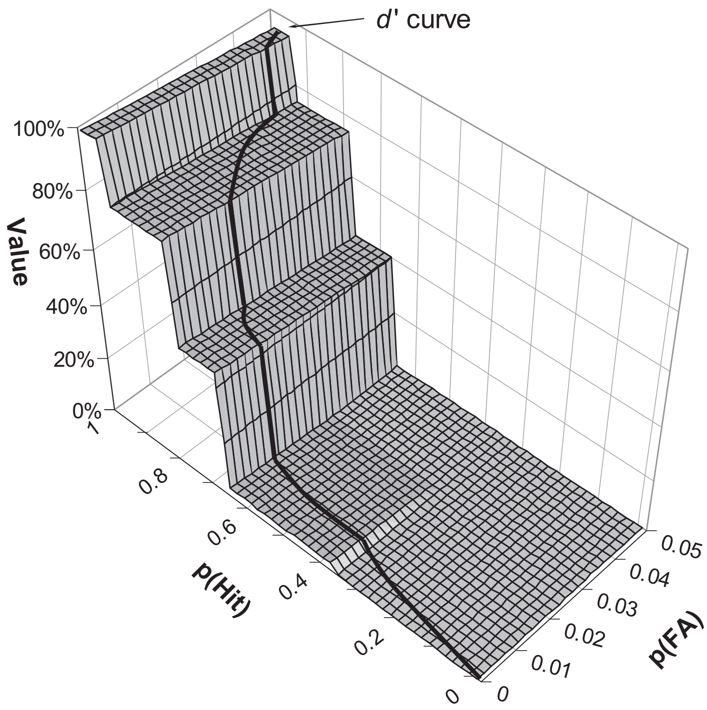


FIGURE 13.6 Example of a payoff matrix with receiver operating characteristic plot and d' curve superimposed.

(increase Hit rate). If the sorters concentrate on reducing good fruit entering the reject bin ($p(FA)$), the consequence will be an increase in the Miss rate of defective product; similarly, the consequence of reducing rejects passing into the final pack ($p(M)$) will be an increase in good fruit entering the reject bin. This situation, as previously discussed, is represented by changing values for set point, S, when moving along the d' line shown in Fig. 13.6.

If a buyer of quality product pays according to the following schedule

Grade I	$<$2% defects
Grade II	$<$10% defects
Grade III	$<$15% defects
Grade IV	$<$25% defects
Will not buy	$>$25% defects

and the packinghouse operator has incoming product with 35% defects, then sorters must achieve a Hit rate of 0.96 to ensure Grade I product, 0.79 for Grade II, 0.67 for Grade III, and 0.38 for Grade IV. Fig. 13.6 shows these Hit rates.

If the operation is maintaining an average Hit rate of 0.8, then, referring to Fig. 13.6, "a reduction in the number of good fruit in the reject bin" by lowering $p(FA)$ to 0.015 would result in a reduction of $p(H)$ to below 0.79. The payout schedule cutoff is represented by $p(H) = 0.79$; therefore any reduction in the False Alarm rate will result in a considerably lower return to the packinghouse.

The second scenario is to "reduce the number of defects in the outgoing product." If the Hit rate was increased to 0.9, the objective would be achieved. However, the increase in $p(H)$ will also result in an increase in False Alarms to above 0.02; thus the return to the packinghouse will be reduced by the loss of salable fruit. Any changes in the instruction to the sorters will result in a reduction in overall packinghouse returns in the illustrated situation.

An operator contemplating an upgrade for the system can benefit from applying SDT techniques. The expected performance of some new equipment is an increase in Hit rate from 0.82 to 0.95 at a False Alarm rate of 0.018. A new d' curve is established for the upgraded system and represents $p(H) = 0.92$ and $p(FA) = 0.02$. Then, if the sorters are suitably instructed, it is possible for the operator to achieve a Hit rate of over 0.95 at a False Alarm rate of 0.02. The change increases the value of the product and determines whether it is a sufficient return on the capital invested in the upgrade.

13.6 Summary

This chapter discusses the pivotal importance of the sorting operation to postharvest value chains. It outlines the approaches researchers have adapted in the past to analyze the operation and details some of their important recommendations. In addition, the chapter introduces new techniques that are being developed to enable the sorting operation to be described and understood in the context of the overall postharvest value chains.

References

Aleixos, N., Blasco, J., Navarron, F., & Molto, E. (2002). Multispectral inspection of citrus in real-time using machine vision and digital signal processors. *Computers and Electronics in Agriculture*, *33*(2), 121–137.

Azarmdel, H., Jahanbakhshi, A., Mohtasebi, S. S., & Muñoz, A. R. (2020). Evaluation of image processing technique as an expert system in mulberry fruit grading based on ripeness level using artificial neural networks (ANNs) and support vector machine (SVM). *Postharvest Biology and Technology*, *166*, Article 111201.

Balakrishnan, J. D., & MacDonald, J. A. (2011). Performance measures for dynamic signal detection. *Journal of Mathematical Psychology*, *55*, 290–301.

Blasco, J., Munera, S., Aleixos, N., Cubero, S., & Molto, E. (2017). Machine vision-based measurement systems for fruit and vegetable quality control in postharvest. *Measurement, modeling and automation in advanced food processing* (pp. 71–91). Cham: Springer.

Bollen, A. F. (1986). *Sorting fruit: Systems design and operation*. *Postharvest Manual*. Unpublished, New Zealand Agricultural Engineering Institute/Ministry of Agriculture and Fisheries. Hamilton, New Zealand.

Chaffin, D., Andersson, G.B.J. & Martin, B. (1999), Occupational biomechanics, (3rd ed.). New York, John Wiley & Sons, Inc.

Chavali, V. G. (2012). *Signal detection and modulation classification in non-Gaussian noise environments* (Ph.D. dissertation). Virginia Polytechnic Institute and State University, Blacksburg, VA. <https://vtechworks.lib.vt.edu/bitstream/handle/10919/28387/Chavali_VG_D_2012.pdf?sequence = 1&isAllowed = y> Accessed 17.12.20.

Cubero, S., Aleixos, N., Molto, E., Gomez-Sanchez, J., & Blasco, J. (2011). Advances in machine vision applications for automatic inspection and quality evaluation of fruits and vegetables. *Food Bioprocess Technology*, *4*, 487–504.

Cubero, S., Lee, W. S., Aleixos, N., Albert, F., & Blasco, J. (2016). Automated systems based on machine vision for inspecting citrus fruits from the field to postharvest—A review. *Food and Bioprocess Technology*, *9*(10), 1623–1639.

Du, C. J., & Sun, D. W. (2006). Learning techniques used in computer vision for food quality evaluation: A review. *Journal of Food Engineering*, *72*, 39–55.

Egan, J. P. (1975). *Signal detection theory and ROC analysis*. Orlando, FL: Academic Press.

Freeman, P. R. (1973). *Tables of d′ and BETA*. Cambridge: Cambridge University Press.

Goh, J. J., & Wiegmann, D. A. (2006). *Effects of automation failures during a visual inspection task on reliance and visual skill acquisition: A comparison between direct and indirect cueing*. (Technical Report HFD-06-06). Urbana-Champaign: Human Factors Division HFD, Institute of Aviation, University of Illinois. <http://citeseerx.ist.psu.edu/viewdoc/download?doi = 10.1.1.133.9668&rep = rep1&type = pdf> Accessed 01.03.21.

Graves, M., & Batchelor, B. G. (2003). *Machine vision for the inspection of natural products*. Springer-Verlag New York, Inc.

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York: John Wiley & Sons.

Guyer, D., Brown, G., Timm, E., Brook, R., & Marshall, D. (1994). *Lighting systems for fruit and vegetable sorting. Extension Bulletin E-2559*. Michigan State University.

Harvey, L.O. (2013). Detection theory: Sensory and decision processes. In: *Class notes for psychology of perception, psychology 4165-100, spring 2013*. University of Colorado, Boulder, CO.

Hautus, M. J., Van Hout, D., Lee, H. S., Stocks, M. A., & Shepherd, D. (2020). Observed discriminability is more variable than predicted by signal detection theory. *Food Quality Preference*, *79*, 103774.

Hunter, J. H., & Yaeger, E. C. (1970). Use of a float roll table in potato grading operations. In: *Maine agricultural experimental station bulletin* (No. 690). Orono, ME.

Iraji, M. S. (2019). Comparison between soft computing methods for tomato quality grading using machine vision. *Journal of Food Measurement and Characterization*, *13*(1), 1–15.

Ip, W. (2011) Designing for an Aging Population. Interface Vol. 1, Issue 2, pp 28-32. A Technical Publication Of The American Society of Safety Engineers.

Jahns, G., Moller-Nielsen, H., & Paul, W. (2001). Measuring image analysis attributes and modelling fuzzy consumer aspects for tomato quality grading. *Computers and Electronics in Agriculture*, *31*(1), 17–29.

Jaraiedi, M., Toth, G. J., Aghazadeh, F., & Herrin, G. (1986). Modeling of decision making behavior of inspectors. *Trends in Ergonomics III*, 351–357.

Karwowski, W., Szopa, A., & Soares, M. M. (2021). *Handbook of standards and guidelines in human factors and ergonomics* ((2nd ed.)). Boca Raton, FL: Taylor and Francis.

Kim, I. A., Hopkinson, A., Van Hout, D., & Lee, H. S. (2017). A novel two-step rating-based ’double-faced applicability’ test. Part 2: Introducing a novel measure of affect magnitude (d′A) for profiling consumers’ product usage experience based on Signal Detection Theory. *Food Quality and Preference*, *59*, 141–149.

Kim, I. A., Yoon, J. Y., & Lee, H. S. (2015). Measurement of consumers’ sensory discrimination and preference: Efficiency of preference-difference test utilizing the 3-point preference test precedes the same-different test. *Food Science and Biotechnology*, *24*(4), 1355–1362.

Kim, M. A., Van Hout, D., & Lee, H. S. (2018). Degree of satisfaction-difference (DOSD) method for measuring consumer acceptance: Comparative and absolute measures of satisfaction based on signal detection theory. *Food Quality and Preference*, *68*, 167–172.

Kleynen, O., Leemans, V., & Destain, M. F. (2005). Development of a multi-spectral vision system for the detection of defects on apples. *Food Engineering*, *60*(1), 41–49.

Kusabs, N. J., Trigg, L., Bollen, A. F., & Holmes, G. (2006). Objective measurement of mushroom quality relative to industry inspectors. *International Journal of Postharvest Technology and Innovation*, *1*(2), 189–201.

Lawless, H. T. (2013). Basics of signal detection theory. *Quantitative sensory analysis: Psychophysics, models and intelligent design* (p. 404) Hoboken, NJ: Wiley-Blackwell, Chapter 3.

Leemans, V., & Destain, M. F. (2004). A real-time grading method of apples based on features extracted from defects. *Food Engineering*, *61*(1), 83–89.

Leemans, V., Destain, M. F., & Magein, H. (2000). Quality fruit grading by colour machine vision: Defect recognition. *Acta Horticulturae*, *517*, 405–412.

Li, J. B., Zhang, R. U., Li, J. B., Wang, Z. L., Zhang, H. L., Zhan, B. S., & Jiang, Y. L. (2019). Detection of early decayed oranges based on multispectral principal component image combining both bi-dimensional empirical mode decomposition and watershed segmentation method. *Postharvest Biology and Technology*, *158*, 110986.

Liu, S. S., Chen, J., Melara, R. D., & Massara, F. (2008). Consumers’ product-locating behavior: Exploring the application of signal detection theory. *Psychology & Marketing*, *25*(6), 506–520.

Lopez-Garcia, F., Andreu-Garcia, G., Blasco, J., Aleixos, N., & Valiente, J. M. (2010). Automatic detection of skin defects in citrus fruits using a multivariate image analysis approach. *Computers and Electronics in Agriculture*, *71*, 189–197.

Mao, J., Vosoughi, A., & Carneya, L. H. (2013). Predictions of diotic tone-in-noise detection based on a nonlinear optimal combination of energy, envelope, and fine-structure cues. *Acoustical Society of America*, *134*(1), 396–406. Available from http://doi.org/10.1121/1.4807815, [Accessed 17.12.20].

Martín-Guerrero, T. L., Ramos-Álvarez, M. M., & Rosas, J. M. (2016). Payoff affects tasters' decisions but it does not affect their sensitivity to basic tastes. *Food Quality and Preference*, *48*(Part A), 11–16.

Meyers, J. B. (1988). *Improving dynamic visual inspection performance* (Master's thesis). University of Georgia, Athens, GA.

Meyers, J. B., Prussia, S. E., & Karwoski, C. J. (1990a). Signal detection theory for optimizing dynamic visual inspection performance. *Applied Engineering in Agriculture*, *6*(4), 412–417.

Meyers, J. B., Prussia, S. E., Thai, C. N., Sadosky, T. L., & Campbell, D. J. (1990b). Visual inspection of agricultural products moving along sorting conveyors. *Transactions of ASAE*, *33*(2), 367–372.

Miller, M. K., & Delwiche, M. J. (1989). A color vision system for peach grading. *Transactions of ASAE*, *32*(32), 1484–1490.

Miller, W. M., & Drouillard, G. P. (2001). Multiple feature analysis for machine vision grading of Florida citrus. *Applied Engineering in Agriculture*, *17*(5), 627–633.

Moreda, G. P., Ortiz-Canavate, J., Garcia-Ramos, F. J., & Ruiz-Altisent, M. (2009). Non-destructive technologies for fruit and vegetable size determination – A review. *Journal of Food Engineering*, *92*, 119–136.

Mun, J. W., Kim, M. A., Sim, H. M., & Lee, H. S. (2019). Investigation of test performance of the dual reminder A-Not A (DR A-Not A) in comparison to 3-AFC for discriminating samples of drinking water. *Food Quality and Preference*, *77*, 43–50.

Ngan, P., Penman, D. & Bowman, C. (2003). On-line automated visual grading of fruit: Practical challenges, In *Machine vision for the inspection of natural products*. Eds. M. Graves & B. Batchelor, Springer-Verlag New York, Inc. pp. 215–239.

Nicholson, J. V. (1985). *Colour and light for the inspection table* (SIRTEC Publication No. 1). New Zealand Department of Scientific and Industrial Research, Wellington, New Zealand.

Pasternak, H., Lidror, A., & Engel, H. (1989). The effect of the incidence of defect on orange inspection time. *Canadian Agricultural Engineering*, *31*(2), 131–134.

Peleg, K. (1985). *Produce handling, packaging, and distribution*. AVI, Westport, CT.

Phate, V. R., Malmathanraj, R., & Palanisamy, P. (2019). Classification and weighing of sweet lime (*Citrus limetta*) for packaging using computer vision system. *Journal of Food Measurement and Characterization*, *13*(2), 1451–1468.

Prussia, S. E., & Meyers, J. B. (1989). Ergonomics for improving visual inspection at fruit packinghouses. *Acta Horticulturae*, *258*, 357–364.

Prussia, S.E. (1985). Visually sorting at ergonomically designed workstations (ASAE Paper No. 85-1618) (p. 13). American Society of Agricultural Engineers, St. Joseph, MI.

Prussia, S.E. (1991). Dynamic visual inspection. In D. L. Roberts & W. L. Becker (Eds.), *Module 9 of human factors*. St. Joseph, MI: American Society of Agricultural Engineers.

Rosenberger, C., Emile, B., & Laurent, H. (2004). Calibration and quality control of cherries by artificial vision. *Journal of Electronic Imaging*, *13*(3), 539–546.

Ruiz-Altisent, M., Ruiz-Garcia, L., Moreda, G., Lu, R., Hernandez-Sanchez, N., Correa, E. C., . . . Garcia-Ramos, J. (2010). Sensors for product characterization and quality of specialty crops – A review. *Computers and Electronics in Agriculture*, *74*, 176–194.

Shearer, S. A., & Payne, F. A. (1990). Color and defect sorting of bell pepper using machine vision. *Transactions of the ASAE*, *33*(6), 2045–2050.

Shin, H. K., Hautus, M. J., & Lee, H. S. (2016). Unspecified duo-trio tests can be as powerful as the specified 2-AFC: Effects of instructions and familiarization procedures on cognitive decision strategies. *Food Research International*, *79*, 114–125.

Stevens, G. N., & Gale, G. E. (1970). Investigations into the feasibility of semi-automatic quality inspection of fruit and vegetables. *Journal of Agricultural Engineering Research*, *15*(1), 52–64.

Tanner, W. P., & Swets, J. A. (1954). A decision-making theory of visual detection. *Psychological Review*, *61*, 283–288.

Tilley, A. R., & Dreyfuss, H. (2002). *The measure of man and woman* (Revised ed.). New York: John Wiley & Sons, Inc.

Tillman, B., Fitts, D. J., Woodson, W. E., Rose-Sundholm, R., & Tillman, P. (2016). *Human factors and ergonomics design handbook* ((3rd ed.)). New York: McGraw-Hill, Inc.

Wu, D., & Sun, D. W. (2013). Colour measurements by computer vision for food quality control – A review. *Trends in Food Science and Technology*, *29*, 5–20.

Xing, J., & De Baerdemaeker, J. (2005). Bruise detection on 'Jonagold' apples using hyperspectral imaging. *Postharvest Bio and Technology*, *37*(2), 152–162.

Yang, Q. (1992). The potential for applying machine vision to defect detection in fruit and vegetable grading. *Agricultural Engineering*, *47*(3), 74–79.

Yaptenco, K. F., Angels, M. P., Esguerra, E. B., Serrano, E. P., Cho, M. A., & Choi, S. T. (2013). Nondestructive firmness measurement as a maturity index for 'Carabao' mango (*Mangifera indica L.*) fruit. *The Philippine Agricultural Scientist*, *96*(1), 55–65.

Zhang, B. H., Gu, B. X., Tian, G. Z., Zhou, J., Huang, J. C., & Xiong, Y. J. (2018). Challenges and solutions of optical-based nondestructive quality inspection for robotic fruit and vegetable grading systems: A technical review. *Trends in Food Science & Technology*, *81*, 213–231.

Zhang, Q. Y., Gu, B. X., Ji, C. Y., Fang, H. M., Guo, J., & Shen, W. L. (2017). Design and experiment of an online grading system for apple. *Journal of South China Agricultural University*, *38*(4), 117–124.

Zheng, C., Sun, D. W., & Zheng, L. (2006). Recent developments and applications of image features for food quality evaluation and inspection – A review. *Trends in Food Science and Technology*, *17*(12), 642–655.

Zhu, B., Jiang, L., & Tao, Y. (2007). Three-dimensional shape enhanced transform for automatic apply stem-end/calyx identification. *Optical Engineering*, *46*(1).

Further reading

Dreyfus, H. (1967). *Measurement of man: Human factors in design*. New York: Whitney Publications.

CHAPTER

14

Nondestructive evaluation: detection of external and internal attributes frequently associated with quality and damage

Bart Nicolaï, Bart De Ketelaere, Angel Dizon, Niels Wouters, Annelies Postelmans, Wouter Saeys, Tim Van de Looverbosch, Pieter Verboven and Maarten L.A.T.M. Hertog

Flanders Centre of Postharvest Technology / BIOSYST-MeBioS, KU Leuven, Leuven, Belgium

Abbreviations

AOTF	Acousto-optical tuneable filters
APCI	Atmospheric pressure chemical ionization
BOP	Bulk optical properties
CCD	Charge coupled device
CFA	Color filter array
GC-MS	Gas chromatography – mass spectrometry
HCS	Hue, chroma, saturation
HFMS	Headspace fingerprint mass spectrometry
HPLC	High pressure liquid chromatography
IMS	Ion mobility spectroscopy
InGaAs	Indium gallium arsenide
LCTF	Liquid crystal tuneable filters
LED	Light emitting diode
LPLS	Local least Squares regression
LS-SVM	Least squares support vector machines
LWR	Locally weighted regression
MC	Monte Carlo
MEMS	Microelectromechanical systems
MLR	Multiple linear regression

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00014-2

MRI	Magnetic resonance imaging
NIR	Near infrared
NMR	Nuclear magnetic resonance
PCR	Principle components regression
PLSR	Partial least squares regression
RGB	Red green blue
RMSEP	Root mean squared error of prediction
SEP	Standard error of prediction
SIFT-MS	Selected ion flow tube mass spectroscopy
SPME	Solid phase micro-extraction
SRS	Spatially resolved spectroscopy
SSC	Soluble solids content
ToF	Time of flight
TRS	Time resolved spectroscopy
TSS	Total soluble solids content
X-ray CT	X-ray computed tomography

14.1 Introduction

While most commercial quality classification systems for fruit and vegetables are based on external aspects (color, size, absence of blemishes, etc.), there is an increasing interest toward incorporating internal quality attributes as well. Consumers now demand fruit and vegetables that not only look nice but also taste well, have an appropriate texture, are free of contaminants, and contain sufficient nutritional and health-promoting substances. Until recently, destructive techniques were used to measure these properties. An obvious disadvantage of such techniques is that the fruit is lost after the measurement, so that only quality inspection at the batch rather than at the individual fruit level is feasible. However, during the last decade, several novel systems have been developed to measure quality attributes nondestructively. Several of them are now commercially available as desktop unit or mounted on a grading line so that quality control of individual fruit becomes feasible. Additional advantages are the fact that no sample pretreatments are required for nondestructive techniques, the absence of waste after the measurement, and often the measurement speed.

The objective of this chapter is to give an overview of some recent developments in nondestructive quality measurements. We will focus on systems to measure external appearance, internal defects, firmness, taste, and aroma.

14.2 External appearance

The external appearance is the main quality aspect each consumer is confronted with when buying food products. Historically, human perception of the product's appearance has been the main "instrument" to qualify aspects like color, blemishes, gloss, shape, and size. The main developments seen in assessing visual quality at links in supply chains are related to moving away from subjective qualitative consumer evaluation by developing objective quantitative instrumental techniques. The first step was the introduction of color charts and other reference charts to standardize the evaluation process. The next step was the development of instrumental techniques such as colorimeters to replace human vision. An additional benefit of introducing such quantitative instrumental techniques is that the quality attributes can be interpreted as continuous variables that allow the use of increasingly sophisticated statistical and numerical modeling techniques to analyze and interpret the data (Hertog, Lammertyn, Ketelaere, Scheerlinck, & Nicolai, 2007).

14.2.1 Color

As observation of objects at ambient temperatures relies on the reflection or transmission of incident radiation by the object, the color perceived is not only related to the nature of the object itself but also to the nature of the incident illumination.

The reflection and transmission of light by an object is determined by its chemical and physical properties.

- *Chemical:* Molecular building blocks (pigments) of an object can exhibit specific color absorbing or reflecting properties. For example, the greenness of a leaf is caused by the presence of chlorophyll, which absorbs both blue and red lights.
- *Physical:* Physical structures (e.g., cell walls, air pores, particle size) determine how objects scatter (refract/reflect) photons. This influences the effective path traveled by photons. For example, the blue color of the sky is a direct effect from light scattering in the upper atmosphere, while finely ground coffee powder appears lighter in color than roughly ground powder.

Moreover, there also exists interaction between these effects: a longer path length due to scattering increases the chances for light absorption, altering the appearance of the objects.

Apart from the properties of the object, the perceived color is also determined by the spectral properties of the light source illuminating the object. If a certain color is not present in the incident light, it cannot be reflected or transmitted by the object. This explains why the color of the same object may be perceived differently in bright daylight or under artificial light.

The human eye has three types of color receptor cells (cones) that are sensitive to wavelength bands that match roughly with red, green, and blue colors. The signals from these color receptor cells are processed by the brain to three color properties: hue, saturation, and intensity (or brightness). This allows us to perceive compound colors (e.g., brown) that cannot be directly linked to a single physical wavelength of light. On the other hand, different reflectance spectra may be perceived as the same color.

Objective measurement of the color of fruit and vegetables thus requires a combination of a calibrated light source with known emission spectrum and a detector that can measure the three basis colors (RGB—red, green, blue) or a full spectrum in the visible range from 400 to 780 nm. Trichromatic colorimeters and spectrophotometers are commercially available to take single spot color measurements under standardized lighting conditions expressing color in units of one of the standardized color spaces (ASTM, 2000). The L*a*b* color space and the hue, chroma, saturation color space are widely used in quality inspection of fruit and vegetables. These colorimeters and spectrophotometers are still widely used in quality labs. Nowadays, machine vision systems that measure the RGB values for every pixel on the product's surface using digital cameras are now widely adopted for on-line sorting of fruit and vegetables. Apart from measuring every product, these systems also provide information on the spatial distribution of the color properties over the product surface (Wu & Sun, 2013). In this configuration images can be rapidly processed and used for online color/ripeness sorting systems (Blasco, Munera, Aleixos, Cubero, & Molto, 2017; Cubero, Lee, Aleixos, Albert, & Blasco, 2016) if the system has been calibrated carefully. Almost all manufacturers of sorting lines now provide online color inspection stations.

Recently, hyperspectral imaging systems have begun to move from lab environments to industry as these cameras are becoming increasingly more affordable and faster. Thanks to the use of multivariate calibration methods, this technology can be used for more accurate color measurements than those obtained with the RGB camera systems (van Roy, Keresztes, Wouters, De Ketelaere, & Saeys, 2017). As will be discussed in Section 15.5.2, this technology also enables a host of new applications besides color grading.

14.2.2 Blemishes

"Blemish" is an umbrella term that can refer to many types of defects in (fresh) food products including rots, bruises, flyspecks, scabs and molds, fungal diseases, and soil contaminations. (Mehl, Chen, Kim, & Chan, 2004; Nicolaï et al., 2014).

Human inspection of food products is slow, laborious, and expensive as well as prone to errors. Ongoing research and developments in vision technology have enabled nondestructive, robust detection of blemishes. This allowed an evolution from sample-based inspection to inspection of all products. The basic principle of these inspection techniques is to take multiple monochromatic images of the food objects at different wavelengths and to search for those wavelengths at which the blemish of interest shows a characteristic absorption behavior different from the unblemished tissue. By combining data for different wavelengths using multivariate techniques the detection of blemishes can be further improved. Bhargava and Bansal (2018) reviewed applications of machine vision to fruit and vegetables. More recently, detection techniques have been developed that can even detect subskin defects such as bruises before these become apparent to humans (Du et al., 2020; Keresztes et al., 2017; López-Maestresalas et al., 2016; Xing et al., 2005) by application of hyperspectral camera sensors that exploit specific wavelengths linked to the appearance of the defect in both the visible (400–700 nm) and the near-infrared radiation (NIR) (700–2500 nm) range of the electromagnetic spectrum. These techniques can for instance be applied in a processing line but could also be adopted in a robotic harvesting systems (Bulanon, Kataoka, Ota, & Hiroma, 2002; Gao et al., 2020; Halstead, McCool, Denman, Perez, & Fookes, 2018; van Henten, 2019).

14.3 Firmness

Firmness is traditionally measured by means of a Magness–Taylor (MT) penetrometer. The penetrometer test simulates the mastication of fruit tissue in the mouth, and the MT firmness incorporates several mechanical properties, including the elastic, shear, and rupture properties, of the fruit tissue. The test is to some extent sensitive to the operator, and the MT firmness may be position dependent. The search for an alternative nondestructive firmness procedure for horticultural products has resulted in several techniques that allow using the same principles under laboratory and on-line conditions (De Ketelaere, Lammertyn, Molenberghs, Nicolai, & De Baerdemaeker, 2003). Among different technologies developed, sensors based on low-mass impact and the acoustic impulse response are commercially available and most widely used. Those are briefly discussed later.

14.3.1 Impact analysis

Impact analysis is a simple and quick method for determining local fruit properties. De Baerdemaeker, Lemaitre, and Meire (1982) and Rohrbach, Franke, and Willits (1982) made efforts to use either time domain or frequency domain characteristics of the impact force as a firmness indicator for a wide variety of fruit and vegetables. Nahir, Schmilovitch, and Ronen (1986) reported that the characteristics of the impact response of dropping tomatoes on a rigid surface are highly correlated with both fruit weight and fruit firmness. Delwiche, Mcdonald, and Bowers (1987) found that impact characteristics derived from the time signal of peaches striking a rigid surface were highly correlated with the elastic modulus and penetrometer values of the fruit. A problem inherent to this technique is the fact that impact characteristics are highly dependent on the mass and radius of curvature of the fruit. A large variation in those parameters affects the accuracy of the technique. A different approach was suggested by Chen, Tang, and Chen (1985) who impacted the fruit with a small spherical impactor of known mass and radius of curvature. The deceleration of the impactor was related to fruit firmness (Chen & Ruiz-Altisent, 1996; Chen et al., 1985; Garcia-Ramos et al., 2003). The advantage of this technique is that the impact response is independent of the fruit mass and less sensitive to its radius of curvature. The technique was further investigated for a wide range of fruit by Jaren, Ruiz-Altisent, and Perez de Rueda (1992), Correa, Ruiz-Altisent, and de la Plaza (1992), Hernández et al. (2005), Molto, Selfa, Pons, and Fornes (1996), and Ragni, Berardinelli, and Guarnieri (2010). De Ketelaere, Ruiz-Altisent, Correa, De Baerdemaeker, and Barreiro (2001, 2006a) used this technique to analyze apples and tomatoes and compared results to acoustic measurements that are discussed next.

14.3.2 Acoustic impulse response measurements

The analysis of the acoustic fruit response to mechanical impulse in the frequency domain detects internal properties of the whole fruit, including firmness (Abbott, Bachman, Childers, Fitzgerald, & Matusik, 1968; Cooke, 1972; De Ketelaere et al., 2001; De Ketelaere, Stulens, Lammertyn, Cuong, & De Baerdemaeker, 2006b; Finney & Norris, 1968; Shmulevich, Galili, & Rosenfeld, 1996). Excitation of the fruit can be performed by a shaker (Peleg, 1993) or by impact excitation (Schotte, De Belie, & De Baerdemaeker, 1999). The fruit's response can be captured by an accelerometer (Peleg, 1993), a piezoelectric sensor (Galili, Rosenhouse, & Mizrach, 1993), or a microphone (De Ketelaere et al., 2004). A computer that is connected to the transducer derives the frequency response spectrum from the time domain signal by means of a fast Fourier transform. A firmness index $F = f^2 m^{2/3}$ is typically calculated, where f is the first resonance frequency (Hz) and m is the mass of the fruit (kg) (Schotte et al., 1999).

The resonant frequencies and dynamic behavior of simply shaped objects (sphere, axisymmetric spheroid) are understood well, and several studies have been carried out on various kinds of near-spherical agricultural objects such as apples (Chen & Baerdemaeker, 1993), peaches (Verstreken & De Baerdemaeker, 1994), melons (Chen, Baerdemaeker, & Bellon, 1996), and tomatoes (Langenakens, Vandewalle, & De Baerdemaeker, 1997). However, if the fruit shape is far from spherical, as in pears, Jancsók, Clijmans, Nicolaï, De, and Baerdemaeker (2001) have shown that an adapted firmness index that includes also a measure of shape S (e.g., the length/diameter ratio) is more appropriate:

$F = \frac{1}{aS + b} f^2 m^{2/3}$ where a and b are constants. As the authors have only considered Conference pears, it is not clear whether the constants a and b depend on the species/cultivar.

As the firmness index is related to the elastic properties of the fruit only, it is fundamentally different from the MT firmness. This is illustrated in Fig. 14.1, where the firmness index of tomato fruit is shown versus the compression force and the MT firmness (Hertog, Ben-Arie, Róth, & Nicolaï, 2004). The compression force (force required to compress the tomato fruit over a well-defined distance) essentially measures the elastic properties, and a relatively good relationship with the firmness index was obtained (Fig. 14.1A). On the other hand, a poor relationship was obtained between firmness index and MT firmness (Fig. 14.1B). Shmulevich, Galili, and Howarth (2003) compared an MT penetrometer, a commercially available low-mass impact device, and an acoustic device for apple firmness evaluation. They found that the correlation between low-mass impact and acoustic firmness sensing was reasonably high ($r = 0.83-0.93$), while correlations with MT were low ($r = 0.43-0.60$). Golding et al. (2005) also reported moderate correlations between MT and nondestructive sensor technologies ($r = 0.62$ for an acoustic sensor and 0.82 for a low-mass impact sensor). Similar conclusions were drawn by Valero, Crisosto, and Slaughter (2007). De Ketelaere et al. (2006a) compared a commercial low-mass impact sensor to a commercial acoustic sensor and reported that the acoustic sensor is preferable for firm products, while for soft products, the low-mass impact sensor has its advantages. The lack of comparisons between techniques together with the different physical backgrounds and related units are the main reasons obstructing the rapid adoption of nondestructive firmness sensors in industry and among postharvest researchers.

Considering the commercial availability of these nondestructive sensors nowadays, and the proof of their ability to sense firmness and firmness changes of fruit with very different properties, the time might have come to consider those nondestructive techniques as new standards for fruit firmness evaluation replacing the older destructive standard. However, to overcome the issues of comparison of technologies, there is a clear need for standardization of nondestructive firmness sensing of fruit and vegetables (De Ketelaere et al., 2006a).

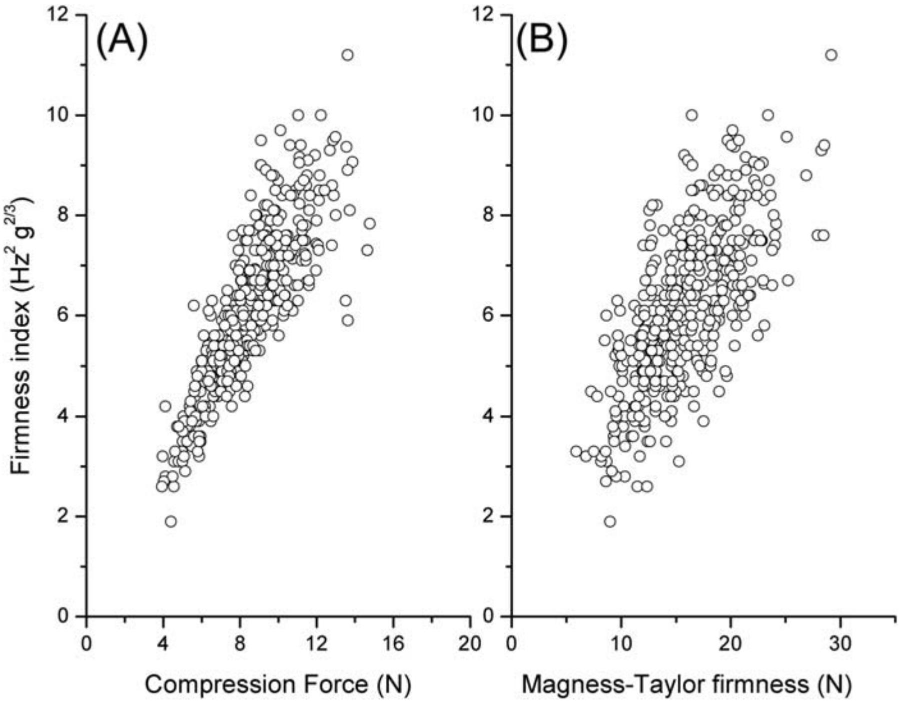


FIGURE 14.1 Firmness index versus compression force (A) and Magness–Taylor firmness (B) for tomato fruit Hertog et al. (2004). Source: *Data from Hertog, M. L.A.T.M. Ben-Arie, R. Róth, E. & Nicolaï, B.M. (2004). 'Humidity and temperature effects on invasive and non-invasive firmness measures'. Postharvest Biology and Technology*, 33, *79–91.*

14.4 Taste components

Taste is defined as the sensation perceived through the tongue when exposed to certain classes of chemicals. Receptors have been identified for at least five taste attributes: sweet, acid, salt, bitter, and umami. The latter attribute represents "savoriness," which is related to the presence of glutamates. In fruit, sweetness and acidity are the most important taste attributes. In vegetables, other attributes may be important as well.

Taste attributes are typically measured through refractometry (sweetness), titration (acidity), high pressure/performance liquid chromatography (bitter and umami components), and atomic absorption (salts). These techniques all require destructive sampling. Nondestructive techniques for taste components are often based on the interaction of fruit or vegetable tissue with NIR radiation (wavelength range from 780 to 2500 nm).

14.4.1 Near-infrared spectroscopy

In NIR spectroscopy, fruit or vegetables are irradiated with NIR light in the wavelength range from 780 to 2500 nm. The interaction of the light with biological tissues is governed by wavelength-dependent reflection, absorption, and scattering of the incident light. NIR

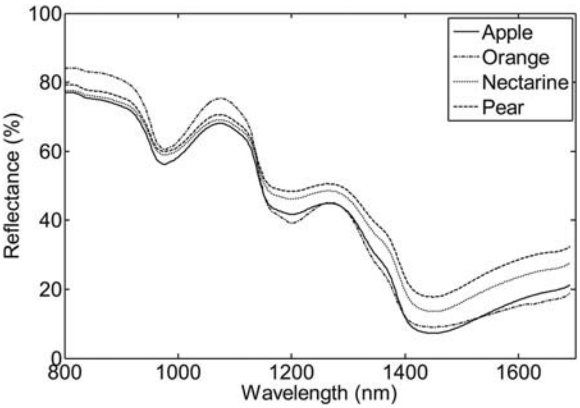


FIGURE 14.2 Typical NIR reflectance spectra of some fruit. The NIR reflectance spectra were recorded using a Corona 45 VIS/NIR diode array spectrophotometer (Carl Zeiss Jena Gmbh, Jena, Germany). *NIR*, Near-infrared radiation; *VIS/NIR*, visible and near-infrared radiation. Nicolaï et al. (2007) Source: *Reprinted from Nicolaï, B.M. Beullens, K. Bobelyn, E. Peirs, A. Theron, K. I. & Lammertyn, J. (2007). 'Nondestructive measurement of fruit and vegetable quality by means of NIR spectroscopy', Postharvest Biology and Technology*, 46, *99–118, with permission from Elsevier.*

spectra can be measured in either reflection, transmission, or interactance (partial transmission) mode and contain a characteristic signature caused by the chemical and microstructural composition of the fruit (Walsh, Blasco, Zude-Sasse, & Sun, 2020). Light absorption is related to chemical composition (water, sugar, acids), because chemical bonds absorb light at specific wavelengths corresponding to the energy level that matches their vibration modes. The visually most clear characteristic in NIR spectra of biological products is the absorption by water. The contributions by other chemical constituents such as sugars or acids are more subtle, and moreover, different broad absorption peaks can overlap. Light scattering, on the other hand, is related to the microstructural composition of a fruit, that is, its texture. Spatial variations in refractive index caused by air pores or cell walls cause photons to deviate from a straight path and being scattered in different directions. Typical NIR reflectance spectra for some fruit are shown in Fig. 14.2.

The combined effect of absorption and scattering causes NIR radiation to have a limited penetration depth in fruit and vegetables. On an intact fruit, the effective path length through the fruit is in the order of magnitude of millimeters or centimeters, with denser tissues having a more limited penetration depth (Walsh et al., 2020). For example, Lammertyn, Aerts, Verlinden, Schotsmans, and Nicolaï (2000a) and Lammertyn, Peirs, De Baerdemaeker, & Nicolai (2000b) found a penetration depth of up to 4 mm in the 700–900 nm range and between 2 and 3 mm in the 900–1900 nm range for apple. In a different optical configuration and based on a different definition of penetration depth, Fraser, Kunnemeyer, McGlone, and Jordan (2001) showed that the penetration depth in apple in the 700–900 nm range was at least 25 mm, while it became less than 1 mm in the 1400–1600 nm range. This poses challenges when measuring fruit with a thick outer layer, such as citrus or melon (Sun, Aernouts, Van Beers, & Saeys, 2020a). Measuring with a higher light intensity can help, but one should be careful not to damage (burn) the sample.

To model the relationship between NIR spectra and the quality attributes of interest, advanced statistical modeling (chemometrics) is required (Nicolaï et al., 2007; Saeys, Do Trong, Van Beers, & Nicolaï, 2019; Walsh et al., 2020). The most popular multivariate data analysis techniques for calibration model building are linear multivariate regression methods, ranging from multiple linear regression to principal component regression and partial least squares regression. Generally, the latter two result in more stable calibrations, because the original wavelengths are transformed into new, less correlated components. More recent developments include the use of nonlinear regression methods such as local least squares regression, locally weighted regression, kernel-based methods, or least squares support vector machines (Saeys et al., 2019).

A drawback of NIR spectroscopy is that the calibration models are species and variety specific and have to be built on a large set of representative fruit or vegetables. Moreover, calibration models are also affected by other factors such as the type of instrument, temperature, seasonal effects, orchard, or cultivating system (Bobelyn et al., 2010; Peirs, Scheerlinck, & Nicolaï, 2003a; Peirs, Tirry, Verlinden, Darius, & Nicolaï, 2003b; Saeys et al., 2019). These "unwanted" variations make it challenging to compare the performance of different instruments and to transfer calibration models between instruments, even two of the same type (Lu, Van Beers, Saeys, Li, & Cen, 2020). Strategies for the transfer of calibration models can comprise to include known sources of variation in the calibration set, modifying the new spectra, or updating the calibration model (Fearn, 2001; Saeys et al., 2019).

NIR spectroscopic applications for determining taste components of horticultural products mainly focus on predicting the total soluble solid or soluble solids content (SSC) related to the sugar content in % Brix and acidity. For example, SSC predictions are described for apple (Luo et al., 2018), watermelon (Tian, Ying, Lu, Fu, & Yu, 2007), peaches (Mukarev & Walsh, 2012), pear (Li, Huang, Zhao, & Zhang, 2013), blueberries (Bai, Yoshimura, & Takayanagi, 2014), and mandarin (Masithoh, Haff, & Kawano, 2016). Although more difficult to predict than SSC, reports can also be found on the prediction of firmness of apples (Bobelyn et al., 2010; Fan, Zha, Du, & Gao, 2009; Van Beers et al., 2015), pH and moisture content of apples (Dong & Guo, 2015), and total acid content in grapes (Chauchard, Cogdill, Roussel, Roger, & Bellon-Maurel, 2004). More elaborated overviews of NIR application for prediction of fruit and vegetable quality can be found in the reviews by Nicolaï et al. (2007, 2014), Cattaneo and Stellari (2019), and Cortés, Blasco, Aleixos, Cubero, and Talens (2019).

NIR solutions are suitable for implementation on fruit grading lines, providing direct results on the fruit quality. However, measuring in-line poses specific challenges, such as measuring on moving fruit with varying size and shape, obtaining a representative view (multiple measurement points) and robust models with low processing time (Cortés et al., 2019). Scientific literature contains numerous prototypes of in-line NIR systems (Cortés et al., 2019). Commercial systems are for example available from Greefa (Holland), Tomra (Norway), Multiscan Technologies (Spain), Aweta (Holland), MAF RODA Agrobotics (France), Sacmi (Italy), and Unitec (Italy) (Walsh et al., 2020).

Recent technological developments have allowed NIR sensors to become more compact thanks to the integration of microelectromechanical systems and the integration of dispersive elements on chips. Moreover, the price of indium gallium arsenide detectors has reduced and less heat-emitting lights sources such as light-emitting diodes are being used (Walsh et al., 2020). Therefore the number of portable NIR spectrophotometers available on the market has increased. Hand-held devices allow measurements in the field, on the work floor, or even by consumers. Some examples of portable NIR spectrometers are: Thermo-Fisher Scientific (MicroPHAZIR), VIAVI (MicroNIR), Texas Instruments (DLP NIRscan Nano EVM), Spectral

Engines (NIRONE), Felix Instruments (F750), Si-Ware Systems (NeoSpectra), Fantec (FQA NIRGun), Integrated Spectronics (Nirvana), Sacmi (Walsh et al., 2020, Yan & Siesler, 2018).

14.4.2 Multi and hyperspectral imaging systems

Apart from the large variability in the chemical and physical quality properties between products, there may also be considerable variability within a food product (e.g., local variation in SSC, starch, or the presence of defects affecting taste). For example, Peiris, Dull, Leffler, and Kays (1999) observed a circumferential variation of up to 2% Brix for the SSC in a variety of fruit; the radial and proximal to distal variation was even larger. This spatial variability is hard to capture with point-measurement techniques such as spectrophotometers. On the other hand, camera vision systems can provide spatial information but lack the spectral resolution to quantify these components.

In recent years, huge strides have been made in the field of spectral imaging, adding a spatial component to the traditional spectral point measurements. This progress first started in laboratory-based research but has recently also found its way into industry, thanks to improvements in both quality, measuring speed, and affordability of spectral imaging sensors.

Over the years, multiple imaging techniques have been developed to simultaneously capture images at few (multispectral) or many (hyperspectral) spectral bands (Ravikanth, Jayas, White, Fields, & Sun, 2017; Yuzhen, Wouter, Moon, Yankun, & Renfu, 2020):

- *Whiskbroom systems:* The simplest configuration to acquire a hyperspectral image is by sequentially acquiring a spectrum for every pixel on the product surface with a spectrophotometer. While this provides very high-quality spectral information, it is very time consuming and therefore only used in research.
- *Line scan systems:* These traditional hyperspectral imagers find their origin in the field of remote sensing. These sensors capture light reflected by a narrow spatial line on an object and split this into spectral components by means of a grating or prism. By moving the product under the imager (e.g., on a conveyor belt) or the imager over the product (e.g., satellite over the earth), spatial-spectral images can be acquired line by line (pushbroom principle).
- *Tunable filters* (i.e., liquid crystal or acousto-optic): These devices can be tuned to generate a custom spectral bandpass filter. When mounted in front of a camera, sequential images of multiple wavebands can be captured. However, this requires that the product is held still during the sequential scanning, which is not compatible with sorting lines.
- Multispectral imagers:
  - *Bandpass imagers:* A traditional camera in front of which traditional bandpass filters are moved to capture multiple spectral colors sequentially.
  - *Multi-charge coupled device (CCD) imagers*: Cameras that use multiple CCD (3−5) sensors and advanced optics to split different spectral components over the different detectors. Alternatively, different CCD chips can be installed side by side and their resulting images are then mapped to the same reference frame.
- *Tuned color filter arrays:* Similar to traditional RGB imagers, these types of cameras have a color filter superimposed on top of each pixel that only accepts photons of specific wavelengths. For a long time, only a limited number of spectral filters could be placed

on a single chip (e.g., RGBNIR cameras). However, in recent years, hyperspectral variants have been developed including 16−25 spectral bands in each superpixel. By implementing the color separating mechanism directly on the camera chip, this type of camera system is faster (sensitive to lower levels of incident light) and more robust than the traditional imagers described earlier, facilitating industrial implementation (Geelen, Blanch, Gonzalez, Tack, & Lambrechts, 2015; Saari et al., 2009).

- *Illumination based:* Multi- and hyperspectral imaging can also be achieved by means of custom illumination capable of switching between many (narrow) color bands (Carstensen, 2018; Wallays, Missotten, De Baerdemaeker, & Saeys, 2009). A traditional grayscale camera, sensitive in the appropriate spectral region, can then be used to capture multiple wavebands sequentially.

Hyperspectral systems have high spectral resolution (10−100 s of spectral bands) and thus have a wide applicability. Multispectral imagers can be tuned to specific problems by proper filter selection and can (generally) achieve higher acquisition speeds and spatial resolution than their hyperspectral counterparts.

For most applications, hyperspectral imaging needs to be accompanied with proper processing tools to develop high-quality, robust calibration, and classification tools. Traditionally, multivariate analysis techniques were used to construct regression models and classifiers (Saeys et al., 2019) in combination with traditional image processing tools. With the recent rise in popularity of convolutional neural networks and other deep learning techniques in computer vision, research has also been conducted to combine this with hyperspectral imaging. This allows to combine the spectral and spatial processing steps in one step, thus making more direct use of spatial patterns in the hyperspectral source data (Signoroni, Savardi, Baronio, & Benini, 2019; Zhou, Zhang, Liu, Qiu, & He, 2019).

Multi- and hyperspectral systems have been used to measure and visualize (taste-related) quality parameters of fruit and vegetables. Martinsen and Schaare (1998) were the first to do this for the SSC distribution in kiwi fruit. Since then, many studies have been conducted on a multitude of fruit and vegetable products to measure the spatial distribution of quality parameters, for example, on apple and mango (Liu et al., 2020; Rungpichayapichet et al., 2017).

14.4.3 Spatially and time resolved spectroscopy

In classical NIR spectroscopy, calibration models link light absorption characteristics to the chemical composition of fruit. The effect of light scattering on the spectra is often regarded as interfering and therefore removed by data preprocessing. However, light scattering is related to textural aspects and fruit porosity (Wang et al., 2020). Instead of discarding this information, one can try to separate the absorption and scattering effects by deriving the bulk optical properties (BOP) from reflectance and/or transmittance spectra, rather than a direct analysis of the spectra (Lu et al., 2020). Several authors have reported on the separation of the absorption and scattering properties of fruit and vegetables (Lu et al., 2020; Sun, Beers, Aernouts, & Saeys, 2020b; Tu, Jancsok, Nicolaï, & De Baerdemaeker, 2000; Van Beers et al., 2017). Since the chemical and microstructural composition of fruit are differently affected by maturation, ripening, and disorders, considering both the absorption and scattering behavior can contribute to an improved spectroscopic determination of quality attributes. However, the presence of an outer layer can complicate the BOP determination of sublayer tissues (Saeys, Velazco-Roa, Thennadil, Ramon, & Nicolaï, 2008; Van Beers et al., 2017).

Two popular measurement techniques are *spatially resolved reflectance spectroscopy* (SRS) and *time domain reflectance spectroscopy* (TRS). Both SRS and TRS combine multiple measurements on the same fruit, respectively, separated in space or time. To extract the BOP from the measured spectra, the diffusion approximation of the radiative transfer equation is often used (Lu, 2016). However, this requires scattering to be dominant over absorption in the tissue, which is often not the case in horticultural products. Other methods to extract the BOP are Monte Carlo simulations (although far more computationally intensive and time consuming) or building a stochastic data-based metamodel (Aernouts et al., 2015; Watté et al., 2013).

SRS makes use of the glow spot that appears upon illumination of a fruit with narrow beam illumination. Due to the interaction of the photons with the fruit tissue, the glow spot is larger than the initial spot of incident illumination and the intensity decreases with increasing distance from the center. In fiber-probe SRS, broadband light is guided to the sample by an optical fiber and the diffusely reflected light is collected at different distances by an array of optical fibers (Nguyen Do Trong et al., 2014). As this fiber probe requires contact with the sample, it is more suitable for liquid samples like juices than for solid samples. Therefore alternative configurations for contactless SRS have been proposed. In hyperspectral scatter imaging, the sample is illuminated by a focused beam of broadband light and the spatially resolved diffuse reflectance spectra are acquired with a multispectral or hyperspectral camera (Aernouts et al., 2015; Qin & Lu, 2008; Qin, Lu, & Peng, 2009). Another contactless configuration involves the combination of a wavelength-tuneable laser with a panchromatic camera (Van Beers et al., 2015). SRS has been used for the nondestructive determination of quality attributes like SSC, firmness, and ripeness of different fruit types, such as apples (Mollazade & Arefi, 2017; Nguyen Do Trong et al., 2014; Van Beers et al., 2015), pear (Adebayo et al., 2017), peach (Cen, Lu, Mendoza, & Ariana, 2012) and tomatoes (Huang, Lu, Hu, & Chen, 2018; Zhu, He, Lu, Mendoza, & Cen, 2015). While the successes in predicting firmness from the scattering properties has so far been limited, good results were obtained in predicting the porosity of apples (Wang et al., 2020).

In TRS, a series of very short NIR light pulses (pico- or femtosecond) is directed into the fruit. Depending on the amount of absorption and scattering in the tissue, a fraction of the photons will reach a detector, located at a certain distance from the point of illumination. Recording the travel time of all photons results in a photon time of flight distribution from which the BOP can be calculated, e.g., using diffusion theory. TRS sensor configurations can include single wavelength, multiwavelength, or broad spectral illumination (Rizzolo & Vanoli, 2016). TRS has for example been used to assess the SSC and firmness of pear (Nicolaï et al., 2008) and kiwi fruit (Valero et al., 2004), the maturity and softening of mango (Eccher Zerbini et al., 2015; Pereira et al., 2010), or internal defects in apple (Vanoli, Rizzolo, Eccher Zerbini, Spinelli, & Torricelli, 2009), pear (Eccher Zerbini, Grassi, Cubeddu, Pifferi, & Torricelli, 2002), and plum (Vangdal et al., 2012). Recently, the potential of TRS and SRS for quality evaluation on apples has been compared by measuring the same "Braeburn" apples after ripening in shelf life with both techniques. Although TRS probes deeper into the fruit flesh to a depth of around 1 cm, both techniques were able to follow the ripening process. The scattering information measured by TRS and SRS were found to correlate in a similar way to the porosity and texture of the flesh (Vanoli et al., 2020).

14.5 Aroma

Aroma, which together with taste is making up flavor, is a crucial quality attribute of most produce. Fruit and vegetables are composed of a great variety of aroma compounds that can be directly sensed through the nose (orthonasal) or after release through chewing (retronasal). These volatile organic compounds can be produced or modified chemically, enzymatically, and/or microbiologically. There are numerous biosynthetic pathways through which aroma compounds can be produced or modified, accounting for their various chemical classes such as alcohols, esters, lactones, aldehydes, ketones, acids, terpenoids, and sulfur compounds. In foods, more than 7000 compounds are found, however, only 5% of these contribute to aroma (Belitz, Grosch, & Schieberle, 2009). These compounds are those that are present in high enough concentration to exceed the human odor thresholds.

It is well established that aroma drives consumer acceptance and preference in different products (Berna et al., 2005a, 2005b; Sukumaran et al., 2019) It also contributes to characterizing the maturity or ripening stage of fruit, as well as in discriminating between different cultivars (Mesquita et al., 2020; Vedashree, Asha, Roopavati, & Naidu, 2020). Aside from this, volatile compounds have been demonstrated to play an effective role in characterizing and monitoring spoilage of fruit such as strawberry (Dong et al., 2013), apple, (Kim, Lee, Seo, & Kim, 2018; Lloyd, Grimm, Klich, & Beltz, 2005; López, Echeverria, Usall, & Teixidó, 2015), pear (López et al., 2015), cantaloupe, pineapple, and orange (Lloyd et al., 2005). In this regard aroma analysis can help to determine quality and safety of food products.

Gas chromatography—mass spectrometry (GC–MS) is the standard method in qualifying and quantifying volatile organic compounds (Czerny, 2017). In this technique, the headspace of the product is sampled, either directly using a gas syringe or via a concentration technique such as purge and trap or solid phase microextraction (Beltran et al., 2006; Ibáñez, López-Sebastián, Ramos, Tabera, & Reglero, 1998; Ruiz-Beviá, Font, García, Blasco, & Ruiz, 2002; Xu et al., 2016). The latter technique has become very popular because it is simple, cheap, and relatively straightforward to automate. After introduction in the GC, the headspace is separated into its different volatile compounds. Each eluting compound is transferred to a mass spectrometer where it is fragmented into a mass spectrum and identified through a library search. With the enrichment and chromatographic steps, this technique is rather slow and is not applicable as a high-throughput routine measurement. As such, several efforts have been made to improve analysis time including the use of accelerated temperature programming (Vandendriessche, Nicolaï, & Hertog, 2013), high inlet pressures and split ratios (Mondello et al., 2004), shorter columns, and high carrier gas velocities (Korytár, Janssen, Matisová, & Brinkman, 2002).

14.5.1 Novel mass spectrometry techniques

While GC–MS remains the standard aroma analysis technique to date, it requires skilled personnel and long analysis time. Besides, this technique usually requires sample preparation and preconcentration to overcome its low sensitivity. Novel technologies have been introduced to measure aroma that can be operated in a faster and nondestructive way such as selected ion flow tube—mass spectrometry (SIFT-MS), proton transfer reaction—mass spectrometry (PTR−MS) and ion mobility spectrometry (IMS).

SIFT was invented in Adams and Smith (1976) as a technique to study ion-neutral reactions. From its original application in relation to interstellar molecular synthesis (Viggiano et al., 1980), its more recent ground-breaking applications focus on breath analysis in medical research, diagnosis, and monitoring (Davies, Španěl, & Smith, 1997; Smith & Španěl, 1996; Španěl, Rolfe, Rajan, & Smith, 1996). Španěl and Smith (1999) later investigated the use of SIFT−MS in monitoring flavors in food products. SIFT−MS uses a microwave discharge to produce reagent ions, which are then selected one at a time by a quadrupole mass filter and transported via a carrier gas to a flow tube in tightly controlled conditions where they react to the sample analyte. The reaction products are filtered by a second quadrupole mass filter and counted by a particle multiplier. With the automated database, SIFT−MS is able to provide real-time and absolute quantification without chromatographic separation and sample preparation. This technique has been used in several aroma studies of fruit and vegetables (Azcarate & Barringer, 2010; Daelemans, 2017; Ozcan & Barringer, 2011; Vendel, Hertog, & Nicolaï, 2019; Xu & Barringer, 2010). It also has the ability to track actual volatile release during and after chewing, which provides a good understanding of sensory experience (Langford, Padayachee, McEwan, & Barringer, 2019).

Another technique gaining interest in aroma research is the PTR−MS. Similar to SIFT−MS, this technique proceeds with soft ionization process but initially uses one specific reagent ion, H_3O^+, for subsequent reaction with sample analyte. It utilizes hollow cathode; thus, no carrier gas and mass filter are necessary (Hansel et al., 1995). In Jordan et al. (2009) and Sulzer et al. (2012) switchable reagent ion capability was introduced that include other ions such as NO^+, O_2^+, and Kr^+ to improve identification of volatile organic compounds (VOCs) and important inorganic compounds. The equipment design was later improved by using time-of-flight (ToF) instead of the conventional quadrupole mass spectrometer, which has more rapid acquisition of the entire VOC profile relevant to real-time measurements (Blake, Whyte, Hughes, Ellis, & Monks, 2004) and provides high mass resolving power allowing distinction between isobaric species (Pleil, Hansel, & Beauchamp, 2019). PTR−MS has been used to explore VOC development in strawberry (Granitto et al., 2007), blackberry, raspberry, blueberry, white and red currant (Boschetti et al., 1999), tomato (Farneti, Cristescu, Costa, Harren, & Woltering, 2012), and apple (Ciesa et al., 2015) while PTR−ToF−MS was utilized to monitor postharvest ripening of some tropical fruit such as avocado, banana, mango, and mangosteen (Taiti et al., 2015) and to discriminate between different cultivars and ripening stages of blueberry (Farneti et al., 2017).

Moreover, IMS is another method to detect trace amounts of compounds at ppb levels (Leonhardt, 2003). In this system, gaseous samples are introduced to a drift tube that consists of reaction and drift regions. Samples are carried into the reaction section where ionization happens. Product ions then move through an electrical potential gradient to the detector. Thanks to the acceleration caused by the electric field and deceleration caused by collisions with a countercurrent drift gas flow, ions achieve different velocities that are dependent mostly on collision cross-section of the ions in the drift gas, ion charge, and mass. As such, ions with different mobilities reach the detector at different times. This IMS technique has been used to detect adulterated and counterfeited sesame oil (Zhang et al., 2016) and to detect

Botrytis cinerea infection in strawberry (Vandendriessche, Keulemans, Geeraerd, Nicolaï, & Hertog, 2012). In addition, IMS has been combined with GC proving its application as a fast screening tool for assessing authenticity of honey (Gerhardt, Birkenmeier, Schwolow, Rohn, & Weller, 2018), categorizing olive oils (Garrido-Delgado, Dobao-Prieto, Arce, & Valcárcel, 2015), determining geographical origin of extra virgin olive oils (Gerhardt, Birkenmeier, Sanders, Rohn, & Weller, 2017) and tea (Jin et al., 2020), and identifying characteristic VOCs of jujube fruit as affected by storage duration (Yang et al., 2019).

14.5.2 Electronic noses

Electronic noses have shown advantages over GC−MS by being a fast, low-cost, easy, and nondestructive technique to measure aroma. These systems are sensor arrays, which mimic the operation of a human nose. When an atmosphere loaded with volatile compounds flows over it, each sensor generates a signal. The combined signal is then correlated to sensory properties or consumer preference (Berna et al., 2005a, 2005b). Different sensors have been developed for a variety of analytes and popular at present are conductive sensors such as metal oxides, polymer composites and polymers as well as optical, surface acoustic wave, gas sensitive field effect transistors, and quartz microbalance (QMB) sensors (Loutfi, Coradeschi, Mani, Shankar, & Rayappan, 2015). Electronic noses have been successful in monitoring the aroma of melon (Benady, Simon, Charles, & Miles, 1995), pear (Oshita et al., 2000), peach (Molto, Selfa, Ferriz, Conesa, & Gutierrez, 1999), nectarine (Di Natale et al., 2001), tomato (Berna, Lammertyn, Saevels, Di Natale, & Nicolai, 2004; Gómez, Hu, Wang, & Pereira, 2006; Maul et al., 1998), mango (Li, Wang, Raghavan, & Vigneault, 2009), citrus (Pallottino et al., 2012), banana (Chen et al., 2018), and apple (Brezmes et al., 2001; Hines, Llobet, & Gardner, 1999; Saevels et al., 2004; Young, Rossiter, Wang, & Miller, 1999). Most studies focused on classification of cultivars or evaluation of changes in the aroma profile during maturation and ripening. Aside from this, metal oxide sensors for e-nose were also utilized to determine bacterial infection in apple (Ezhilan, Nesakumar, Jayanth Babu, Srinandan, & Rayappan, 2018). Furthermore, electrochemical gas sensors that have ultralow power consumption and can work below room temperature and at a wide range of humidity were used to detect bacterial infection in potatoes (Rutolo, Clarkson, & Covington, 2018).

As another effort to improve the sensitivity of these systems, a mass spectrometry-based e-nose was developed. In this setup a headspace sample is directly injected into the ionization chamber of the mass spectrometer that then creates a fingerprint of the sample. In horticulture it was found that MS e-nose was more sensitive than QMB-based e-nose in discriminating between tomato cultivars and shelf life duration (Berna et al., 2004). Aside from this, MS e-nose found its application to check for geographical origin (Berna et al., 2004), temperature sensitivity (Cozzolino et al. 2010), and spoilage (Berna et al., 2004; Cynkar, Cozzolino, Dambergs, Janik, & Gishen, 2007) of wines, authenticity of honey (Romano et al., 2016) and purity of oil (Hong et al., 2011).

An important step in miniaturization and cost reduction was made by Rakow and Suslick (2000) who developed a two-dimensional array of metallo-porphyrins as sensor elements for the visual identification of a wide range of olfactants and even weakly ligating solvent vapors. The color of the sensors change depending on the absorbed volatile molecules, and the resulting 2D fingerprint can be measured with a scanner. These kinds of approaches open up the possibility to low cost, disposable sensors that could eventually be integrated into a fruit package to give the consumer an idea of the ripeness of the fruit.

14.6 Internal defects

The most effective methods for nondestructive internal disorder detection are based on visible and NIR (Vis-NIR) spectroscopy, (nuclear) magnetic resonance, or X-ray imaging. These techniques and how they have been used in the scientific literature are discussed further. Other methods for internal quality evaluation are reviewed by Arendse, Fawole, Magwaza, & Opara (2018), Butz, Hofmann, & Tauscher (2005), Lu & Lu 2017, and Nicolaï et al. (2014).

14.6.1 Visible and near-infrared

Visible and NIR (Vis—NIR) spectroscopy-based methods are widely used for external quality inspection and chemical composition of horticultural product and are often integrated in commercial quality grading systems. The use of Vis—NIR sensors for the nondestructive detection of internal disorders has also been investigated, using either reflectance or transmittance spectroscopy (Lu and Lu 2017; Nicolaï et al., 2014). Han, Tu, Lu, Liu, and Wen (2006) used Vis—NIR transmission to detect internal browning in pears. Fu, Ying, Lu, and Xu (2007) compared the use of Vis—NIR reflectance and transmittance for the detection of internal browning in pears. Transmission mode was reported to be more informative than reflection to detect the disorder.

Vis—NIR transmission for the detection of internal browning in apples was studied extensively (Clark, McGlone, & Jordan, 2003; Huang, Lu, & Chen, 2020; Khatiwada, Subedi, Hayes, Carlos, & Walsh, 2016; McGlone, Martinsen, Clark, & Jordan, 2005; Upchurch, Throop, & Aneshansley, 1997). Kafle, Khot, Jarolmasjed, Yongsheng, and Lewis (2016) and Jarolmasjed, Espinoza, and Sankaran (2017) studied the detection of bitter pit by Vis—NIR reflectance. Mogollon et al. (2020) investigated the use of Vis—NIR transmission for the early detection of internal browning in apples. Vanoli et al. (2014) and Torres, Sánchez-Contreras, Hernández, and León (2015) studied the detection of internal defects in apple using Vis—NIR reflectance. Vis—NIR reflectance was also explored by Gabriëls, Mishra, Mensink, Spoelstra, and Woltering (2020) for the detection of internal browning in mangoes.

The main issues for Vis—NIR-based methods are the limited penetration depth of visible and NIR light, and small or nonuniform distributed internal defects in products. Therefore multiple measurements at different positions, precise positioning or orientation of the samples, and/or long exposure times are often required. Moreover, the measured spectrum depends on the fruit size, cultivar, and season. Subsequently, large datasets are required for calibration (Bobelyn et al., 2010; Nicolaï et al., 2007).

14.6.2 Nuclear magnetic resonance and magnetic resonance imaging

Magnetic resonance employs static magnetic fields and radio frequencies to obtain signals of proton mobility in biologic systems. The proper radio frequency will rotate its magnetic moment by 90°. After removal of the radio frequency energy, relaxation results in a signal in the receiver. The energy loss depends on the environment surrounding the nucleus, leading to different but characteristic relaxation times. Sample preparation is not required. By applying magnetic field gradients in three directions, two- and three-dimensional magnetic resonance imaging (MRI) images can be created (Butz et al., 2005). Basically, the signal comes from the aqueous fraction in the sample and is, therefore, mainly used to measure nondestructively water content and profiles in products (Nguyen et al., 2006). Recently, the usage of MRI for the quality evaluation of horticultural products has been reviewed by Srivastava, Talluri, Khasim Beebi, and Kumar (2018). The recent advances in nuclear magnetic resonance (NMR) and MRI sensors for food applications have been reviewed by Kirtil, Cikrikci, McCarthy, and Oztop (2017); McCarthy, Zhang, McCarthy, and Coulthard (2016).

NMR relaxometry has been studied to detect internal defects in mandarin (Zhang and McCarthy 2016), pomegranate (Zhang & McCarthy 2012), mango (Bizzani et al., 2020), and pears (Hernandez-Sanchez, Hills, Barreiro, & Marigheto, 2007).

MRI has been applied on apple for the detection of watercore (Clark & Richardson 1999; Clark, MacFall, & Bieleski, 1998; Herremans et al., 2014; Melado-Herreros et al., 2013; Wang, Wang, & Faust, 1988), internal browning (Chayaprasert & Stroshine 2005; Clark & Burmeister 1999; Defraeye et al., 2013; Gonzalez et al., 2001), and bruises (Chen, McCarthy, & Kauten, 1989; Cheng, Lin, Chou, & Chen, 2008; McCarthy et al., 1995; Zion, Chen, & McCarthy, 1995). Wang and Wang (1989), Lammertyn et al. (2000a, 2000b, 2003b, 2003a), Hernandez-Sanchez et al. (2007), and Suchanek, Kordulska, Olejniczak, Figiel, and Turek (2017) used MRI to study internal browning and core breakdown in pears, a storage disorder, which is characterized by brown discoloration of the tissue and development of cavities. MRI was able to differentiate between unaffected tissue, brown tissue, and cavities (Fig. 14.3). The area percentage brown tissue per slice increased with the diameter of the pear (Lammertyn et al., 2003a). Similar findings were reported by Suchanek et al. (2017) using low-field MRI. Hernandez-Sanchez et al. (2007) used fast low angle shot Mr images acquired for pears on a sorting line and discriminated for internal breakdown according to histogram characteristics. Up to 96% of pears were correctly classified. MRI was also used to detect bruises (Chen et al., 1989) and estimate the bruise volume (Razavi, Asghari, Azadbakh, & Shamsabadi, 2018) in pears. Bruise detection in avocado by means of MRI was investigated by Mazhar et al. (2015). MRI for bruise and spraing disease detection in potato was studied by Thybo, Jespersen, Lærke, and Stødkilde-Jørgensen (2004). Sonego, Benarie, Raynal, and Pech (1995) used MRI to evaluate the characteristics of nectarines affected by woolly breakdown. MRI has also been applied to the detection of internal disorders in watermelon/melons (Saito et al., 1996; Sun, Huang, Xu, & Ying, 2010), mango (Joyce, Hockings, Mazucco, Shorter, & Brereton, 1993), and tomato (Tao, Zhang, McCarthy, Beckles, & Saltveit, 2014).

MRI shows large potential for online grading, sorting, or quality evaluation of fresh produce (Kirtil et al., 2017; McCarthy et al., 2016; Hernández et al., 2005; Srivastava et al., 2018). The main challenges are high equipment cost, the requirement of large magnets to create a strong and homogeneous magnetic field, external electromagnetic fields and metallic materials that cause interferences, the requirement of a high-throughput and handling disturbances by mechanical vibrations and other motion-based artifacts (Colnago et al., 2014; Srivastava et al., 2018). Current research aims at developing cost-effective but fast equipment that can achieve

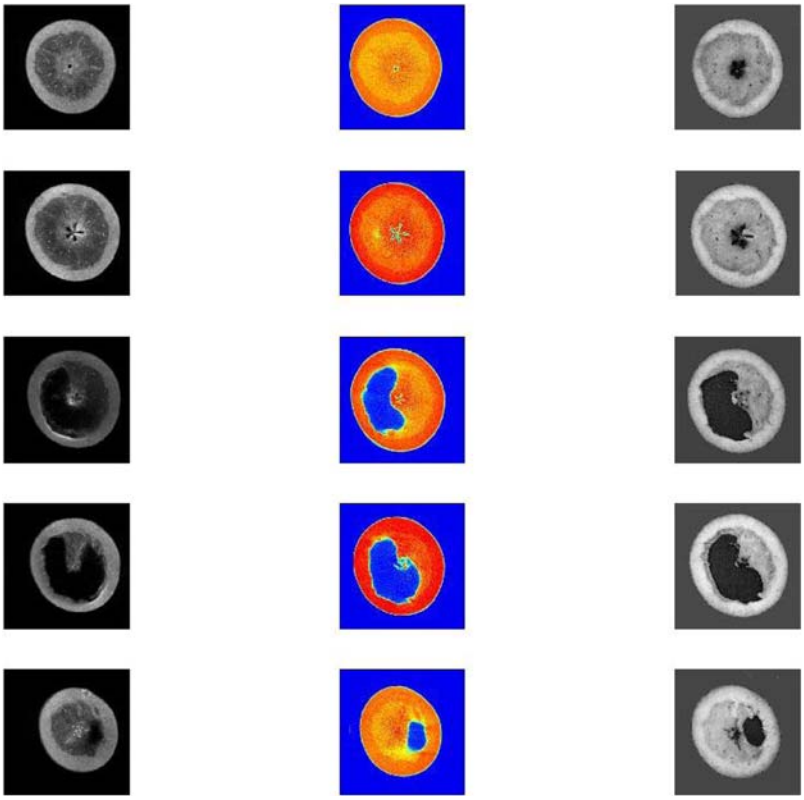


FIGURE 14.3 Comparative overview of the corresponding X-ray CT scans (left), MRI images (middle) and actual photographs (right) of core breakdown of pear tissue. Sound tissue, brown tissue and cavities are light gray, dark gray, and black in the CT scans, and light orange, dark orange, and blue in the MRI scans, respectively. There is a good correspondence between the different images (Lammertyn et al., 2003b). *MRI*, Magnetic resonance imaging; *X-ray CT*, X-ray computed tomography. Source*: Lammertyn, J. Dresselaers, T. Van Hecke, P. Jancsok, P. Wevers, M. & Nicolaï, B.M. 2003b, 'MRI and X-ray CT study of spatial distribution of core breakdown in 'Conference' pears', Magnetic Resonance Imaging, 21, pp. 805–815, used with permission from Elsevier Science Ltd.*

commercial throughputs. In particular, the focus is on using cheaper, faster, low-field, wide-bore MRI scanners (Chayaprasert & Stroshine 2005; Hernandez-Sanchez et al., 2007; Milczarek & McCarthy 2009; Van As and van Duynhoven, 2013), on the development of cheaper and smaller magnets (Colnago et al., 2014), on smaller, mobile devices (Danieli, Mauler, Perlo, Blümich, & Casanova, 2009, 2010; Geya et al., 2013), and on faster pulse sequences [e.g., gradient echo method (Abbott 1999)]. McCarthy et al. (2016) reported on a prototype MRI-based sorting system capable of imaging seven fruit simultaneously in one second.

14.6.3 X-ray radiography and computed tomography

X-rays are short wave radiations, which can penetrate through plant tissue. In X-ray radiography, an X-ray beam is radiated toward the sample and the transmitted beam is recorded by a detector. The resulting image is superimposed information (a projection) of a volume in a 2D plane. The level of transmission of the X-rays depends mainly on the mass density and mass absorption coefficient of the material (Maire et al., 2001; Salvo et al., 2003). Due to the high moisture content in fruit and vegetables, water dominates X-ray absorption. Most internal disorders affect the density and water content of the internal tissue and, hence, are detectable by means of X-ray measurements (Wang et al., 2018).

X-ray computed tomography (X-ray CT) is the 3D extension of X-ray radiography. The classical way to get 3D information is to perform a large number of radiographs while rotating the sample between 0° and 180°. The filtered back-projection algorithm can then be used to reconstruct the volume of the sample from these radiographs (Herman 1980). Just like MRI, no sample preparation or chemical fixation is required. X-ray CT allow visualization and analysis of the architecture of cellular plant materials with a resolution down to a few micrometers, and, as the resolution of the method is constantly improving, X-ray CT has been applied to study the fine structures of horticultural products at the submicron scale. X-ray CT is thus an excellent tool to study physical and physiological internal processes (Ho et al., 2011; Kuroki, Oshita, Sotome, Kawagoe, & Seo, 2004; Lim and Barigou 2004; Maire et al., 2003; Mendoza et al., 2007; Musse et al., 2010; van Dalen, Blonk, van Aalst, & Hendriks, 2003; Verboven et al., 2008; Wang et al., 2018). Generally, there are two different source types to perform X-ray CT. The first one uses a divergent cone beam produced by a microfocus X-ray tube and the second one uses parallel synchrotron radiation (Salvo et al., 2003).

X-ray radiography has been applied to detect internal disorders in citrus fruit, apples, mango, and pistachio pecan and almond nuts (Casasent, Sipe, Schatzki, Keagy, & Lee, 1998; van Dael et al., 2016; Schatzki et al., 1997; Kim & Schatzki, 2000, 2001; Kotwaliwale, Weckler, Brusewitz, Kranzler, & Maness, 2007; Thomas, Saxena, Chandra, Rao, & Bhatia, 1993; van Dael et al., 2015, 2017; van Dael, Zanella, Sijbers, & Nicolai, 2018) proposed a multisensor method that combines X-ray radiography with prior knowledge in the form of parameterized shape and density distribution models. The method has been demonstrated in silico for tomato, pear, and apple but remains to be tested on actual hardware. X-ray CT has been studied to detect internal browning and core breakdown (Lammertyn et al., 2003b; 2003a; Van De Looverbosch et al., 2020), and mealiness (Muziri et al., 2016) in pears. For apple, the detection of internal browning (Herremans et al., 2013), watercore (Herremans et al., 2014), bitter pit (Jarolmasjed, Espinoza, Sankaran, & Khot, 2016), and bruises (Diels et al., 2017) was investigated by means of X-ray CT. Sonego et al. (1995) investigated the detection of woolliness in nectarines using X-ray CT. Donis-González, Guyer, Pease, and Fulbright (2012) and (Donis-González et al., 2012) used X-ray CT to evaluate the internal quality of chestnuts and Donis-González, Guyer, and Pease, (2016a, 2016b) used X-ray CT to evaluate fibrous tissue in asparagus and carrots.

Lammertyn et al. (2003b, 2003a) used X-ray CT to study the development of core breakdown disorder in "Conference" pears (*Pyrus communis* cv. Conference). After image processing of X-ray tomography slices of pears (Fig. 14.3; left series of images), it was possible to measure nondestructively the breakdown development (in terms of area percentage of affected and unaffected tissue as well as the cavity and core area per slice) during storage measured on actual slices (Fig. 14.3; right series of images) with an underestimation of 12% (Fig. 14.3; middle series of images) (Lammertyn et al., 2003b). Herremans et al. (2013) investigated the microstructural changes during the development of internal browning in

"Braeburn" apples (Malus × domestica Borkh. cv. Braeburn) using X-ray CT. van Dael et al. (2018) followed the development of internal browning in 26 "Braeburn" apples with X-ray CT images at five different time points during storage. To quantify the internal changes occurring in the samples, the mean-squared-error between each time point and the first time point was used.

In the last decade, inline X-ray CT has been studied intensively. Donis-González et al. (2012) used a medical CT system for evaluating the feasibility of inline sorting of chestnuts based on the presence of internal quality defects. The authors concluded that further progress was required in hardware, image reconstruction, and image processing algorithms to achieve sufficiently fast and affordable inline CT systems for product quality evaluation. De Schryver et al. (2016) proposed a translational X-ray CT method, in which a sample is translated and rotated simultaneously while X-ray projections are acquired. This idea was further investigated using a limited number of projections for advanced, and even application specific, reconstruction algorithms (Janssens et al., 2016, 2018; Pereira et al., 2017). Further developments in both hardware and software are required for inline X-ray CT to become affordable, faster, and more effective.

14.7 Conclusion

Many novel nondestructive systems have become available to measure internal quality attributes of fruit and vegetables. Some of them, in particular vibration and impact-based techniques for measuring firmness as well as NIR spectroscopy for measuring SSC, are now implemented on sorting lines. As a consequence, sorting based on internal quality attributes rather than external appearance becomes possible, and this is expected to radically change the way fresh fruit are handled in commercial systems. Their market penetration is yet still relatively low, though, and depends as always on whether the value added by grading outweighs the investment cost. Also, a successful commercial implementation of these techniques will depend on the reliability of the measurements, their correlation with attributes that matter to consumers as well as existing techniques and their speed.

Recent advances in portable NIR spectrophotometers open up the possibility to use nondestructive techniques in the orchard. Such information can be helpful to determine harvest maturity and optimal picking dates and to construct quality maps in precision horticulture applications.

Acknowledgment

We would like to acknowledge the Fund for Scientific Research Flanders (project G.0298.06), the IWT-Vlaanderen (project 20670, 70585 and SBO/120033), and the University of Leuven through a bilateral scientific collaboration between Flanders and Russia (BIL/05/47).

References

Abbott, J. A. (1999). Quality measurement of fruits and vegetables. *Postharvest Biology and Technology*, *15*, 207–225.

Abbott, J. A., Bachman, G. S., Childers, R. F., Fitzgerald, J. V., & &Matusik, F. J. (1968). Sonic technique for measuring texture of fruit and vegetables. *Food Technology*, *22*, 101–112.

Adams, N. G., & Smith, D. (1976). The selected ion flow tube (SIFT); A technique for studying ion-neutral reactions. *International Journal of Mass Spectrometry and Ion Physics*, *21*, 349–359.

Adebayo, S. E., Hashim, N., Hass, R., Reich, O., Regen, C., Münzberg, M., … Zude-Sasse, M. (2017). Using absorption and reduced scattering coefficients for non-destructive analyses of fruit flesh firmness and soluble solids content in pear (Pyrus communis 'Conference')—An update when using diffusion theory. *Postharvest Biology and Technology*, *130*, 56–63.

Aernouts, B., Erkinbaev, C., Watté, R., Van Beers, R., Do Trong, N. N., Nicolai, B., & Saeys, W. (2015). Estimation of bulk optical properties of turbid media from hyperspectral scatter imaging measurements: Metamodeling approach. *Optics Express*, *23*(20), 26049.

Arendse, E., Fawole, O. A., Magwaza, L. S., & Opara, U. L. (2018). Non-destructive prediction of internal and external quality attributes of fruit with thick rind: A review. *Journal of Food Engineering* (217).

ASTM. (2000). *Standards on color and appearance measurements* (6th ed.). Philadelphia, PA: American Society for Testing and Materials.

Azcarate, C., & Barringer, S. A. (2010). Effect of enzyme activity and frozen storage on Jalapeño pepper volatiles by selected ion flow tube-mass spectrometry. *Journal of Food Science*, *75*, C710–C721.

Bai, W., Yoshimura, N., & Takayanagi, M. (2014). Quantitative analysis of ingredients of blueberry fruits by near infrared spectroscopy. *Journal of Near Infrared Spectroscopy*, *22*, 357–365.

Belitz, H. D., Grosch, W., & Schieberle, P. (2009). Aroma compounds. *Food chemistry* (pp. 340–402). Berlin, Heidelberg: Springer.

Beltran, J., Serrano, E., López, F. J., Peruga, A., Valcarcel, M., & Rosello, S. (2006). Comparison of two quantitative GC–MS methods for analysis of tomato aroma based on purge-and-trap and on solid-phase microextraction'. *Analytical and Bioanalytical Chemistry*, *385*, 1255–1264.

Benady, M., Simon, J. E., Charles, D. J., & Miles, G. E. (1995). Fruit ripeness determination by electronic sensing of aromatic volatiles. *Transactions of the ASAE*, *38*, 251–257.

Berna, A. Z., Buysens, S., Di Natale, C., Grun, I. U., Lammertyn, J., & Nicolaï, B. M. (2005a). Relating sensory analysis with electronic nose and headspace fingerprint MS for tomato aroma profiling. *Postharvest Biology and Technology*, *36*, 143–155.

Berna, A. Z., Lammertyn, J., Buysens, S., Di Natale, C., & Nicolaï, B. M. (2005b). Mapping consumer liking of tomatoes with fast aroma profiling techniques. *Postharvest Biology and Technology*, *38*, 115–127.

Berna, A. Z., Lammertyn, J., Saevels, S., Di Natale, C., & Nicolai, B. M. (2004). Electronic nose systems to study shelf life and cultivar effect on tomato aroma profile. *Sensors and Actuators B-Chemical*, *97*, 324–333.

Bhargava, A., & Bansal, A. (2018). Fruits and vegetables quality evaluation using computer vision: A review. *Journal of King Saud University-Computer and Information Sciences*, *33*, 243–257.

Bizzani, M. W., Menezes Flores, D., Bueno Moraes, T., Alberto Colnago, L., David., Ferreira, M., & Helena Fillet Spoto, M. (2020). Non-invasive detection of internal flesh breakdown in intact Palmer mangoes using time-domain nuclear magnetic resonance relaxometry. *Microchemical Journal*, *158*, 105208.

Blake, R. S., Whyte, C., Hughes, C. O., Ellis, A. M., & Monks, P. S. (2004). 'Demonstration of proton-transfer reaction time-of-flight mass spectrometry for real-time analysis of trace volatile organic compounds. *Analytical Chemistry*, *76*, 3841–3845.

Blasco, J., Munera, S., Aleixos, N., Cubero, S., & Molto, E. (2017). Machine vision-based measurement systems for fruit and vegetable quality control in postharvest. *Measurement, modeling and automation in advanced food processing* (pp. 71–91). Cham: Springer.

Bobelyn, E., Serban, A. S., Nicu, M., Lammertyn, J., Nicolai, B. M., & Saeys, W. (2010). Postharvest quality of apple predicted by NIR-spectroscopy: Study of the effect of biological variability on spectra and model performance. *Postharvest Biology and Technology*, *55*(3), 133–143.

Boschetti, A., Biasioli, F., van Opbergen, M., Warneke, C., Jordan, A., Holzinger, R., … Iannotta, S. (1999). PTR-MS real time monitoring of the emission of volatile organic compounds during postharvest aging of berryfruit. *Postharvest Biology and Technology*, *17*, 143–151.

Brezmes, J., Llobet, E., Vilanova, X., Orts, J., Saiz, G., & Correig, X. (2001). Correlation between electronic nose signals and fruit quality indicators on shelf-life measurements with pinklady apples. *Sensors and Actuators B-Chemical*, *80*, 41–50.

Bulanon, D. M., Kataoka, T., Ota, Y., & Hiroma, T. (2002). Segmentation algorithm for the automatic recognition of Fuji apples at harvest. *Biosystems Engineering*, *83*, 405–412.

Butz, P., Hofmann, C., & Tauscher, B. (2005). Recent developments in noninvasive techniques for fresh fruit and vegetable internal quality analysis. *Journal of Food Science*, *70*, R131–R141.

Carstensen, J. M. (2018). LED spectral imaging with food and agricultural applications. *Image sensing technologies: Materials, devices, systems, and applications V* (vol. 10656, p. 1065604). International Society for Optics and Photonics.

Casasent, D. A., Sipe, M. A., Schatzki, T. F., Keagy, P. M., & Lee, L. C. (1998). Neural net classification of X-ray pistachio nut data. *LWT–Food Science and Technology*, *31*(2), 122–128.

Cattaneo, T. M. P., & Stellari, A. (2019). Review: NIR spectroscopy as a suitable tool for the investigation of the horticultural field. *Agronomy*, *9*(9), 503.

Cen, H., Lu, R., Mendoza, F. A., & Ariana, D. P. (2012). Assessing multiple quality attributes of peaches using optical absorption and scattering properties. *Transactions of the ASABE*, *55*(2), 647–657.

Chauchard, F., Cogdill, R., Roussel, S., Roger, J. M., & Bellon-Maurel, V. (2004). Application of LS-SVM to non-linear phenomena in NIR spectroscopy: Development of a robust and portable sensor for acidity prediction in grapes. *Chemometrics and Intelligent Laboratory Systems*, *71*(2), 141–150.

Chayaprasert, W., & Stroshine, R. (2005). Rapid sensing of internal browning in whole apples using a low-cost, low-field proton magnetic resonance sensor. *Postharvest Biology and Technology*, *36*, 291–301.

Chen, H. D., & Baerdemaeker, J. (1993). Finite-element-based modal analysis of fruit firmness. *Transactions of the ASAE*, *36*, 1827–1833.

Chen, H. D., Baerdemaeker, J., & Bellon, V. (1996). Finite element study of the melon for nondestructive sensing of firmness. *Transactions of the ASAE*, *39*, 1057–1065.

Chen, L. Y., Wong, D. M., Fang, C. Y., Chiu, C. I. Chou, T. I. Wu, C. C., ... Tang, K. T. (2018). 'Development of an electronic-nose system for fruit maturity and quality monitoring'. In *2018 IEEE international conference on applied system invention (ICASI)* (pp. 1129–1130). IEEE.

Chen, P. & Ruiz-Altisent, M. (1996), 'A Low-mass impact sensor for high-speed firmness sensing of fruits', In *Proceedings of the agricultural engineering international conference 96*". AGENG 96, Madrid, Spain, 23–26 September 1996, paper 96F-003.

Chen, P., McCarthy, M. J., & Kauten, R. (1989). NMR for internal quality evaluation of fruits and vegetables. *Transactions of the ASAE*, *32*, 1747–1753.

Chen, P. Tang, S. & Chen, S. (1985). 'Instrument for testing the response of fruits to impact', *ASAE paper 75–3537*, ASAE, St. Joseph, MI.

Cheng, Y. C. Lin, T. T. Chou, C. Y. & Chen, J. H. (2008). *Physico-chemical analysis of internal bruise of selected fruits using chemical shift imaging. 2008 providence*, Rhode Island, June 29–July 2, 2008, St. Joseph, MI.

Ciesa, F., Höller, I., Guerra, W., Berger, J., Dalla Via, J., & Oberhuber, M. (2015). Chemodiversity in the fingerprint analysis of volatile organic compounds (VOCs) of 35 old and 7 modern apple cultivars determined by proton-transfer-reaction mass spectrometry (PTR-MS) in two different seasons. *Chemistry and Biodiversity*, *12*, 800–812.

Clark, C. J., MacFall, J. S., & Bieleski, R. L. (1998). Loss of watercore from 'Fuji' apple observed by magnetic resonance imaging. *Scientia Horticulturae*, *73*(4), 213–227.

Clark, C. J., McGlone, V. A., & Jordan, R. B. (2003). Detection of Brownheart in 'Braeburn' apple by transmission NIR spectroscopy. *Postharvest Biology and Technology*, *28*(1), 87–96.

Clark, C. J., & Burmeister, D. M. (1999). Magnetic resonance imaging of browning development in 'Braeburn' apple during controlled-atmosphere storage under high CO_2. *HortScience: A publication of the American Society for Horticultural Science*, *vol. 34*, 915–919.

Clark, C. J., & Richardson, C. A. (1999). Observation of watercore dissipation in 'Braeburn' apple by magnetic resonance imaging. *New Zealand Journal of Crop and Horticultural Science*, *27*, 47–52.

Colnago, L. A., Andrade, F. D., Souza, A. A., Azeredo, R. B. V., Lima, A. A., Cerioni, L. M., ... Pusiol, D. J. (2014). Why is inline NMR rarely used as industrial sensor? Challenges and opportunities. *Chemical Engineering and Technology*, *37*(2), 191–203.

Cooke, J. R. (1972). Interpretation of resonant behavior of intact fruits and vegetables'. *Transactions of the ASAE*, *15*, 1075–1080.

Correa, P. Ruiz-Altisent, M. & de la Plaza, J. L. (1992). 'Physical parameters in relation to physiological changes of avocado during ripening (20°C) and cold storage (6°C) in different conditions'. In *Proceedings of the agricultural engineering international conference 92*., AGENG 92, Uppsala, Sweden, 1–4 June 1992, paper 9211-16.

Cortés, V., Blasco, J., Aleixos, N., Cubero, S., & Talens, P. (2019). Monitoring strategies for quality control of agricultural products using visible and near-infrared spectroscopy: A review'. *Trends in Food Science and Technology*, *85*, 138–148.

Cozzolino, D., Cynkar, W., Dambergs, R., & Smith, P. (2010). Two-dimensional correlation analysis of the effect of temperature on the fingerprint of wines analysed by mass spectrometry electronic nose. *Sensors and Actuators, B: Chemical*, *145*(2), 628–634. Available from https://doi.org/10.1016/j.snb.2010.01.003.

Cubero, S., Lee, W. S., Aleixos, N., Albert, F., & Blasco, J. (2016). Automated systems based on machine vision for inspecting citrus fruits from the field to postharvest—A review. *Food and Bioprocess Technology*, *9*(10), 1623–1639.

Cynkar, W., Cozzolino, D., Dambergs, B., Janik, L., & Gishen, M. (2007). Feasibility study on the use of a head space mass spectrometry electronic nose (MS e_nose) to monitor red wine spoilage induced by Brettanomyces yeast. *Sensors and Actuators, B: Chemical*, *124*, 167–171.

Czerny, M. (2017). Odors in paper and cardboard packaging. In A. Buettner (Ed.), *Springer handbook of odor* (pp. 329–340). Cham: Springer International Publishing AG.

Daelemans, L. (2017). *Investigation of spoilage related volatile organic compounds in Lactuca sativa L*. University of Ghent.

Danieli, E., Berdel, K., Perlo, J., Michaeli, W., Masberg, U., Blümich, B., & Casanova, F. (2010). 'Determining object boundaries from MR images with sub-pixel resolution: Towards in-line inspection with a mobile tomograph. *Journal of Magnetic Resonance*, *207*, 53–58.

Danieli, E., Mauler, J., Perlo, J., Blümich, B., & Casanova, F. (2009). Mobile sensor for high resolution NMR spectroscopy and imaging. *Journal of Magnetic Resonance*, *198*, 80–87.

Davies, S., Španěl, P., & Smith, D. (1997). Quantitative analysis of ammonia on the breath of patients in end-stage renal failure'. *Kidney International*, *52*, 223–228.

De Baerdemaeker, J., Lemaitre, L., & Meire, R. (1982). 'Quality detection by frequency-spectrum analysis of the fruit impact force'. *Transactions of the ASAE*, *25*, 175–178.

De Ketelaere, B., Howarth, M. S., Crezee, L., Lammertyn, J., Viaene, K., Bulens, I., & De Baerdemaeker, J. (2006a). Postharvest firmness changes as measured by acoustic and low-mass impact devices: A comparison of techniques. *Postharvest Biology and Technology*, *41*, 275–284.

De Ketelaere, B., Lammertyn, J., Molenberghs, G., Desmet, M., Nicolaï, B., & De Baerdemaeker, J. (2004). Tomato cultivar grouping based on firmness change, shelf life and variance during postharvest storage. *Postharvest Biology and Technology*, *34*, 187–201.

De Ketelaere, B., Lammertyn, J., Molenberghs, G., Nicolai, B., & De Baerdemaeker, J. (2003). Statistical models for analyzing repeated quality measurements of horticultural products. Model evaluations and practical example. *Mathematical Biosciences*, *185*, 169–189.

De Ketelaere, B. Ruiz-Altisent, M. Correa, E. De Baerdemaeker, J. & Barreiro, P. (2001). 'Reliability of vibration measurements and impact response characteristics for the quality assessment of tomatoes', In *Proceedings of the 6th international symposium on fruit, nut and vegetable production engineering*.(pp. 487–492), Potsdam, Germany, 11–14 September 2001.

De Ketelaere, B., Stulens, J., Lammertyn, J., Cuong, N. V., & De Baerdemaeker, J. (2006b). A methodological approach for the identification and quantification of sources of biological variance in postharvest research. *Postharvest Biology and Technology*, *39*, 1–9.

De Schryver, T., Dhaene, J., Dierick, M., Boone, M. N., Janssens, E., Sijbers, J., . . . Nicolai, B. (2016). In-line NDT with X-Ray CT combining sample rotation and translation. *NDT and E International*, *84*, 89–98.

Defraeye, T., Lehmann, V., Gross, D., Holat, C., Herremans, E., Verboven, P., . . . Nicolai, B. M. (2013). Application of MRI for tissue characterisation of 'Braeburn' apple. *Postharvest Biology and Technology*, *75*, 96–105.

Delwiche, M. J., Mcdonald, T., & Bowers, S. V. (1987). Determination of peach firmness by analysis of impact forces. *Transactions of the ASAE*, *30*, 249–254.

Di Natale, C., Macagnano, A., Martinelli, E., Proietti, E., Paolesse, R., Castellari, L., . . . D'Amico, A. (2001). 'Electronic nose based investigation of the sensorial properties of peaches and nectarines. *Sensors and Actuators B-Chemical*, *77*, 561–566.

Diels, E., van Dael, M., Keresztes, J., Vanmaercke, S., Verboven, P., Nicolai, B., ... Smeets, B. (2017). Assessment of bruise volumes in apples using X-ray computed tomography. *Postharvest Biology and Technology*, *128*, 24–32.

Dong, D., Zhao, C., Zheng, W., Wang, W., Zhao, X., & Jiao, L. (2013). Analyzing strawberry spoilage via its volatile compounds using longpath Fourier transform infrared spectroscopy. *Scientific Reports*, *3*, 1–7.

Dong, J., & Guo, W. (2015). Nondestructive determination of apple internal qualities using near-infrared hyperspectral reflectance imaging. *Food Analytical Methods*, *8*(10), 2635–2646.

Donis-González, I. R., Guyer, D. E., & Pease, A. (2016a). Postharvest noninvasive classification of tough-fibrous asparagus using computed tomography images. *Postharvest Biology and Technology*, *121*, 27–35.

Donis-González, I. R., Guyer, D. E., & Pease, A. (2016b). 'Postharvest noninvasive assessment of undesirable fibrous tissue in fresh processing carrots using computer tomography images'. *Journal of Food Engineering*, *190*, 154–166.

Donis-González, I. R., Guyer, D. E., Pease, A., & Fulbright, D. W. (2012). Relation of computerized tomography Hounsfield unit measurements and internal components of fresh chestnuts', (Castanea spp.). *Postharvest Biology and Technology*, *64*(1), 74–82.

Du, Z., Zeng, X., Li, X., Ding, X., Cao, J., & Jiang, W. (2020). 'Recent advances in imaging techniques for bruise detection in fruits and vegetables. *Trends in Food Science and Technology*, *99*, 133–141.

Eccher Zerbini, P., Grassi, M., Cubeddu, R., Pifferi, A., & Torricelli, A. (2002). Nondestructive detection of brown heart in pears by time-resolved reflectance spectroscopy. *Postharvest Biology and Technology*, *25*, 87–97.

Eccher Zerbini, P., Vanoli, M., Rizzolo, A., Grassi, M., Pimentel, R. A., Spinelli, L., & Torricelli, A. (2015). Optical properties, ethylene production and softening in mango fruit. *Postharvest Biology and Technology*, *101*, 58–65.

Ezhilan, M., Nesakumar, N., Jayanth Babu, K., Srinandan, C. S., & Rayappan, J. B. B. (2018). An electronic nose for Royal Delicious apple quality assessment – A tri-layer approach. *Food Research International* (109, pp. 44–51).

Fan, G., Zha, J., Du, R., & Gao, L. (2009). Determination of soluble solids and firmness of apples by Vis/NIR transmittance. *Journal of Food Engineering*, *93*(4), 416–420.

Farneti, B., Cristescu, S. M., Costa, G., Harren, F. J. M., & Woltering, E. J. (2012). 'Rapid tomato volatile profiling by using proton-transfer reaction mass spectrometry (PTR-MS). *Journal of Food Science*, *77*, 551–559.

Farneti, B., Khomenko, I., Grisenti, M., Ajelli, M., Betta, E., Algarra, A. A., ... Giongo, L. (2017). 'Exploring blueberry aroma complexity by chromatographic and direct-injection spectrometric techniques. *Frontiers in Plant Science*, *8*, 1–19.

Fearn, T. (2001). Standardisation and calibration transfer for near infrared instruments: A review. *Journal of Near Infrared Spectroscopy*, *9*(4), 229–244.

Finney, D. D., & Norris, K. H. (1968). Instrumentation for investigating dynamic mechanical properties of fruits and vegetables. *Transactions of the ASAE*, *11*, 94–97.

Fraser, D. G., Kunnemeyer, R., McGlone, V. A., & Jordan, R. B. (2001). Near infra-red (NIR) light penetration into an apple. *Postharvest Biology and Technology*, *22*, 191–194.

Fu, X., Ying, Y., Lu, H., & Xu, H. (2007). Comparison of diffuse reflectance and transmission mode of visible-near infrared spectroscopy for detecting brown heart of pear'. *Journal of Food Engineering*, *83*(3), 317–323.

Gabriëls, S. H. E. J., Mishra, P., Mensink, M. G. J., Spoelstra, P., & Woltering, E. J. (2020). Non-destructive measurement of internal browning in mangoes using visible and near-infrared spectroscopy supported by artificial neural network analysis'. *Postharvest Biology and Technology*, *166*, 111–206.

Galili, N. Rosenhouse, G. & Mizrach, A. (1993). 'Ultrasonic technique for fruit and vegetable quality evaluation'. In *Proceedings of the 4th International symposium on fruit, nut and vegetable production engineering* (pp. 281–289). Valencia-Zaragoza, Spain, 22–26 March 1993.

Gao, Z., Shao, Y., Xuan, G., Wang, Y., Liu, Y., & Han, X. (2020). Real-time hyperspectral imaging for the in-field estimation of strawberry ripeness with deep learning. *Artificial Intelligence in Agriculture*, *4*, 31–38.

Garcia-Ramos, F. J., Ortiz-Canavate, J., Ruiz-Altisent, M., Diez, J., Flores, L., Homer, I., & Chavez, J. M. (2003). Development and implementation of an on-line impact sensor for firmness sensing of fruits. *Journal of Food Engineering*, *58*, 53–57.

Garrido-Delgado, R., Dobao-Prieto, M. D. M., Arce, L., & Valcárcel, M. (2015). 'Determination of volatile compounds by GC–IMS to assign the quality of virgin olive oil. *Food Chemistry*, *187*, 572–579.

Geelen, B., Blanch, C., Gonzalez, P., Tack, N., & Lambrechts, A. (2015). A tiny VIS-NIR snapshot multispectral camera. *Advanced fabrication technologies for micro/nano optics and photonics VIII* (9374, p. 937414). International Society for Optics and Photonics, March.

Gerhardt, N., Birkenmeier, M., Sanders, D., Rohn, S., & Weller, P. (2017). Resolution-optimized headspace gas chromatography-ion mobility spectrometry (HS−GC−IMS) for non-targeted olive oil profiling. *Analytical and Bioanalytical Chemistry*, *409*, 3933−3942.

Gerhardt, N., Birkenmeier, M., Schwolow, S., Rohn, S., & Weller, P. (2018). Volatile-compound fingerprinting by headspace-gas-chromatography ion-mobility spectrometry (HS−GC−IMS) as a benchtop alternative to 1H NMR profiling for assessment of the authenticity of honey. *Analytical Chemistry*, *90*, 1777−1785.

Geya, Y., Kimura, T., Fujisaki, H., Terada, Y., Kose, K., Haishi, T., . . . Sekozawa, Y. (2013). Longitudinal NMR parameter measurements of Japanese pear fruit during the growing process using a mobile magnetic resonance imaging system'. *Journal of Magnetic Resonance*, *226*, 45−51.

Golding, J. B. Spohr, L. Newman, S. Tanner D. J. Orszulok, E. Smale, N., . . . McGlasson, W. B. (2005). 'Nondestructive assessment of peach and nectarine firmness'. In *ISHS acta horticulturae 687: International conference postharvest unlimited downunder 2004* (pp. 261−270).

Gómez, A. H., Hu, G., Wang, J., & Pereira, A. G. (2006). Evaluation of tomato maturity by electronic nose. *Computers and Electronics in Agriculture*, *54*, 44−52.

Gonzalez, J. J., Valle, R. C., Bobroff, S., Viasi, W. V., Mitcham, E. J., & McCarthy, M. J. (2001). Detection and monitoring of internal browning development in 'Fuji' apples using MRI. *Postharvest Biology and Technology*, *22*, 179−188.

Granitto, P. M., Biasolli, F., Aprea, E., Mott, D., Furlanello, C., Märk, T. D., & Gasperi, F. (2007). Rapid and nondestructive identification of strawberry cultivars by direct PTR-MS headspace analysis and data mining techniques. *Sensors and Actuators B: Chemical*, *121*, 379−385.

Halstead, M. McCool, C. Denman, S. Perez, T. & Fookes, C. (2018). *Fruit quantity and ripeness estimation using a robotic vision system IEEE robotics and automation LETTERS*, 3, 4, pp. 2995−3002.

Han, D., Tu, R., Lu, C., Liu, X., & Wen, Z. (2006). Nondestructive detection of brown core in the Chinese pear 'Yali' by transmission visible−NIR spectroscopy. *Food Control*, *17*(8), 604−608.

Hansel, A., Jordan, A., Holzinger, R., Prazeller, P., Vogel, W., & Lindinger, W. (1995). Proton transfer reaction mass spectrometry: On-line trace gas analysis at the ppb level. *International Journal of Mass Spectrometry and Ion Processes*, *609−619*, 149−150.

Herman, G. (1980). *Image reconstruction from projections*. New York: Academic Press.

Hernández, N., Barreiro, P., Ruiz-Altisent, M., Ruiz-Cabello, J., & Encarnación Fernández-Valle, M. (2005). Detection of seeds in citrus using MRI under motion conditions and improvement with motion correction. Concepts in Magnetic Resonance, Part B. *Magnetic Resonance Engineering*. 26B, 81−92.

Hernandez-Sanchez, N., Hills, B. P., Barreiro, P., & Marigheto, N. (2007). An NMR study on internal browning in pears'. *Postharvest Biology and Technology*, *44*, 260−270.

Herremans, E., Melado-Herreros, A., Defraeye, T., Verlinden, B., Hertog, M., Verboven, P., . . . Nicolaï, B. M. (2014). Comparison of X-ray CT and MRI of watercore disorder of different apple cultivars. *Postharvest Biology and Technology*, *87*, 42−50.

Herremans, E., Verboven, P., Bongaers, E., Estrade, P., Verlinden, B., Wevers, M., . . . Nicolaï, B. M. (2013). Characterization of 'Braeburn' browning disorder by means of X-ray micro-CT. *Postharvest Biology and Technology*, *75*, 114−124.

Hertog, M. L. A. T. M., Ben-Arie, R., Róth, E., & Nicolaï, B. M. (2004). Humidity and temperature effects on invasive and non-invasive firmness measures. *Postharvest Biology and Technology*, *33*, 79−91.

Hertog, M. L. A. T. M., Lammertyn, J. De, Ketelaere, B., Scheerlinck, N., & Nicolai, B. A. (2007). Managing quality variance in the postharvest food chain'. *Trends in Food Science and Technology*, *18*, 320−332.

Hines, E. L., Llobet, E., & Gardner, J. W. (1999). Neural network based electronic nose for apple ripeness determination. *Electronics Letters*, *35*, 821−823.

Ho, Q. T., Verboven, P., Verlinden, B., Herremans, E., Wevers, M., Carmeliet, J., & Nicolaï, B. (2011). A 3-D multiscale model for gas exchange in fruit. *Plant Physiology*, *155*, 1158−1168.

Hong, E. J., Son, H. J., Choi, J. Y., & Noh, B. S. (2011). Authentication of rapeseed oil using an electronic nose based on mass spectrometry. *Korean Journal of Food Science and Technology*, *43*(1), 105−109.

Huang, Y., Lu, R., & Chen, K. (2020). Detection of internal defect of apples by a multichannel Vis/NIR spectroscopic system. *Postharvest Biology and Technology*, *161*, 111065.

Huang, Y., Lu, R., Hu, D., & Chen, K. (2018). Quality assessment of tomato fruit by optical absorption and scattering properties. *Postharvest Biology and Technology*, *143*, 78−85.

Ibáñez, E., López-Sebastián, S., Ramos, E., Tabera, J., & Reglero, G. (1998). Analysis of volatile fruit components by headspace solid-phase microextraction. *Food Chemistry*, *63*, 281–286.

Jancsók, P., Clijmans, L., Nicolaï, B. M., De., & Baerdemaeker, J. (2001). Investigation of the effect of shape on the acoustic response of Conference pears by finite element modelling. *Postharvest Biology and Technology*, *23*, 1–12.

Janssens, E. A., Pereira, L. F., De Beenhouwer, J., Tsang, I. R., Van Dael, M., Verboven, P., . . . Sijbers, J. (2016). Fast inline inspection by neural network based filtered backprojection: Application to apple inspection. *Case Studies in Nondestructive Testing and Evaluation*, *6*, 14–20.

Janssens, E. De, Beenhouwer, J., Van Dael, M., De Schryver, T., Van Hoorebeke, L., Verboven, P., . . . Sijbers, J. (2018). Neural network Hilbert transform based filtered backprojection for fast inline x-ray inspection. *Measurement Science and Technology*, *29*(3).

Jaren, C. Ruiz-Altisent, M. & Perez de Rueda, R. (1992). 'Sensing physical stage of fruit by their response to non-destructive impacts'. In *Proceedings of the Agricultural Engineering International Conference 92*". AGENG 92, Uppsala, Sweden, 1–4 June 1992, paper 9211-113.

Jarolmasjed, S., Espinoza, C. Z., Sankaran, S., & Khot, L. R. (2016). Postharvest bitter pit detection and progression evaluation in 'Honeycrisp' apples using computed tomography images. *Postharvest Biology and Technology*, *118*, 35–42.

Jarolmasjed, S. Z., Espinoza, C., & Sankaran, S. (2017). Near infrared spectroscopy to predict bitter pit development in different varieties of apples. *Journal of Food Measurement and Characterization*, *11*(3), 987–993.

Jin, J., Zhao, M., Zhang, N., Jing, T., Liu, H., & Song. (2020). Stable isotope signatures vs gas chromatography-ion mobility spectrometry to determine the geographical origin of Fujian Oolong tea (*Camellia sinensis*) samples. *European Food Research and Technology*, *246*, 955–964.

Joyce, D. C., Hockings, P. D., Mazucco, R. A., Shorter, A. J., & Brereton, I. M. (1993). Heat treatment injury of mango fruit revealed by nondestructive magnetic resonance imaging. *Postharvest Biology and Technology*, *3*(4), 305–311.

Kafle, G. K., Khot, L. R., Jarolmasjed, S., Yongsheng, S., & Lewis, K. (2016). Robustness of near infrared spectroscopy based spectral features for non-destructive bitter pit detection in honeycrisp apples. *Postharvest Biology and Technology*, *120*, 188–192.

Keresztes, J. C., Diels, E., Goodarzi, M., Nguyen-Do-Trong, N., Goos, P., Nicolai, B., & Saeys, W. (2017). Glare based apple sorting and iterative algorithm for bruise region detection using shortwave infrared hyperspectral imaging. *Postharvest Biology and Technology*, *130*, 103–115.

Khatiwada, B. P., Subedi, P. P., Hayes, C., Carlos, L. C. C., & Walsh, K. B. (2016). Assessment of internal flesh browning in intact apple using visible-short wave near infrared spectroscopy. *Postharvest Biology and Technology*, *120*, 103–111.

Kim, S., & Schatzki, T. (2000). Apple watercore sorting system using X-ray imagery: I. Algorithm development. *Transactions of the American Society of Agricultural and Biological Engineers*, *43*(6), 1695–1702.

Kim, S., & Schatzki, T. (2001). Detection of pinholes in almonds through X-ray imaging. *Transactions of the ASAE*, *44*(4), 997–1003.

Kim, S. M., Lee, S. M., Seo, J. A., & Kim, Y. S. (2018). Changes in volatile compounds emitted by fungal pathogen spoilage of apples during decay. *Postharvest Biology and Technology*, *146*, 51–59.

Kirtil, E., Cikrikci, S., McCarthy, M. J., & Oztop, M. H. (2017). Recent advances in time domain NMR and MRI sensors and their food applications. *Current Opinion in Food Science*, *17*, 9–15.

Korytár, P., Janssen, H. G., Matisová, E., & Brinkman, U. A. T. (2002). Practical fast gas chromatography: Methods, instrumentation and applications. *Trends in Analytical Chemistry*, *21*, 558–572.

Kotwaliwale, N., Weckler, P. R., Brusewitz, G. H., Kranzler, G. A., & Maness, N. O. (2007). Non-destructive quality determination of pecans using soft X-rays. *Postharvest Biology and Technology*, *45*(3), 372–380.

Kuroki, S., Oshita, S., Sotome, I., Kawagoe, Y., & Seo, Y. (2004). 'Visualization of 3-D network of gas-filled intercellular spaces in cucumber fruit after harvest. *Postharvest Biology and Technology*, *33*, 255–262.

Lammertyn, J., Aerts, M., Verlinden, B. E., Schotsmans, W., & Nicolaï, B. M. (2000a). 'Logistic regression analysis of factors influencing core breakdown in "Conference" pears. *Postharvest Biology and Technology*, *20*(1), 25–37.

Lammertyn, J., Dresselaers, T., Van, H., PJancsok, P., Wevers, M., & Nicolai, B. M. (2003a). Analysis of the time course of core breakdown in 'Conference' pears by means of MRI and X-ray CT. *Postharvest Biology and Technology*, *29*, 19–28.

Lammertyn, J., Dresselaers, T., Van Hecke, P., Jancsok, P., Wevers, M., & Nicolaï, B. M. (2003b). MRI and X-ray CT study of spatial distribution of core breakdown in 'Conference' pears. *Magnetic Resonance Imaging*, *21*, 805–815.

Lammertyn, J., Peirs, A., De Baerdemaeker, J., & Nicolai, B. (2000b). Light penetration properties of NIR radiation in fruit with respect to non-destructive quality assessment. *Postharvest Biology and Technology*, *18*, 121–132.

Langenakens, J., Vandewalle, X., & De Baerdemaeker, J. (1997). Influence of global shape and internal structure of tomatoes on the resonant frequency. *Journal of Agricultural Engineering Research*, *66*, 41–49.

Langford, V. S., Padayachee, D., McEwan, M. J., & Barringer, S. A. (2019). Comprehensive odorant analysis for on-line applications using selected ion flow tube mass spectrometry (SIFT-MS). *Flavour and Fragrance Journal* (34, pp. 393–410).

Leonhardt, J. W. (2003). A new ppb-gas analyzer by means of GC-ion mobility spectrometry (GC–IMS). *Journal of Radioanalytical and Nuclear Chemistry*, *257*, 133–139.

Li, J., Huang, W., Zhao, C., & Zhang, B. (2013). A comparative study for the quantitative determination of soluble solids content, pH and firmness of pears by Vis/NIR spectroscopy. *Journal of Food Engineering*, *116*(2), 324–332.

Li, Z. F., Wang, N., Raghavan, G. S. V., & Vigneault, C. (2009). Ripeness and rot evaluation of 'Tommy Atkins' mango fruit through volatiles detection. *Journal of Food Engineering*, *91*, 319–324.

Lim, K. S., & Barigou, M. (2004). X-ray micro-computed tomography of cellular food products. *Food Research International*, *37*, 1001–1012.

Liu, J., Liu, S., Shin, S., Liu, F., Shi, T., Lv, C., & Men, H. (2020). Detection of apple taste information using model based on hyperspectral imaging and electronic tongue data. *Sensors and Materials*, *32*(5), 1767–1784.

Lloyd, S. W., Grimm, C. C., Klich, M. A., & Beltz, S. B. (2005). Fungal infections of fresh-cut fruit can be detected by the gas chromatography-mass spectrometric identification of microbial volatile organic compounds. *Journal of Food Protection*, *68*, 1211–1216.

López, L., Echeverria, G., Usall, J., & Teixidó, N. (2015). The detection of fungal diseases in the "Golden Smoothee" apple and "Blanquilla" pear based on the volatile profile. *Postharvest Biology and Technology* (99, pp. 120–130).

López-Maestresalas, A., Keresztes, J. C., Goodarzi, M., Arazuri, S., Jarén, C., & Saeys, W. (2016). Non-destructive detection of blackspot in potatoes by Vis-NIR and SWIR hyperspectral imaging. *Food Control*, *70*, 229–241.

Loutfi, A., Coradeschi, S., Mani, G. K., Shankar, P., & Rayappan, J. B. B. (2015). 'Electronic noses for food quality: A review. *Journal of Food Engineering*, *144*, 103–111.

Lu, R. (2016). In R. Lu (Ed.), *Light scattering technologies for food property, quality and safety assessment*. CRC Press.

Lu, R., Van Beers, R., Saeys, W., Li, C., & Cen, H. (2020). Measurement of optical properties of fruits and vegetables: A review'. *Postharvest Biology and Technology*, *159*, 111003.

Lu, Y., & Lu, R. (2017). Non-destructive defect detection of apples by spectroscopic and imaging technologies: A review. *Transactions of the ASABE*, *60*(5), 1765.

Luo, X., Ye, Z., Xu, H., Zhang, D., Bai, S., & Ying, Y. (2018). Robustness improvement of NIR-based determination of soluble solids in apple fruit by local calibration. *Postharvest Biology and Technology*, *139*, 82–90. Available from https://doi.org/10.1016/j.postharvbio.2018.01.019.

Maire, E., Buffière, J. Y., Salvo, L., Blandin, J. J., Ludwig, W., & Létang, J. M. (2001). On the application of X-ray microtomography in the field of materials science. *Advanced Engineering Materials*, *3*(8), 539–546.

Maire, E., Fazekas, A., Salvo, L., Dendievel, R., Youssef, S., Cloetens, P., & Letang, J. M. (2003). X-ray tomography applied to the characterization of cellular materials. Related finite element modeling problems. *Composites Science and Technology*, *63*, 2431–2443.

Martinsen, P., & Schaare, P. (1998). Measuring soluble solids distribution in kiwifruit using near-infrared imaging spectroscopy. *Postharvest Biology and Technology*, *14*, 271–281.

Masithoh, R. E., Haff, R., & Kawano, S. (2016). Determination of soluble solids content and titratable acidity of intact fruit and juice of Satsuma Mandarin using a hand-held near infrared instrument in transmittance mode. *Journal of near Infrared Spectroscopy*, *24*, 83–88.

Maul, F., Sargent, S. A., Balaban, M. O., Baldwin, E. A., Huber, D. J., & Sims, C. A. (1998). Aroma volatile profiles from ripe tomatoes are influenced by physiological maturity at harvest: An application for electronic nose technology. *Journal of the American Society for Horticultural Science*, *123*, 1094–1101.

Mazhar, M., Joyce, D., Cowin, G., Brereton, I., Hofman, P., Collins, R., & Gupta, M. (2015). Non-destructive 1H-MRI assessment of flesh bruising in avocado (*Persea americana* M.) cv. Hass. *Postharvest Biology and Technology*, *100*, 33–40.

McCarthy, M. J., Zhang, L., McCarthy, K. L., & Coulthard, T. (2016). Status and future of magnetic resonance imaging sensors for in-line assessment and sorting of fruit. *Acta Horticulturae*, *1119*, 121–126.

McCarthy, M. J., Zion, B., Chen, P., Ablett, S., Darke, A. H., & Lillford, P. J. (1995). Diamagnetic susceptibility changes in apple tissue after bruising. *Journal of the Science of Food and Agriculture*, *67*(1), 13–20.

McGlone, V. A., Martinsen, P. J., Clark, C. J., & Jordan, R. B. (2005). On-line detection of Brownheart in Braeburn apples using near infrared transmission measurements. *Postharvest Biology and Technology*, *37*(2), 142−151.

Mehl, P. M., Chen, Y. R., Kim, M. S., & Chan, D. E. (2004). Development of hyperspectral imaging technique for the detection of apple surface defects and contaminations. *Journal of Food Engineering*, *61*, 67−81.

Melado-Herreros, A., Muñoz-García, M. A., Blanco, A., Val, J., Fernández-Valle, M. E., & Barreiro, P. (2013). Assessment of watercore development in apples with MRI: Effect of fruit location in the canopy. *Postharvest Biology and Technology*, *86*, 125−133.

Mendoza, F., Verboven, P., Mebatsion, H. K., Kerckhofs, G., Wevers, M., & Nicolaï, B. (2007). Three-dimensional pore space quantification of apple tissue using X-ray computed microtomography. *Planta*, *226*, 559−570.

Mesquita, P. R. R., Pena, L. C., dos Santos, F. N., de Oliveira, C. C., Magalhães-Junior, J. T., Nascimento, A. S., & Rodrigues, F. M. (2020). Mango (*Mangifera indica*) aroma discriminate cultivars and ripeness stages. *Journal of the Brazilian Chemical Society*, *31*, 1424−1433.

Milczarek, R. R., & McCarthy, M. J. (2009). Low-field MR sensors for fruit inspection. In S. Codd, & J. Seymour (Eds.), *Magnetic resonance microscopy, spatially resolved NMR techniques and applications* (pp. 289−299). Weinheim: Wiley.

Mogollon, M. R., Jara, A. F., Contreras, C., & Zoffoli, J. P. (2020). Quantitative and qualitative VIS-NIR models for early determination of internal browning in' Cripps Pink' apples during cold storage. *Postharvest Biology and Technology*, *161*. Available from https://doi.org/10.1016/j.postharvbio.2019.111060.

Mollazade, K., & Arefi, A. (2017). Optical analysis using monochromatic imaging-based spatially-resolved technique capable of detecting mealiness in apple fruit. *Scientia Horticulturae*, *225*, 589−598.

Molto, E., Selfa, E., Ferriz, J., Conesa, E., & Gutierrez, A. (1999). An aroma sensor for assessing peach quality. *Journal of Agricultural Engineering Research*, *72*, 311−316.

Molto, E. Selfa, E. Pons, R. & Fornes, I. (1996). 'Non destructive measuring of firmness using impact sensors'. In *Proceedings of the Agricultural Engineering International Conference 96*. AGENG 96, Madrid, Spain, 23−26 September 1996, paper 96F-014.

Mondello, L., Casilli, A., Tranchida, P. Q., Costa, R., Dugo, P., & Dugo, G. (2004). Fast GC for the analysis of citrus oils. *Journal of Chromatographic Science*, *42*, 410−416.

Mukarev, M. I., & Walsh, K. B. (2012). Prediction of brix values of intact peaches with least squares support vector machine regression models. *Journal of Near Infrared Spectroscopy*, *20*, 647−655.

Musse, M., De Guio, F., Quellec, S., Cambert, M., Challois, S., & Davenel, A. (2010). 'Quantification of microporosity in fruit by MRI at various magnetic fields: Comparison with X-ray microtomography. *Magnetic Resonance Imaging*, *28*, 1525−1534.

Muziri, T., Theron, K. I., Cantre, D., Wang, Z., Verboven, P., Nicolai, B. M., & Crouch, E. M. (2016). Microstructure analysis and detection of mealiness in 'Forelle' pear (*Pyrus communis* L.) by means of X-ray computed tomography. *Postharvest Biology and Technology*, *120*, 145−156.

Nahir, D. Schmilovitch, Z. & Ronen, B. (1986). 'Tomato grading by impact force response', *ASAE paper 86−3028*, ASAE, St. Joseph, MI.

Nguyen Do Trong, N., Erkinbaev, C., Tsuta, M., De Baerdemaeker, J., Nicolaï, B., & Saeys, W. (2014). Spatially resolved diffuse reflectance in the visible and near-infrared wavelength range for non-destructive quality assessment of 'Braeburn' apples. *Postharvest Biology and Technology*, *91*, 39−48.

Nguyen, T. A., Dresselaers, T., Verboven., P D'hallewin, G., Culeddu, N., Van Hecke, P., & Nicolai, B. M. (2006). Finite element modelling and MRI validation of 3D transient water profiles in pears during postharvest storage. *Journal of the Science of Food and Agriculture*, *86*, 745−756.

Nicolaï, B. M., Defraeye, T., De Ketelaere, B., Herremans, E., Hertog, M. L. A. T. M., Saeys, W., ... Verboven, P. (2014). Nondestructive measurement of fruit and vegetable quality. *Annual Review of Food Science and Technology*, *5*, 285−312.

Nicolaï, B. M., Beullens, K., Bobelyn, E., Peirs, A., Theron, K. I., & Lammertyn, J. (2007). Nondestructive measurement of fruit and vegetable quality by means of NIR spectroscopy. *Postharvest Biology and Technology*, *46*, 99−118.

Nicolaï, B. M., Verlinden, B. E., Desmet, M., Saevels, S., Theron, K., Cubeddu, R., ... Torricelli, A. (2008). Time-resolved and continuous wave NIR reflectance spectroscopy to predict firmness and soluble solids content of conference pears. *Postharvest Biology and Technology*, *47*, 68−74.

Oshita, S., Shima, K., Haruta, T., Seo, Y., Kawagoe, Y., Nakayama, S., & Takahara, H. (2000). Discrimination of odors emanating from 'La France' pear by semi-conducting polymer sensors. *Computers and Electronics in Agriculture*, *26*, 209–216.

Ozcan, G., & Barringer, S. (2011). 'Effect of enzymes on strawberry volatiles during storage, at different ripeness level, in different cultivars, and during eating. *Journal of Food Science*, *76*, 324–333.

Pallottino, F., Costa, C., Antonucci, F., Strano, M. C., Calandra, M., Solaini, S., & Menesatti, P. (2012). 'Electronic nose application for determination of *Penicillium digitatum* in Valencia oranges. *Journal of the Science of Food and Agriculture*, *92*, 2008–2012.

Peiris, K. H. S., Dull, G. G., Leffler, R. G., & Kays, S. J. (1999). Spatial variability of soluble solids or dry-matter content within individual fruits, bulbs, or tubers: Implications for the development and use of NIR spectrometric techniques. *HortScience: A Publication of the American Society for Horticultural Science*, *34*, 114–118.

Peirs, A., Scheerlinck, N., & Nicolaï, B. M. (2003a). Temperature compensation for near infrared reflectance measurement of apple fruit soluble solids contents. *Postharvest Biology and Technology*, *30*, 233–248.

Peirs, A., Tirry, J., Verlinden, B., Darius, P., & Nicolaï, B. M. (2003b). Effect of biological variability on the robustness of NIR models for soluble solids content of apples. *Postharvest Biology and Technology*, *28*, 269–280.

Peleg, K. (1993). 'Comparison of nondestructive and destructive measurement of apple firmness. *Journal of Agricultural Engineering Research*, *55*, 227–238.

Pereira, L. F. A., Janssens, E., Cavalcanti, G. D. C., Tsang, I. R., Van Dael, M., Verboven, P., Nicolai, B., & Sijbers, J. (2017). Inline discrete tomography system: Application to agricultural product inspection. *Computers and Electronics in Agriculture*, *138*, 117–126.

Pereira, T., Tijskens, L. M. M., Vanoli, M., Rizzolo, A., Zerbini, P. E., Torricelli, A., Spinelli, L., & Filgueiras, H. (2010). Assessing the harvest maturity of Brazilian mangoes. *Acta Horticulturae*, *880*, 269–276.

Pleil, J. D., Hansel, A., & Beauchamp, J. (2019). Advances in proton transfer reaction mass spectrometry (PTR-MS): Applications in exhaled breath analysis, food science, and atmospheric chemistry. *Journal of Breath Research.*, *13*, 039002.

Qin, J. W., & Lu, R. F. (2008). 'Measurement of the optical properties of fruits and vegetables using spatially resolved hyperspectral diffuse reflectance imaging technique. *Postharvest Biology and Technology*, *49*, 355–365.

Qin, J., Lu, R., & Peng, Y. (2009). Prediction of apple internal quality using spectral absorption and scattering properties. *Transactions of the ASABE*, *52*, 499–507.

Ragni, L., Berardinelli, A., & Guarnieri, A. (2010). Impact device for measuring the flesh firmness of kiwifruits. *Journal of Food Engineering*, *96*, 591–597.

Rakow, N. A., & Suslick, K. S. (2000). A colorimetric sensor array for odour visualization. *Nature*, *406*, 710–713.

Ravikanth, L., Jayas, D. S., White, N. D., Fields, P. G., & Sun, D. W. (2017). Extraction of spectral information from hyperspectral data and application of hyperspectral imaging for food and agricultural products. *Food and Bioprocess Technology*, *10*(1), 1–33.

Razavi, M. S., Asghari, A., Azadbakh, M., & Shamsabadi, H. A. (2018). Analyzing the pear bruised volume after static loading by magnetic resonance imaging (MRI). *Scientia Horticulturae*, *229*, 33–39.

Rizzolo, A., & Vanoli, M. (2016). Time-resolved technique for measuring optical properties and quality of food'. In R. Lu (Ed.), *Light scattering technology for food property, quality and safety assessment* (pp. 178–224). CRC Press.

Rohrbach, R. P., Franke, J. E., & Willits, D. H. (1982). A firmness sorting criterion for blueberries. *Transactions of the ASAE*, *25*, 261–265.

Romano, A., Cuenca, M., Makhoul, S., Biasioli, F., Martinello, L., Fugatti, A., & Scampicchio, M. (2016). Comparison of e-noses: The case study of honey. *Italian Journal of Food Science*, *28*, 326–337.

Ruiz-Beviá, F., Font, A., García, A. N., Blasco, P., & Ruiz, J. J. (2002). Quantitative analysis of the volatile aroma components of pepino fruit by purge-and-trap and gas chromatography. *Journal of the Science of Food and Agriculture*, *82*, 1182–1188.

Rungpichayapichet, P., Nagle, M., Yuwanbun, P., Khuwijitjaru, P., Mahayothee, B., & Müller, J. (2017). Prediction mapping of physicochemical properties in mango by hyperspectral imaging. *Biosystems Engineering*, *159*, 109–120.

Rutolo, M. F., Clarkson, J. P., & Covington, J. A. (2018). The use of an electronic nose to detect early signs of soft-rot infection in potatoes. *Biosystems Engineering*, *167*, 137–143.

Saari, H. Aallos, V. V. Akujärvi, A. Antila, T. Holmlund, C. Kantojärvi, U. & Ollila, J. (2009, September). Novel miniaturized hyperspectral sensor for UAV and space applications. In *Sensors, systems, and next-generation satellites XIII* (Vol. 7474, p. 74741M). International Society for Optics and Photonics.

Saevels, S., Lammertyn, J., Berna, A. Z., Veraverbeke, E. A., Di Natale, C., & Nicolaï, B. M. (2004). An electronic nose and a mass spectrometry-based electronic nose for assessing apple quality during shelf life. *Postharvest Biology and Technology*, *31*, 9−19.

Saeys, W. N., Do Trong, N., Van Beers, R., & Nicolaï, B. M. (2019). Multivariate calibration of spectroscopic sensors for postharvest quality evaluation: A review. *Postharvest Biology and Technology*, *158*, 110981.

Saeys, W., Velazco-Roa, M. A., Thennadil, S. N., Ramon, H., & Nicolaï, B. M. (2008). 'Optical properties of apple skin and flesh in the wavelength range from 350 to 2200 nm. *Applied Optics*, *47*(7), 908−919.

Saito, K., Miki, T., Hayashi, S., Kajikawa, H., Shimada, M., Kawate, Y., Nishizawa, T., Ikegaya, D., Kimura, N., Takabatake, K., Sugiura, N., & Suzuki, M. (1996). Application of magnetic resonance imaging to nondestructive void detection in watermelon. *Cryogenics*, *36*(12), 1027−1031.

Salvo, L., Cloetens, P., Maire, E., Zabler, S., Blandin, J. J., Buffiere, J. Y., Ludwig, W., Boller, E., Bellet, D., & Josserond, C. (2003). X-ray micro-tomography an attractive characterisation technique in materials science. *Nuclear Instruments and Methods in Physics Research Section B-Beam Interactions with Materials and Atoms*, *200*, 273−286.

Schatzki, T. F., Haff, R. P., Young, R., Can, I., Le, L. C., & Toyofuku, N. (1997). Defect detection in apples by means of x-ray imaging. *Transactions of the ASAE*, *40*, 1407−1415.

Schotte, S., De Belie, N., & De Baerdemaeker, J. (1999). Acoustic impulse-response technique for evaluation and modelling of firmness of tomato fruit. *Postharvest Biology and Technology*, *17*, 105−115.

Shmulevich, I., Galili, N., & Howarth, M. S. (2003). Nondestructive dynamic testing of apples for firmness evaluation. *Postharvest Biology and Technology*, *29*, 287−299.

Shmulevich, I., Galili, N., & Rosenfeld, D. (1996). Detection of fruit firmness by frequency analysis. *Transactions of the ASAE*, *39*, 1047−1055.

Signoroni, A., Savardi, M., Baronio, A., & Benini, S. (2019). Deep learning meets hyperspectral image analysis: A multidisciplinary review. *Journal of Imaging*, *5*(5), 52.

Smith, D., & Španěl, P. (1996). Application of ion chemistry and the SIFT technique to the quantitative analysis of trace gases in air and on breath. *International Reviews in Physical Chemistry*, *15*, 231−271.

Sonego, L., Benarie, R., Raynal, J., & Pech, J. C. (1995). Biochemical and physical evaluation of textural characteristics of nectarines exhibiting woolly breakdown − NMR imaging, X-ray computed-tomography and pectin composition. *Postharvest Biology and Technology*, *5*, 187−198.

Španěl, P., & Smith, D. (1999). Selected ion flow tube−mass spectrometry: Detection and real-time monitoring of flavours released by food products. *Rapid Communications in Mass Spectrometry*, *13*, 585−596.

Španěl, P., Rolfe, P., Rajan, B., & Smith, D. (1996). The selected ion flow tube (SIFT)—A novel technique for biological monitoring. *Annals of Occupational Hygiene*, *40*, 615−626.

Srivastava, R. K., Talluri, S., Khasim Beebi, S., & Kumar, R. (2018). Magnetic resonance imaging for quality evaluation of fruits: A review. *Food Analytical Methods*, *11*(10), 2943−2960.

Suchanek, M., Kordulska, M., Olejniczak, Z., Figiel, H., & Turek, K. (2017). Application of low-field MRI for quality assessment of 'conference' pears stored under controlled atmosphere conditions. *Postharvest Biology and Technology*, *124*, 100−106.

Sukumaran, A. T., Coatney, K., Ellington, J., Holtcamp, A. J., Schilling, M. W., & Dinh, T. T. N. (2019). Consumer acceptability and demand for cooked beef sausage formulated with pre- and post-rigor deboned beef. *Meat and Muscle Biology*, *3*, 210−218.

Sun, C., Aernouts, B., Van Beers, R., & Saeys, W. (2020a). Simulation of light propagation in citrus fruit using Monte Carlo multi-layered (MCML) method. *Journal of Food Engineering*, *291*, 110225.

Sun, C. V., Beers, R., Aernouts, B., & Saeys, W. (2020b). Bulk optical properties of citrus tissues and the relationship with quality properties. *Postharvest Biology and Technology*, *163*(111127).

Sun, T., Huang, K., Xu, H., & Ying, Y. (2010). Research advances in nondestructive determination of internal quality in watermelon/melon: A review. *Journal of Food Engineering*, *100*(4), 569−577.

Taiti, C., Costa, C., Menesatti, P., Caparrotta, S., Bazihizina, N., Azzarello, E., Petrucci, W. A., Masi, E., & Giordani, E. (2015). Use of volatile organic compounds and physicochemical parameters for monitoring the post-harvest ripening of imported tropical fruits. *European Food Research and Technology*, *241*, 91−102.

Tao, F., Zhang, L., McCarthy, M. J., Beckles, D. M., & Saltveit, M. (2014). Magnetic resonance imaging provides spatial resolution of Chilling Injury in Micro-Tom tomato (*Solanum lycopersicum* L.) fruit. *Postharvest Biology and Technology*, *97*, 62−67.

Thomas, P., Saxena, S. C., Chandra, R., Rao, R., & Bhatia, C. R. (1993). 'X-ray-imaging for detecting spongy tissue, an internal disorder in fruits of Alphonso mango (*Mangifera-Indica* L). *Journal of Horticultural Science*, *68*, 803−806.

Thybo, A. K., Jespersen, S. N., Lærke, P. E., & Stødkilde-Jørgensen, H. J. (2004). Nondestructive detection of internal bruise and spraing disease symptoms in potatoes using magnetic resonance imaging. *Magnetic Resonance Imaging*, *22*(9), 1311−1317.

Tian, Hq, Ying, Yb, Lu, Hs, Fu, Xp, & Yu, Hy (2007). Measurement of soluble solids content in watermelon by Vis/NIR diffuse transmittance technique. *Journal of Zhejiang University*. *Science*. *B*, *8*, 105−110.

Torres, C. A., Sánchez-Contreras, J., Hernández, O., & León, L. F. (2015). 'Flesh browning assessment in "Cripps Pink" apples using vis-NIR spectroscopy. *Acta Horticulturae*, *1079*, 415−420.

Tu, K., Jancsok, P., Nicolaï, B., & De Baerdemaeker, J. (2000). Use of laser-scattering imaging to study tomato-fruit quality in relation to acoustic and compression measurements. *International Journal of Food Science and Technology*, *35*, 503−510.

Upchurch, B. L., Throop, J. A., & Aneshansley, D. J. (1997). Detecting internal breakdown in apples using interactance measurements. *Postharvest Biology and Technology*, *10*(1), 15−19.

Valero, C., Crisosto, C. H., & Slaughter, D. (2007). Relationship between nondestructive firmness measurements and commercially important ripening fruit stages for peaches, nectarines and plums. *Postharvest Biology and Technology*, *44*(3), 248−253.

Valero, C., Ruiz-Altisent, M., Cubeddu, R., Pifferi, A., Taroni, P., Torricelli, A., Valentini, G., Johnson, D. S., & Dover, C. J. (2004). Detection of internal quality in kiwi with time-domain diffuse reflectance spectroscopy. *Applied Engineering in Agriculture*, *20*, 223−230.

Van As, H., & van Duynhoven, J. (2013). MRI of plants and foods. *Journal of Magnetic Resonance*, *229*, 25−34.

Van Beers, R., Aernouts, B., León Gutiérrez, L., Erkinbaev, C., Rutten, K., Schenk, A., Nicolaï, B., & Saeys, W. (2015). Optimal illumination-detection distance and detector size for predicting Braeburn apple maturity from Vis/NIR laser reflectance measurements. *Food and Bioprocess Technology*, *8*(10), 2123−2136.

Van Beers, R., Aernouts, B., Watté, R., Schenk, A., Nicolaï, B., & Saeys, W. (2017). Effect of maturation on the bulk optical properties of apple skin and cortex in the 500−1850 nm wavelength range. *Journal of Food Engineering*, *214*, 79−89.

van Dael, M., Lebotsa, S., Herremans, E., Verboven, P., Sijbers, J., Opara, U. L., Cronje, P. J., & Nicolaï, B. M. (2016). A segmentation and classification algorithm for online detection of internal disorders in citrus using X-ray radiographs. *Postharvest Biology and Technology*, *112*, 205−214.

van Dael, M., Rogge, S., Verboven, P., Saeys, W., Sijbers, J., & Nicolai, B. (2015). 'Online tomato inspection using X-ray radiographies and 3-dimensional shape models'. *Chemical Engineering Transactions*, *44*, 37−42.

van Dael, M., Verboven, P., Dhaene, J., Van Hoorebeke, L., Sijbers, J., & Nicolai, B. M. (2017). Multisensor X-ray inspection of internal defects in agrofood products. *Postharvest Biology and Technology*, *128*(C), 33−43.

van Dael, V. P., Zanella, A., Sijbers, J., & Nicolai, B. (2018). Combination of shape and X-ray inspection for apple internal quality control: In silico analysis of the methodology based on X-ray computed tomography. *Postharvest Biology and Technology*, *148*, 218−227.

van Dalen, G., Blonk, H., van Aalst, H., & Hendriks, C. L. (2003). 3-D imaging of foods using X-ray microtomography'. *GIT Imaging and Microscopy*, *3*, 18−21.

Van De Looverbosch, T., Bhuiyan, Md. H. R., Verboven, P., Dierick, M., Van Loo, D., De Beenbouwer, J., Sijbers, J., & Nicolaï, B. (2020). Nondestructive internal quality inspection of pear fruit by X-ray CT using machine learning. *Food Control*, *113*, 107170.

van Henten, E. (2019). *Automation and robotics in greenhouses. Achieving sustainable greenhouse cultivation*. Burleigh Dodds Science Publishing Limited.

van Roy, J., Keresztes, J. C., Wouters, N., De Ketelaere, B., & Saeys, W. (2017). Measuring colour of vine tomatoes using hyperspectral imaging. *Postharvest Biology and Technology*, *129*, 79−89.

Vandendriessche, T., Keulemans, J., Geeraerd, A., Nicolaï, B. M., & Hertog, M. L. A. T. M. (2012). Evaluation of fast volatile analysis for detection of Botrytis cinerea infections in strawberry. *Food Microbiology*, *32*, 406−414.

Vandendriessche, T., Nicolaï, B. M., & Hertog, M. L. A. T. M. (2013). Optimization of HS SPME fast GC−MS for high-throughput analysis of strawberry aroma. *Food Analytical Methods*, *6*, 512−520.

Vangdal, E., Zerbini, P. E., Vanoli, M., Rizzolo, A., Lovati, F., Torricelli, A., & Spinelli, L. (2012). Detecting internal physiological disorders in stored plums (*Prunus domestica* L.) by time-resolved reflectance spectroscopy. *Acta Horticulturae*, *945*, 197−204.

Vanoli, M., Rizzolo, A., Eccher Zerbini, P., Spinelli, L., & Torricelli, A. (2009). Nondestructive detection of internal defects in apple fruit by time-resolved reflectance spectroscopy. In C. Nuenes (Ed.), *Environmentally friendly and safe technologies for quality of fruits and vegetables* (pp. 20−26). Universidade do Algarve.

Vanoli, M., Rizzolo, A., Grassi, M., Spinelli, L., Verlinden, B. E., & Torricelli, A. (2014). Studies on classification models to discriminate 'Braeburn' apples affected by internal browning using the optical properties measured by time-resolved reflectance spectroscopy. *Postharvest Biology and Technology*, *91*, 112−121.

Vanoli, M. V., Beers, R., Sadar, N., Rizzolo, A., Buccheri, M., Grassi, M., Lovati, F., Nicolaï, B., Aernouts, B., Watté, R., Torricelli, A., Spinelli, L., Saeys, W., & Zanella, A. (2020). 'Time- and spatially-resolved spectroscopy to determine the bulk optical properties of 'Braeburn' apples after ripening in shelf life. *Postharvest Biology and Technology*, *168*, 111233.

Vedashree, M., Asha, M. R., Roopavati, C., & Naidu, M. M. (2020). Characterization of volatile components from ginger plant at maturity and its value addition to ice cream. *Journal of Food Science and Technology*, *57*, 3371−3380.

Vendel, I., Hertog, M., & Nicolaï, B. (2019). Fast analysis of strawberry aroma using SIFT-MS: A new technique in postharvest research. *Postharvest Biology and Technology*, *152*, 127−138.

Verboven, P., Kerckhofs, G., Mebatsion, H., Ho, Q. T., Temst, K., Wevers, M., Cloetens, P., & Nicolaï, B. M. (2008). Three-dimensional gas exchange pathways in pome fruit characterized by synchrotron X-ray computed tomography. *Plant Physiology*, *147*, 518−527.

Verstreken, E., & De Baerdemaeker, J. (1994). Evolution of maturity of peaches: Non-destructive firmness measurement from the acoustic impulse response. *International Agrophysics*, *8*, 469−473.

Viggiano, A. A., Howorka, F., Albritton, D. L., Fehsenfeld, F. C., Adams, N. G., & Smith, D. (1980). Laboratory studies of some ion-atom reactions related to interstellar molecular synthesis. *The Astrophysical Journal*, *236*, 492−497.

Wallays, C., Missotten, B., De Baerdemaeker, J., & Saeys, W. (2009). Hyperspectral waveband selection for on-line measurement of grain cleanness. *Biosystems Engineering*, *104*(1), 1−7.

Walsh, K. B., Blasco, J., Zude-Sasse, M., & Sun, X. (2020). Visible-NIR 'point' spectroscopy in postharvest fruit and vegetable assessment: The science behind three decades of commercial use. *Postharvest Biology and Technology*, *168*, 111246.

Wang, C. Y., & Wang, P. C. (1989). Nondestructive detection of core breakdown in Bartlett pears with nuclear magnetic-resonance imaging. *HortScience: A Publication of the American Society for Horticultural Science*, *24*, 106−109.

Wang, S. Y., Wang, P. C., & Faust, M. (1988). Non-destructive detection of watercore in apple with nuclear magnetic-resonance imaging. *Scientia Horticulturae*, *35*, 227−234.

Wang, Z., Herremans, E., Janssen, S., Cantre, D., Verboven, P., & Nicolaï, B. (2018). Visualizing 3D food microstructure using tomographic methods: Advantages and disadvantages. *Annual Review of Food Science and Technology*, *9*(1), 323−343.

Wang, Z. Van, Beers, R., Aernouts, B., Watté, R., Verboven, P., Nicolaï, B., & Saeys, W. (2020). Microstructure affects light scattering in apples. *Postharvest Biology and Technology*, *159*, 110996.

Watté, R. Do, Trong, N. N., Aernouts, B., Erkinbaev, C., De Baerdemaeker, J., Nicolaï, B., & Saeys, W. (2013). Metamodeling approach for efficient estimation of optical properties of turbid media from spatially resolved diffuse reflectance measurements'. *Optics Express*, *21*(26), 32630−32642.

Wu, D., & Sun, D. W. (2013). Colour measurements by computer vision for food quality control—A review. *Trends in Food Science and Technology*, *29*, 5−20.

Xing, J., Bravo, C., Jancsók, P. T., Ramon, H., De., & Baerdemaeker, J. (2005). Detecting bruises on 'Golden Delicious' apples using hyperspectral imaging with multiple wavebands. *Biosystems Engineering*, *90*(1), 27−36.

Xu, C. H., Chen, G. S., Xiong, Z. H., Fan, Y. X., Wang, X. C., & Liu, Y. (2016). Applications of solid-phase microextraction in food analysis'. *Trends in Analytical Chemistry*, *80*, 12−29.

Xu, Y., & Barringer, S. (2010). 'Comparison of volatile release in tomatillo and different varieties of tomato during chewing. *Journal of Food Science*, *75*, 352−358.

Yan, H., & Siesler, H. W. (2018). 'Hand-held near-infrared spectrometers: State-of-the-art instrumentation and practical applications. *NIR News*, *29*(7), 8−12.

Yang, L., Liu, J., Wang, X., Wang, R., Ren, F., Zhang, Q., Shan, Y., & Ding, S. (2019). 'Characterization of volatile component changes in jujube fruits during cold storage by using headspace-gas chromatography-ion mobility spectrometry. *Molecules (Basel, Switzerland)*, *24*, 1−21.

Young, H., Rossiter, K., Wang, M., & Miller, M. (1999). Characterization of Royal Gala apple aroma using electronic nose technology-potential maturity indicator. *Journal of Agricultural and Food Chemistry*, *47*, 5173−5177.

Yuzhen, L. Wouter S. Moon K. Yankun P. Renfu L. (2020). *Hyperspectral imaging technology for quality and safety evaluation of horticultural products: A review and celebration of the past 20-year*, Vol 170, pp. 1873−2356.

Zhang, L., & McCarthy, M. J. (2012). Black heart characterization and detection in pomegranate using NMR relaxometry and MR imaging. *Postharvest Biology and Technology*, *67*, 96−101.

Zhang, L., & McCarthy, M. J. (2016). NMR relaxometry study of development of freeze damage in mandarin orange. *Journal of the Science of Food and Agriculture*, *96*(9), 3133−3139.

Zhang, L., Shuai, Q., Li, P., Zhang, Q., Ma, F., Zhang, W., & Ding, X. (2016). Ion mobility spectrometry fingerprints: A rapid detection technology for adulteration of sesame oil'. *Food Chemistry* (192, pp. 60−66).

Zhou, L., Zhang, C., Liu, F., Qiu, Z., & He, Y. (2019). Application of deep learning in food: A review. *Comprehensive Reviews in Food Science and Food Safety*, *18*(6), 1793−1811.

Zhu, Q., He, C., Lu, R., Mendoza, F., & Cen, H. (2015). Ripeness evaluation of "Sun Bright" tomato using optical absorption and scattering properties. *Postharvest Biology and Technology*, *103*, 27−34.

Zion, B., Chen, P., & McCarthy, M. J. (1995). Detection of bruises in magnetic resonance images of apples. *Computers and Electronics in Agriculture*, *13*(4), 289−299.

Further reading

Abbott, J. A., Lu, R., Upchurch, B. L., & Stroshine, R. L. (1997). Technologies for non-destructive quality evaluation of fruits and vegetables. *Horticultural Reviews*, *20*, 1−120.

Barcelon, E. G., Tojo, S., & Watanabe, K. (1999). X-ray CT imaging and quality detection of peach at different physiological maturity. *Transactions of the ASAE*, *42*, 435−441.

Bearman, G. & Levenson, R. (2001). *Biological imaging spectroscopy*. http://hdl.handle.net/2014/11729.

Berna, A. Z., Geysen, S., Li, S., Verlinden, B., Lammertyn, J., & Nicolai, B. M. (2007). Headspace fingerprint mass spectrometry to characterize strawberry aroma at super atmospheric oxygen conditions. *Postharvest Biology and Technology*, *46*, 230−236.

Boukobza, F., Dunphy, P. J., & Taylor, A. J. (2001). Measurement of lipid oxidation-derived volatiles in fresh tomatoes. *Postharvest Biology and Technology*, *23*, 117−131.

Brecht, J. K., Shewfelt, R. L., Garner, J. C., & Tollner, E. W. (1991). Using X-ray-computed tomography to nondestructively determine maturity of green tomatoes'. *HortScience: A Publication of the American Society for Horticultural Science*, *26*, 45−47.

Brosnan, T., & Sun, D. W. (2004). 'Improving quality inspection of food products by computer vision—A review. *Journal of Food Engineering*, *61*, 3−16.

Carlini, P., Massantini, R., & Mencarelli, F. (2000). Vis-NIR measurement of soluble solids in cherry and apricot by PLS regression and wavelength selection. *Journal of Agricultural and Food Chemistry*, *48*, 5236−5242.

Clark, C. J., Drummond, L. N., & MacFall, J. S. (1998a). Quantitative NMR imaging of kiwifruit (*Actinidia deliciosa*) during growth and ripening. *Journal of the Science of Food and Agriculture*, *78*, 349−358.

Clark, C. J., MacFall, J. S., & Bieleski, R. L. (1998b). Loss of watercore from 'Fuji' apple observed by magnetic resonance imaging'. *Scientia Horticulturae*, *73*, 213−227.

Cloetens, P., Mache, R., Schlenker, M., & Lerbs-Mache, S. (2006). 'Quantitative phase tomography of Arabidopsis seeds reveals intercellular void network. *Proceedings of the National Academy of Sciences of the United States of America*, *103*, 14626−14630.

Cubeddu, R., D'Andrea, C., Pifferi, A., Taroni, P., Torricelli, A., Valentini, G., ... Valero, C. (2001). Nondestructive quantification of chemical and physical properties of fruits by time-resolved reflectance spectroscopy in the wavelength range 650−1000 nm. *Applied Optics*, *40*, 538−543.

Di Natale, C. Mantini, A. Macagnano, A. Paolesse, R. & D'Amico, A. (2000). The application of an electronic nose to the analysis of post-harvested fruits. In *Proceedings of the 14th European conference on solid-state transducers, eurosensors XIV* (pp. 61−62). Copenhagen, Denmark, 27−30 August 2000.

Donis-Gonzalez, I. R., Guyer, D. E., & Pease. (2012b). Application of response surface methodology to systematically optimize image quality in computer tomography: A case study using fresh chestnuts', (Castanea spp.). *Computers and Electronics in Agriculture*, *87*, 94−107.

Donis-Gonzalez, I. R., Guyer, D. E., Pease, A., & Fulbright, D. W. (2012a). 'Relation of computerized tomography Hounsfield unit measurements and internal components of fresh chestnuts' (Castanea spp.). *Postharvest Biology and Technology*, *64*, 74–82.

Eccher Zerbini, P., Vanoli, M., Grassi, M., Rizzolo, A., Fibiani, M., Cubeddu, R., . . . Torricelli, A. (2006). A model for the softening of nectarines based on sorting fruit at harvest by time-resolved reflectance spectroscopy. *Postharvest Biology and Technology*, *39*, 223–232.

Gardner, J. W., & Bartlett, P. N. (1994). A brief-history of electronic noses. *Sensors and Actuators B-Chemical*, *18*, 211–220.

Garratt, L. C., Linforth, R., Taylor, A. J., Lowe, K. C., Power, J. B., & Davey, M. R. (2005). Metabolite fingerprinting in transgenic lettuce. *Plant Biotechnology Journal*, *3*, 165–174.

Guthrie, J. A., Wedding, B., & Walsh, K. B. (1998). Robustness of NIR calibrations for soluble solids in intact melon and pineapple. *Journal of Near Infrared Spectroscopy*, *6*, 259–265.

Jordan, A., Haidacher, S., Hanel, G., Hartungen, E., Herbig, J., Märk, L., . . . Märk, T. D. (2009). An online ultra-high sensitivity proton-transfer-reaction mass-spectrometer combined with switchable reagent ion capability (PTR + SRI − MS). *International Journal of Mass Spectrometry* (286, pp. 32–38).

Kawano, S., Fujiwara, T., & Iwamoto, M. (1993). Nondestructive determination of sugar content in Satsuma Mandarin using near-infrared (NIR) transmittance. *Journal of the Japanese Society for Horticultural Science*, *62*, 465–470.

Kondo, N., Nishitsuji, Y., Ling, P. P., & Ting, K. C. (1996). Visual feedback guided robotic cherry tomato harvesting. *Transactions of the ASAE*, *39*, 2331–2338.

Lammertyn, J., Nicolaï, B., Ooms, K., De Smedt, V., & De Baerdemaeker, J. (1998). Non-destructive measurement of acidity, soluble solids, and firmness of Jonagold apples using NIR-spectroscopy. *Transactions of the ASAE*, *41*, 1089–1094.

Liao, K. Reid, J. F. Paulsen, M.R. Ni, B. (1992). 'Knowledge based color discrimination of corn kernels', *ASAE paper 923579*, ASAE, St. Joseph, MI.

Long, R. L., & Walsh, K. B. (2006). Limitations to the measurement of intact melon total soluble solids using near infrared spectroscopy. *Australian Journal of Agricultural Research*, *57*, 403–410.

Lu, R. (2001). 'Predicting firmness and sugar content of sweet cherries using near-infrared diffuse reflectance spectroscopy'. *Transactions of the ASAE*, *44*, 1265–1271.

Lu, R. F. (2004). 'Prediction of apple fruit firmness by near-infrared multispectral scattering. *Journal of Texture Studies*, *35*, 263–276.

Macdougall, D. B. (1982). Changes in the color and opacity of meat. *Food Chemistry*, *9*, 75–88.

McGlone, V. A., & Kawano, S. (1998). Firmness, dry-matter and soluble-solids assessment of postharvest kiwifruit by NIR spectroscopy. *Postharvest Biology and Technology*, *13*, 131–141.

McGlone, V. A., Abe, H., & Kawano, S. (1997). 'Kiwifruit firmness by near infrared light scattering. *Journal of Near Infrared Spectroscopy*, *5*, 83–89.

Mehinagic, E., Royer, G., Symoneaux, R., Bertrand, D., & Jourjon, F. (2004). Prediction of the sensory quality of apples by physical measurements. *Postharvest Biology and Technology*, *34*, 257–269.

Mendoza, F., Verboven, P., Ho, Q. T., Kerckhofs, G., Wevers, M., & Nicolaï, B. M. (2010). 'Multifractal properties of pore-size distribution in apple tissue using X-ray imaging. *Journal of Food Engineering*, *99*, 206–215.

Micholt, E., Jans, E., Callewaert, E., Bartic, C., Lammertyn, J., & Nicolaï, B. M. (2013). Extracellular recordings from rat olfactory epithelium slices using micro electrode arrays. *Sensors and Actuators B-Chemical*, *184*, 40–47.

Park, B., Chen, Y. R., & Nguyen, M. (1998). Multi-spectral image analysis using neural network algorithm for inspection of poultry carcasses. *Journal of Agricultural Engineering Research*, *69*, 351–363.

Peirs, A., Scheerlinck, N., Touchant, K., & Nicolai, B. M. (2002). Comparison of Fourier transform and dispersive near-infrared reflectance spectroscopy for apple quality measurements. *Biosystems Engineering*, *81*, 305–311.

Rizzolo, A., Vanoli, M., Zerbini, P. E., Jacob, S., Torricelli, A., Spinelli, L., Schouten, R. E., & Tijskens, L. M. M. (2009). Prediction ability of firmness decay models of nectarines based on the biological shift factor measured by time-resolved reflectance spectroscopy. *Postharvest Biology and Technology*, *54*, 131–140.

Saevels, S., Lammertyn, J., Berna, A. Z., Veraverbeke, E. A., Di Natale, C., & Nicolai, B. M. (2003). Electronic nose as a non-destructive tool to evaluate the optimal harvest date of apples. *Postharvest Biology and Technology*, *30*, 3–14.

Shiers, V. Adechy, M. & Squibb, A. (1999). 'A new mass spectrometry-based electronic nose for headspace characterisation'. In *Electronic noses and sensor array based systems; design and application. Proceedings of the 5th international symposium on olfaction and the electronic nose* (pp. 289−295). Baltimore, Maryland, USA, 27−30 September 1998.

Slaughter, D. C. (1995). Nondestructive determination of internal quality in peaches and nectarines. *Transactions of the ASAE*, *38*, 617−623.

Stuppy, W. H., Maisano, J. A., Colbert, M. W., Rudall, P. J., & Rowe, T. B. (2003). Three-dimensional analysis of plant structure using high-resolution X-ray computed tomography. *Trends in Plant Science*, *8*, 2−6.

Sugiyama, J. (1999). Visualization of sugar content in the flesh of a melon by near-infrared imaging. *Journal of Agricultural and Food Chemistry*, *47*, 2715−2718.

Sulzer, P., Edtbauer, A., Hartungen, E., Jürschik, S., Jordan, A., Hanel, G., Feil, S., Jaksch, S., Märk, L., & Märk, T. D. (2012). From conventional proton-transfer-reaction mass spectrometry (PTR-MS) to universal trace gas analysis. *International Journal of Mass Spectrometry*, *321−322*, 321−322, 66−70.

Swatland, H. J. (1995). *On-line evaluation of meat*. Lancaster, PA: Technomic Publishing Company, Inc.

Tao, Y., Heinemann, P. H., Varghese, Z., Morrow, C. T., & Sommer, H. J. (1995). Machine vision for color inspection of potatoes and apples. *Transactions of the ASAE*, *38*, 1555−1561.

Throop, J. A., Aneshansley, D. J., Anger, W. C., & Peterson, D. L. (2005). Quality evaluation of apples based on surface defects: Development of an automated inspection system. *Postharvest Biology and Technology*, *36*, 281−290.

Tollner, E. W., Hung, Y. C., Upchurch, B. L., & Prussia, S. E. (1992). 'Relating X-ray absorption to density and water-content in apples. *Transactions of the ASAE*, *35*, 1921−1928.

Tu, K De Busscher, R. De Baerdemaeker, J. & Schrevens, E. 1995, 'Using laser beam as light source to study tomato and apple quality non-destructively'. In *Proceedings of the food processing automation IV conference* (pp. 528−536). Chicago, Illinois, 3−5 November 1995.

Van Henten, E. J., Hemming, J., Van Tuijl, B. A. J., Kornet, J. G., Meuleman, J., Bontsema, J., & Van Os, E. A. (2002). An autonomous robot for harvesting cucumbers in greenhouses. *Autonomous Robots*, *13*, 241−258.

This page intentionally left blank

CHAPTER

15

Cooling fresh produce

Malcolm C. Dodd[1] *and Jacobus Bouwer*[2]

[1]Department of Horticultural Science, Stellenbosch University, Stellenbosch, South Africa

[2]Koos Bouwer Consulting, Cape Town, South Africa

Abbreviations

Cal	calories
DC	distribution center
J	Joule
M^4	man must measure to manage
RFID	radio-frequency identification
RH	relative humidity
TD	temperature difference
VSD	variable speed drive

15.1 Introduction

Fresh produce is an essential part of mankind's daily diet. According to the FAO (2013), "Food security exists when all people at all times have physical, social and economic access to sufficient safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life." To achieve food security, food outlets around the world, from street vendors to massive supermarkets, must always be stocked with healthy food. An expanding world population and a growing global middle class are increasing demand for fresh produce at a rate of some 6% per annum (FAO, 2013). This fresh produce must be transported from farms to consumers. Farms are often remote from where consumers live (see also Chapter 12 on logistics). This is a challenge because harvested fresh produce remains alive. Reducing the temperature by refrigeration slows the rate of deterioration. It is the single most powerful technology available to extend storage and shelf life of fresh produce. To maintain top condition, fresh produce is usually delivered from farms to consumers through a "cold chain." A cold supply chain may be defined as "A cold chain is the seamless movement of chilled fresh produce from production area to

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00015-4

market through various storage and transport mediums without any change in the optimum storage temperature and relative humidity." (Dodd, 2013; Mercier, Villeneuve, Mondor, & Uysal, 2017). Multiple technologies are integrated to create viable and efficient local, interregional, transcontinental, and intercontinental cold chains that deliver high-quality products to consumers.

15.2 The importance of refrigeration

All fresh produce is living when it is picked or harvested. Prior to harvesting or picking the produce is in an anabolic phase, receiving nutrients from the parent plant or tree. As soon as the produce is harvested or picked, this supply of nutrients and water ceases and the metabolic processes become catabolic. During this phase the vital metabolic processes associated with being alive continue. These biochemical processes rely on energy reserves that are stored in the produce as starches or sugars. These carbohydrates are metabolized with oxygen to give energy and carbon dioxide and the produce enters the senescent phase. As time progresses, these reserves are gradually or rapidly utilized. The shorter the storage/shelf life the product has, the higher the respiration rate and the faster these reserves are used up. When the reserves are exhausted, the produce will be withered, shriveled, and discolored and of little nutritional value to humans. The rate at which these biochemical or life processes proceed is determined largely by the ambient temperature. This has been clearly explained mathematically by Van'T Hoff, who determined that the rate of a chemical reaction doubles for each 10°C rise in temperature. This means that the lower the temperature the slower the respiration and metabolic rates, which includes ripening rate. Hence the critical need for refrigeration to extend the storage and shelf life of produce.

Considering that lowering the respiration rate of fresh fruit and vegetables is the most effective way of maintaining nutritional integrity and quality and thus value (Duan et al., 2020; Jones, 1996; Thomson, Mitchell, Rumsey, Kasmire, & Crisosto, 2002), the use of refrigeration is essential. Placing the product under cooling as quickly as possible after harvest is essential. Hardenburg, Watada, and Wang (1986) report that this preserves the product quality by:

- lowering of the respiration rate by slowing down enzyme activity,
- inhibiting the growth of decay causing enzymes,
- reducing water loss,
- limiting ethylene production.

Fresh produce varies considerably as to the type of plant that it originates from as well as the plant structure that it develops (Gehhardt, Cutrifelli, & Matthews,1982; Haytowitz & Matthews, 1984). For example, an apple develops from floral carpels, broccoli is a swollen inflorescence, whereas asparagus is a shoot tip and mushrooms are the fruiting body of a fungus. Consequently, the morphology and physiology vary greatly as does the chemical composition (Holland et seq, 1991). These differences influence both the way the produce is managed directly after harvest as well as the optimum temperature at which the produce should be stored at Tables 15.1 and 15.2. The most important fundamental step in

TABLE 15.1 Shelf life and compatibility information of fresh vegetables[1]√.

Vegetables	Temperature 0°C–3°C	Temperature 5°C–10°C	Temperature 13°C–18°C	RH Less than 75%	RH 85%–95%	RH Greater than 95%	Ethylene Produce	Ethylene Sensitive	Chilling or freezing sensitive[2]	Shelf life (days)
Alfalfa sprout	√					√				14–42
Artichoke	√					√				10–16
Arugula	√					√		√		5–7
Asparagus	√					√		√		10–21
Basil		√			√			√		5–7
Beans; fava, lima	√					√				7–14
Beans; snap, green, wax		√			√				c	7–10
Beet	√					√				120–150
Belgian endive	√					√		√		10–14
Bitter melon			√		√				c	10–14
Bok choy	√					√		√		7–10
Boniato			√		√			√	c	180–270
Broccoli	√					√		√		10–14
Broccoflower	√					√		√		14–21
Brussels sprouts	√					√		√		21–28
Cabbage	√					√		√		90–180
Cactus leaves (nopales)		√			√					7–10
Calabaza		√			√				c	60–90
Carrot	√					√		√	f	28–180
Cassava			√		√					21–28
Cauliflower	√					√		√	f	14–21

(*Continued*)

TABLE 15.1 (Continued)

Vegetables	Temperature			RH			Ethylene		Chilling or freezing sensitive[2]	Shelf life (days)
	0°C–3°C	5°C–10°C	13°C–18°C	Less than 75%	85%–95%	Greater than 95%	Produce	Sensitive		
Celeriac	√					√				180–240
Celery	√					√		√	f	35–49
Chard	√					√		√		
Chayote		√			√			√	c	
Chinese cabbage	√					√		√		60–90
Chinese turnip	√					√				120–150
Collard	√					√		√		
Corn; sweet, baby	√					√				5–8
Cowpea (Southern pea)		√			√					
Cucumber		√			√			√	c	10–14
Cut vegetables	√					√				14–21
Daikon	√					√		√		120
Dry onion			√		√				f	180–350
Eggplant		√			√			√	c	10–14
Endive-chicory	√					√		√		14–21
Escarole	√					√		√		14–21
Fennel	√					√		√		10–14
Garlic	√			√						90–210
Ginger			√		√				c	60–90
Green onion	√					√		√		7–10
Herbs (not basil)		√				√		√		5–7

Horseradish	√					√			240–350
Jerusalem artichoke	√					√			180–350
Jicama			√		√			c	60–90
Kailon	√					√	√		
Kale	√					√	√		10–14
Kiwano (horned melon)		√			√			c	
Kohlrabi	√					√			45–60
Leek	√					√	√		60–90
Lettuce	√					√	√	f	14–21
Lettuce, Romaine	√					√			14–21
Long bean		√							
Malanga		√			√		√	c	
Mint	√					√	√		
Mushroom	√				√				5–7
Mustard greens	√					√	√		
Onion	√			√					30–180
Okra		√			√		√	c	7–10
Parsley	√					√	√	f	30–60
Parsnip	√					√			90–120
Peas	√					√	√	f	7–10
Pepper; bell		√			√			c	14–21
Pepper; hot	√			√					14–21
Potato		√			√			c	56–140
Pumpkin			√	√				c	84–160

(*Continued*)

TABLE 15.1 (Continued)

Vegetables	Temperature			RH			Ethylene		Chilling or freezing sensitive[2]	Shelf life (days)
	0°C–3°C	5°C–10°C	13°C–18°C	Less than 75%	85%–95%	Greater than 95%	Produce	Sensitive		
Quince	√					√				60–90
Radicchio	√					√				14–21
Radish	√					√			f	10–21
Rutabaga	√					√				120–180
Rhubarb	√					√				14–28
Salsify	√					√				90–120
Satsuma	√				√					56–84
Scorzonera	√					√				
Shallot	√					√		√		180–240
Snow pea	√					√		√		
Spinach	√					√		√	f	10–14
Sprouts	√				√					5–10
Squash; Summer, (soft rind)		√				√		√	c	7–14
Squash; Winter, (hard rind)		√		√					f	30–180
Sweet pea	√					√		√		
Sweet potato			√		√			√	c	120–210
Swiss chard	√					√		√		7–14
Taro (dasheen)			√		√				c	90–120
Tomatillo		√			√				c	21
Tomato; green			√		√			√	c	21–28

Tomato; ripe, partially ripe		√		√		√	c	7–14
Turnip	√				√			120
Turnip greens	√				√	√		10–14
Water chestnut	√				√			30–60
Watercress	√				√	√		14–21
Winged bean		√		√				
Yam			√	√		√	c	180–240

[1]*Information compiled from Ashby (1995), McGregor (1989),* Wilson et al. (1999), *Boyhan et al. (2004), and Thompson and Kader (2004).*
[2]*"c" for both chilling and freezing sensitive and "f" for freezing sensitive.*
RH, Relative humidity.

TABLE 15.2 Shelf life and compatibility information of fresh fruits.[1]

Fruits	Temperature			RH		Ethylene			Chilling sensitive[2]	Shelf life (days)
	0°C–2°C	7°C–10°C	13°C–18°C	Less than 75%	85%–95%	Greater than 95%	Produce	Sensitive		
Apple	√				√		√			90–350
Apricot	√				√		√			21–28
Atemoya			√				√		c	14–21
Avocado; ripe	√				√		√			14–21
Avocado; unripe		√				√			√	28–42
Babaco		√			√					28–56
Banana			√		√		√		c	21–35
Barbados cherry	√				√					14–21
Blackberry	√				√					7–14
Blueberry	√				√					10–18
Boysenberry	√				√					2–5
Breadfruit			√		√		√			14–21
Cactus pear; tuna		√			√					28–56
Caimito	√				√					21–35
Calamondin		√			√					14–28
Canistel			√		√		√			10–21
Cantaloupe		√			√		√		c	14–21
Carambola		√			√					21–35
Casaba melon			√		√					21–28
Cashew apple	√				√					
Cherimoya			√		√		√		c	14–21

Cherry; sweet	√			√				14–28
Coconut	√			√				90–150
Cranberry		√		√			c	60–120
Crenshaw melon			√	√	√			14–21
Currant	√			√				14–21
Custard apple		√		√	√			
Date	√			√				240–350
Dewberry	√			√				
Durian; ripe		√		√	√			
Elderberry	√			√				14–21
Feijoa		√		√				
Fig Fresh-cut fruits	√			√				7–10
Gooseberry	√			√				
Granadilla		√		√	√			
Grape	√			√				56–180
Grapefruit			√	√		√		28–56
Guava		√		√	√		c	7–21
Honeydew melon			√	√	√			14–21
Jaboticaba			√	√				
Jackfruit			√	√				
Juan canary melon		√		√	√			
Kiwifruit	√			√	√	√		90–150
Kumquat		√		√				
Lemon		√		√		√	c	120–180

(*Continued*)

TABLE 15.2 (Continued)

Fruits	Temperature			RH			Ethylene		Chilling sensitive[2]	Shelf life (days)
	0°C–2°C	7°C–10°C	13°C–18°C	Less than 75%	85%–95%	Greater than 95%	Produce	Sensitive		
Lime		√			√			√		42–56
Limequat		√			√					7–10
Loganberry	√				√					
Longan	√				√					21–35
Loquat	√				√					21–28
Litchi	√				√					
Mamey			√		√		√			21–35
Mandarin		√			√				c	21–28
Mango; ripe		√			√		√			14–28
Mangosteen			√		√		√		c	35–49
Nectarine	√				√					
Olive		√			√				c	90–120
Orange		√			√					60–90
Papaya			√		√		√		c	14–21
Passion fruit		√			√				c	14–35
Peach	√				√		√			14–28
Pear (Asian and European)	√				√					60–180
Pepino		√			√					
Persian melon			√		√		√			
Persimmon			√		√		√			35–84
Pineapple		√			√				c	14–28

Plantain				√		√	√	c	21–35
Plum; ripe	√					√	√		14–28
Plumcot; ripe	√					√	√		
Pomegranate	√					√		c	
Prune	√					√	√		
Pummelo			√			√			30–60
Quince	√					√	√		60–90
Rambutan				√		√			14–21
Raspberry	√					√			5–7
Sapodilla				√		√	√		35–56
Sapote				√		√	√		14–21
Soursop					√	√	√		7–10
Strawberry	√					√			7–14
Sugar apple		√				√			14–21
Tamarillo		√				√		c	35–63
Tamarind		√				√			42–63
Tangelo		√				√		c	21–35
Tangerine		√				√			14–28
Ugli fruit		√				√			
Watermelon					√	√			14–21

[1]*Information compiled from McGregor (1989), Ashby (1995), Boyhan et al. (2004), and Thompson and Kader (2004).*
[2]*"c" for both chilling and freezing sensitive.*
RH, Relative humidity.

the postharvest process for virtually all fresh produce is to remove the field heat (Kader, 2002). Leafy vegetables such as lettuce require rapid precooling in a manner that does not dehydrate the leaves. The most effective technique to achieve this is vacuum cooling (Barger, 1962); however, care must be taken not to dehydrate the leaves. Peaches and nectarines are better served by using hydrocooling (Crisosto & Mitchell, 2002).

15.3 Precooling

It must be remembered that fresh produce continues to respire after it has been picked. This is a biochemical process in which energy reserves such as sugars are drawn upon to create energy for the life processes and during this reaction the heat of respiration occurs. It is very important to manage the temperature of the produce as this will in turn regulate the respiration rate and thus storage and shelf life of the product. To achieve this all the steps in the cold chain must be carefully monitored and managed. This begins with the picking of produce that should be done as early in the day as possible to ensure that the field heat is as low as possible. The produce should be kept out of direct sunlight and if possible be covered with wet fabric to enhance evaporative cooling.

At the packing facility the produce should be cooled to the temperature recommended in Tables 15.1 and 15.2. Cooling time for small products like cherries can be as little as 10 min (Kader, 2002). In general, produce is precooled up to 10 times faster by hydrocooling compared to forced air-cooling. There is a limitation, however, in that this technique cannot be used on some products that are delicate and sensitive to wetting.

The produce should be graded and packed as soon as possible. Thereafter the produce should be cooled to the optimal temperature for that produce. Reducing the produce temperature is the best way of maintaining product quality because it slows the respiration rate and reduces the rate of ethylene production. Additionally, the rate of moisture loss will be slowed down as will the growth of microorganisms. It is a general rule of thumb that for every hour delay from picking to cooling causes 1 day of shelf-life lost (Dodd, 2020[1]; Raffo et al., 2020) (as shown in Chapter 5: Models for Improving Fresh Produce Chains).

The industry has a standard term to describe the time of precooling, this being the 7/8ths cooling time (Gentry & Nelson, 1964). This describes the time taken to force air-cool product from the starting produce pulp temperature down to 87.5% (7/8ths) of set point (the temperature at which the refrigeration unit is set to achieve). This is a convenient descriptor of the practical temperature the product will reach with the set point. It must be remembered that the product temperature will never reach the set point temperature because of the internal vital heat of the produce.

This means that if the desired pulp temperature of produce like an apple is 0°C then the set point will need to be −1.0°C to achieve this. An example of this is of a freshly harvested peach with a pulp temperature of 32°C being cooled in a 0°C airflow and reaching 4°C in 9 h, then the 7/8ths cooling time is 9 h. This means that a 28°C drop in temperature occurs within the product. It must be remembered that the higher the pulp temperature at

[1] Personal experience, unpublished and confidential work conducted for a Southern African supermarket chain during 2020.

the commencement of cooling and the lower the set point the longer the time it takes to cool the product. The 7/8ths cooling time will in theory take three times as long to achieve as the 1/2 cooling time. Therefore the same peach that took 9 h to cool to 4°C would take only 3 h to reach 16°C, the 1/2 cooling time. If everything else remained the same the 7/8ths cooling time would be 7.5, 4.5, 3, and 1.5 times longer than the 1/4, 3/8, 1/2, and 3/4 cooling times, respectively.

The previously mentioned fact must be borne in mind when considering the precooling of produce (see also Chapter X on sorting). The physiological characteristics of the produce will determine what represents appropriate postharvest handling. Produce such as broccoli, asparagus, sweet corn, leaf lettuce, and mushrooms with very high respiration rate must be cooled as soon as possible after harvest (within 90 min) and as rapidly as possible (Wills, McGlasson, Graham, & Joyce, 2007).

By way of example consumers will soon notice poorly precooled broccoli because it will start to show signs of wilting and yellowing a day before the use by date (Dodd, 2020; see footnote 1). Most of these crops are hydrocooled, iced, or vacuum-cooled. They can also be force air-cooled provided high air speeds are used and there is control over the relative humidity (RH).

The latter being the most important consideration due to high vapor pressure deficits leading to dehydration and shrivel in many types of fresh fruit and vegetables.

Produce with a high respiration rate at harvest such as blueberries, raspberries, strawberries, sweet cherries, snap beans, and head lettuce should be cooled as quickly as possible after harvest and at least within 3 h (Nunes, Nicometo, Emond, Melis, & Uysal, 2014; Wills et al., 2007). Moderately respiring products such as apples, pears, cabbage, cantaloupes, celery, peaches, nectarines, plums, and peppers should be cooled within 5 h to reduce quality loss and ensure maximum storage or shelf life (Wills et al., 2007).

15.3.1 Techniques

15.3.1.1 Vacuum cooling

Vacuum cooling is the most effective technique to cool leafy vegetables (Barger, 1962). Vacuum cooling exploits the latent heat of vaporization of water. It is a very effective way of precooling products like leafy vegetables. The produce is placed inside a vacuum chamber and sealed. A vacuum is then drawn, which causes water to evaporate off the surface of the produce. Through the physical process called the latent heat of evaporation, the heat that evaporates the water is removed from the produce. The higher the surface to volume ratio of the product the more effective the cooling, particularly if the produce is presprayed with water. The downside of this technique is the heavy investment cost due to the vacuum tube and pump. This technique also requires precise management. Because of these two critical factors, it is not as widely used as the technique called hydrocooling.

15.3.1.2 Hydrocooling

The latter entails the use of chilled water in either a bath or spray (Wills et al., 2007). Water has a far greater heat capacity than air so this system removes heat more effectively than chilled air.

Hydrocooling can be used for a variety of fruits and vegetables whereby the produce is placed in water-tolerant containers and placed in a racking system and chilled water is showered over the produce. Peaches and nectarines are often cooled using hydrocooling (Crisosto & Mitchell, 2002).

15.3.1.3 Forced air-cooling

In addition to hydrocooling the other forms of cooling are room cooling where the produce is placed in a cold store and the produce cools slowly and nonuniformly though the conductive cooling process. This should not be considered a means of getting the produce to set point temperature. The best way to get produce to set point temperature other than hydrocooling is by forced air-cooling. This is a technique which, inside a cold store set at the ideal set point, high capacity fans and tarpaulins are arranged to suck chilled air through the stacks of packaged produce on pallets. Rapid and even cooling is achieved by convective cooling of the produce. Pulling the air through rather than blowing it through the stack of produce is preferable as it achieves an even airflow and thus even cooling (Thomson et al., 2002).

15.3.1.4 Top-icing

Top-icing is a simple technique using crushed ice that is placed in suitable containers on top of the produce. The freezing water/ice slurry then moves by gravity through the produce stack and cools it. This is an effective technique for dense product such as broccoli that is difficult to cool with forced chilled air. There is an additional advantage with this technique in that it helps remove subsequent respiratory heat. It is calculated that 1 kg of ice can cool 3 kg of produce (Anonymous, 1989). The downside of this technique is that there is extra weight and a lot of cold water to remove from the storage area or transport vehicle.

15.3.2 Which precooling technique to use?

When planning the process of precooling produce there are several factors to consider:

- The density of the produce and how tightly it nests together in the container. The denser the product the more difficult and time-consuming the precooling process.
- The packaging must be designed to ensure that there is sufficient surface area open in the form of ventilation holes or slots. These slots must be orientated to ensure that the chilled air can move freely over the produce. The direction of airflow in land-based cold stores is always horizontally, whereas in specialized reefer ships and refrigerated shipping containers the movement is in a vertical direction. The slots must be orientated to accommodate both these storage considerations.
- The lower the ratio of volume to surface area of the produce the faster the cooling, for example, cherries cool faster than melons. However, the packaging configuration must also be considered as grapes are small with a high volume to surface ratio but they are usually packed inside a liner bag to keep sulfur dioxide in and around the produce and keep the RH high. Therefore micro perforations must be placed in the film to balance the needs of providing a barrier film and allowing chilled air in micro perforations

must be placed in the film. A tradeoff between moisture control and speed of cooling has to be established.

- The distance the chilled air has to move must be considered. The shorter the distance the faster the cooling. In shipping containers, there is a drop-off in cooling efficiency along the length of the container.
- The volume of air used, the higher the volume of air the faster the cooling.
- Sensitivity to water prevents using hydrocooling or ice for produce such as green beans.

15.4 Packaging

The packaging used for the product is important for three reasons:

- Keeping the product in discreet manageable units such that the content can be traced.
- Holding the produce in such a way as to ensure there is no bruising or friction damage caused during handling and long-distance transportation.
- Enabling the free movement of chilled air across the produce through suitably shaped and positioned vents.

In selecting the type of packing to be used the three aforementioned characteristics must be considered along with the length and complexity of the value chain (Kader, 2002) (see also Chapter X on packaging). The longer the length of the value chain the greater the number of forklift movements and changes in storage and transport medium. Each change places the produce at risk of being damaged through shock or compression; therefore the packing must be robust enough to withstand these forces but still enable the three characteristics without costing too much (Dehghannya, Ngadi, & Vigneault, 2012). Compromises are often sought in balancing these attributes and often the choice is made for cheaper packaging that does not have the strength to withstand the rigors of transport and handling. The result is packaging that collapses and in so doing damages the produce and reduces or destroys its value. In all decision-making around what products or materials to use in the supply chain, it is important to default to what is fit for purpose rather than what is the cheapest. Cheap packaging does not necessarily translate into being cost-effective.

Wire-bound or nailed wooden crates or wax impregnated fiberboard cartons can be used to pack product that is to be handled in water or ice for cooling. Other packing methods require that the produce be taken to a packing facility where upon arrival the produce should be cooled as soon as possible after grading and trimming.

Compromises are often sought in balancing these attributes and often the choice is made for cheaper packaging that does not have the strength to withstand the rigors of transport and handling. The result is packaging that collapses and in so doing damages the produce and reduces or destroys its value. In all decision-making around what products or materials to use in the value chain, it is important to default to what is fit for purpose rather than what is the cheapest. Cheap packaging does not necessarily translate into cost-effectiveness for the complete chain.

15.5 Cold chains

A cold chain may be defined as "A cold chain is the seamless movement of chilled fresh produce from production area to market through various storage and transport mediums without any change in the optimum storage temperature and relative humidity." (Dodd, 2013). The key to the successful utilization of a cold chain is the uninterrupted exposure of the product to the appropriate temperature of chilled air and percentage level of RH. It must be remembered the maximum quality of the fresh produce is at the moment when it has been harvested. The highest value is when that produce reaches the market place. Fresh produce is alive when picked and must be kept at the lowest possible temperature and highest RH to maintain freshness as long as possible.

15.5.1 Maintaining quality

There are many critical steps that need to be taken to maintain the quality of the food stuff. The complexity of this chain is illustrated in Fig. 15.1. At each link there is a hand over of responsibility and the value of the product increases. The key to the successful utilization of a cold chain is the uninterrupted exposure of the product to the appropriate temperature of chilled air and percentage level of RH. The highest value is when that produce reaches the market place. Fresh produce is alive when picked and must be kept at the lowest possible temperature and highest RH to maintain freshness as long as possible. There are many critical steps that need to be taken to maintain the quality of the food stuff. There is also a great deal of heterogeneity in temperatures within a supply chain

FIGURE 15.1 Illustration of the links in an intercontinental cold supply chain.

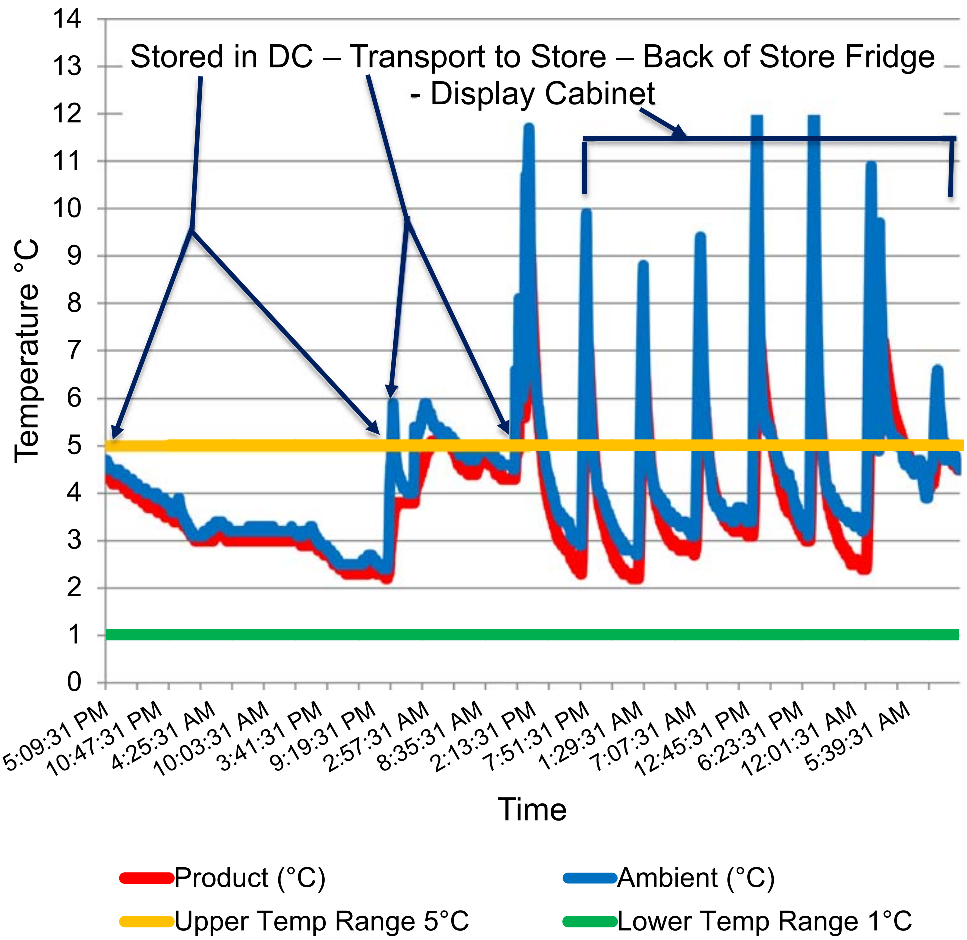


FIGURE 15.2 Graph of air temperature and product pulp temperature (broccoli) from a DC through a long-distance road refrigerated transport to a back of store chiller and into an "open throat" refrigerated display cabinet. Data segmented into storage and transport links in the cold supply chain. *DC*, Distribution center.

(Fig. 15.2). At each link there is a transfer of responsibility and the value of the product increases as a result of the services provided. Maintaining the product quality along this value chain is dependent upon several supporting technologies like refrigeration, packaging, and track and trace systems. These technologies rely on the coordination of activities between service providers through the services of logistics suppliers. The fundamentals of a cold value chain are the same for short-distance transport from farm to a local city compared to transcontinental and intercontinental markets. However, the complexity of the chain increases with distance, change of transport or storage mode, shipping transportation, border crossings, and intergovernmental phytosanitary certification.

15.5.2 Maintaining cold chains

This chain is only as strong as the weakest link (Mercier et al., 2017). When there is a weakness or error in one of the links or at the interface between these links, the integrity is compromised. If one link fails, then the whole value chain invariably fails to deliver the expected value of the product and in some cases a high percent of the shipment is never consumed. According to Katzorke and Lee (1998), problems develop at the interfaces of supply chains and the best way to overcome these challenges is to ensure good management. This management must be with the fundamental understanding that "Controlling product temperature and reducing the amount of time the product is at less-than-optimal temperatures are the most important methods of slowing quality loss in perishables," (Thomson et al., 2002).

The management of cold chains is often difficult because of their inherent complexity and the lack of communication and visibility between the service providers at each link. Many service providers work in silo situations and according to Tarnowski (2006) they cannot see past their own business concerns. This leads to a breakdown of communication and integrity of value chains. The visibility within the cold value chain is thus lost and production and purchasing schedules become compromised. In addition, the velocity of the value chain is reduced, which can compromise marketing plans.

15.5.3 Controlling temperature and relative humidity

Temperature and RH fluctuations within the value chain can occur either during the storage or shipping phases or critically at the change of storage or transport medium. These fluctuations are additive in nature in the way they impact the respiration of the produce. Once a temperature break occurs, the air temperature increases with a concomitant decrease in the RH. This results in the product respiration increasing and possible water loss due to a high vapor pressure deficit between the product and the storage air. When the product is placed back under refrigeration, the respiration rarely returns to the lower level it was at prior to the break and the product weight loss due to moisture loss cannot be regained (Wills et al., 2007). The full value of the product is only realized when it is sold to a consumer. This value can only be achieved if the product is in the best possible condition.

15.5.4 Maintaining quality

Maintaining the product quality is dependent upon several supporting technologies like refrigeration, packaging, and track and trace systems. These technologies rely on the coordination of activities between service providers through the services of logistics suppliers (see also Chapter X on logistics). The fundamentals of a cold supply chain are the same for short-distance transport from farm to a local city as for transcontinental and intercontinental markets. However, the complexity of the chain increases with distance, change of transport or storage mode, shipping transportation, border crossings, and intergovernmental phytosanitary certification.

15.6 Logistics

Logistics is one of the key disciplines to ensuring efficient cold supply chains. Mercier et al. (2017) describe logistics as the process of planning, implementing, and controlling the efficient flow and storage of goods, services, and related information from point of origin to point of consumption to meet customers' requirements. In the case of fruits and vegetables, this business process is complicated by the overlaying of the need for the supply chain to be chilled by refrigeration. Any break in this supply chain will result in a compromising of the temperature and RH control leading to a reduction in the quality and value of the produce. The only way to ensure that best practice is followed is through good management. This requires an understanding of the guiding principles of a cold chain.

15.6.1 Guiding principles

1. The produce must be cooled as soon as possible after harvest as the highest quality is at the time of harvest. Thereafter the produce will commence the aging process and as a consequence lose both nutritive and monetary values.
2. The appropriate packaging must be used. This will serve the function of holding the produce in discreet units whilst preventing damage due to rubbing or bruising.

15.6.1.1 Heat sources

The heat that has to be removed from either storage or transport systems emanates from several sources.

- The vital heat from the product itself.
- External heat ingress from solar radiation through the container's insulation.
- The quality of the insulation is therefore critical. It is also important to ensure that no water seeps into the insulation as this will compromise the efficiency of the insulating material.
- On road vehicles, in addition to solar radiation on the roof and side walls, there is the reflected heat off the road surface onto the base of the unit. Once again, the quality of the insulation is critical. There must also be no ways that heat can bridge the insulation through bolts that hold the insulated body onto the chassis.

15.6.1.2 Heat removal

After product is precooled to the shipping temperature the design of the packaging must enable the chilled air in the transport container to remove the heat of respiration (vital heat) from the product. To do this efficiently, the chilled air should come into direct contact with the produce. This removes heat by a process known as *convective* cooling. If the chilled air does not come into direct contact with the produce then the vital heat gets *conducted* across the packaging or whatever else is acting as a barrier between the air and the produce. The heat is then removed from the surface of the barrier by the chilled air by *convective* cooling. This is a much less efficient method of cooling compared to conductive cooling (Dehghannya, Ngadi, & Vigneault, 2010).

Air delivery systems vary according to the storage or transport medium. The packaging must allow for sufficient air to move across the produce or consumer bags. Land-based forced air precooling facilities mainly have horizontal airflow delivery systems. Therefore there must be some ventilation holes in the sides of the packing cartons. Refrigerated road transport vehicles have top air delivery systems that cause the chilled air to move through the load in a vertical direction. Similarly, in specialized reefer ships and refrigerated shipping containers the air is delivered in a vertical direction. Thus the base and the top of packing cartons must have sufficient ventilation holes to allow for the movement of the chilled air over the produce.

The efficacy of maintaining the product at the correct temperature and RH depends upon the use of a suitable packing material that is stacked in such a way as to ensure the movement of chilled air over the product (Wills et al., 1998). Packaging must therefore be well ventilated with apertures placed on all six surfaces of the carton.

When considering the design of the packaging, it must be born in mind that the chilled air is supplied to remove the heat of respiration (vital heat) from the product. To do this efficiently, the chilled air should come into direct contact with the produce. This removes heat by conductive cooling, the most efficient means of cooling (Boyette, Sanders, & Rutledge, 1996). If the chilled air does not come into direct contact with the produce then the vital heat gets conducted across the packaging or whatever else is acting as a barrier between the air and the produce. The heat is then removed from the surface of the barrier by the chilled air in a process known as convective cooling. This is a much less efficient method of cooling compared to conductive cooling (Dehghannya et al., 2010). Air delivery systems vary according to the storage or transport medium. The packaging must allow for sufficient air to move across the produce. Land-based forced air precooling facilities mainly have horizontal airflow delivery systems. Therefore there must be some ventilation holes in the sides of the packing cartons. Refrigerated road transport vehicles have top air delivery systems that cause the chilled air to move through the load in a vertical direction. Similarly, in specialized reefer ships and refrigerated shipping containers, the air is delivered in a vertical direction. Thus the base and the top of packing cartons must have sufficient ventilation holes to allow for movement of the chilled air over the produce.

The efficacy of maintaining the product at the correct temperature and RH depends upon the use of suitable packing material that is stacked in such a way as to ensure the movement of chilled air over the product (Wills et al., 2007). Packaging must therefore be well ventilated with apertures placed on all six sides of the carton.

The heat that has to be removed from either storage or transport systems emanates from several sources.

- The vital heat from the product itself.
- External heat ingress from solar radiation through the insulation.
- The quality of the insulation is therefore critical. It is also important to ensure that no water seeps into the insulation as this will compromise the efficiency of the insulating material.
- On road vehicles, as well as solar radiation on the roof and side walls, there is the reflected heat off the road surface onto the base of the unit. Once again the quality of the insulation is critical. There must also be no ways that heat can bridge the insulation through bolts that hold the insulated body onto the chassis.

TABLE 15.3 Cost centers and US$ values within a fruit value chain of a 12.5-kg carton of apples, 70 cartons per pallet, and therefore 1400 cartons per a 40-ft reefer container.

Cost center	US$ value	Percentage of the cost in the chain
Sale price	25.00	100
Supermarket	7.00	28
UK transport	0.60	2
Importers commission	1.23	5
UK logistics	1.85	7
Freight (reefer container)	3.95	16
Insurance (maritime and debtor)	0.27	1
FOB cost (incl. port costs)	1.46	6
Exporters commission	0.43	2
Transport to port	0.33	1
Finance charges	0.14	1
Hortgro levies	0.04	0.04
Perishable Product Export Control Board sea levy	0.05	0.05
Packaging materials	1.58	6
Packing cost	1.61	6
Grower Ex Farm-Gate	4.46	17.91

The carton of apples was produced in the Western Cape region of South Africa and exported to a supermarket in the United Kingdom (Dodd, 2012; with update 2021).

15.6.2 Costs for cold chains

See Table 15.3. The costs associated with each link in an international fresh produce supply chain are shown in table 15.3. This analysis is very helpful in identifying cost centres that may be impacting on the sustainability or profitability of an international fresh produce cold chain. A one percent reduction in the margin made by the retailer translates to a 5.5% increase in the return to the farm gate. Attention to the detail is very important in maintaining cost effective cold supply chains.

15.7 Cold chain management

The most effective way of managing the integrity of a cold chain and thus the quality of the produce carried therein is to measure the air temperature or product temperature from end to end. To achieve this, the mnemonic Man Must Measure to Manage (M^4) is entirely appropriate. Real-time temperatures (live) or as recorded by devices for later download (after the event) should be used to view the cold chain. The former method allows for instantaneous (proactive) correction of any deviation from the desired temperature protocol. The latter allows for a subsequent (reactive) correction of the event or rejection of produce that has been subject to temperature abused. By measuring the temperatures in each step of the cold chain, preferably in real time, it is possible to effectively manage said cold chain.

15.7.1 Temperature management

Having factual knowledge (Fig. 15.2) of the temperatures along the length of a cold chain enables an understanding of its integrity. Where the integrity is compromised, steps can be taken to rectify the breaks. By ensuring that a cold chain operates at the ideal temperature, fresh produce can be kept in the best possible condition and waste reduced to a minimum. There are many temperature recording systems available that offer varying levels of feedback. The challenge in using these devices is in having to recover them from the shipment to capture the data. However, the effort in recovering the recorders is critically important as the data contained therein provide a view of the actual temperature experienced by the produce in that particular section of a value chain. Radio-enabled [radio-frequency identification (RFID)] systems do offer the advantage of data being uploaded onto the internet without the recorder having to be physically retrieved and data captured.

15.7.2 Transportation equipment

The following types of refrigerated transportation equipment are available:

- road trucks and trailers;
- air cargo containers;
- piggy back trailers for road, rail and roll on/roll off ocean transport;
- rail box cars;
- specialized reefer vessels;
- reefer shipping containers.

In almost all cases the refrigeration system in all but the airfreight containers is achieved with vapor-compression refrigeration with HFC refrigerants (IIR, 2003).

15.7.2.1 Road trucks and trailers

In the cold value chain distribution system the road transport vehicles are refrigerated and the refrigeration capacity is specified to maintain temperatures, not to pull temperatures down (Mercier et al., 2017). It is therefore essential to the maintenance of the cold chain to only load the transport vehicles with produce that is within the specified temperature range. This requires that the cold store or DC manage the temperatures within the prescribed protocol. The condition of the insulation and design of the air distribution systems in the transport equipment are important as is the loading pattern of the produce within the vehicle. If any of these parameters are not on specification the temperatures and RH levels will not be correct and the produce quality will not be maintained (Ashby, 1995; McGregor, 1989).

Refrigeration systems on road vehicles are diesel powered with the ability to plug into local electrical grids when parked in depots. In the smaller road transport vehicles (up to 4 m long) the refrigeration can be powered off the vehicle engine. In larger vehicles or semitrailers (4–9 m) the refrigeration is powered by its own diesel engine. In some cities where noise restrictions are in place refrigeration in trucks is achieved through the use of eutectic plates. These plates are frozen in a depot and then placed in the vehicle body before loading and so provide the chilled air for the duration of the transport. Upon returning to depot the plates are removed and refrozen for the next load.

In some instances, the trailer compartment can be separated into two sections with different temperatures. This is achieved by an internal insulated movable wall and having two evaporator units set to different temperatures. The chilled air is delivered horizontally at roof height of the truck or trailer from the front-mounted refrigeration unit. This delivery system is sometimes aided by canvas chutes hung from the roof in long trailers to ensure that some of the chilled air reaches the rear of the trailer.

The important consideration with all road transport is to remember that the refrigeration capacity is sized to the cubic capacity of the storage area and it has a capacity to maintain temperatures, not reduce them. The product must be loaded at the correct temperature and the refrigeration will maintain that temperature.

15.7.2.2 Airfreight

Dry ice, in the form of solid carbon dioxide, can be placed in special trays or compartments within the cargo area and provide cool air to control the temperature (McGregor, 1989). Fresh produce must never come into direct contact with dry ice as it will be damaged. Wet ice is used in some instances in containers placed on top of the pallets. In this case the packaging must be water-resistant and there must be a means of draining the subsequently produced water out of the vehicle. In the case of airfreight, some airlines do permit the use of ice; however, it must be placed inside a sealed polyethylene bag inside a leak proof container and also have a moisture absorbent pad. Gel refrigeration uses frozen containers of chemical eutectic gel to maintain temperature within the airfreight container. This is the preferred refrigeration system of most airlines.

15.7.2.3 Sea freight

There are two ways of transporting perishable products by sea, specialized refrigerated ships and marine reefer containers, which are transported by container ships. In both these transport mediums the refrigeration equipment is driven by electricity. In the holds of vessels and in reefer containers the chilled air is delivered through the floor in a vertical direction. It is therefore essential that the pallets and cartons have air vents positioned in such a way as to allow for free movement of air to allow for efficient cooling (Thomson et al., 2002).

15.7.3 Systems for produce in grocery stores and display cases

Fresh produce delivered to supermarkets and grocery stores must immediately be placed in a cold room set at the appropriate temperature and RH. Ideally, there should be, as proposed by Kader and Thompson (2001), three storage rooms with settings of 0°C to −2°C, 7°C−10°C, and 13°C−18°C with an RH of 85%−95%. These storage rooms should have good air circulation and fresh air exchange to maintain the correct temperature and limit ethylene build up. To maintain fresh produce shelf life into the homes of consumers, refrigeration must be maintained. This procedure often does not occur inside grocery stores or supermarkets. Products such as citrus and apples are often placed on displays rather than in refrigerated cabinets. Refrigerated display cabinets should be well maintained and have an easy to read accurate thermometer.

To protect the produce from excessive moisture loss, automatic sprayers are installed in many display cabinets, particularly those with loose leafy vegetables. Kader and Thompson (2001) have published a list of products that will benefit from a misting system. Many supermarkets report significant shrinkage displayed at the front portion of display cabinets as this area is out of reach of the chilled air and mist.

The large variation of air temperatures recorded within a typical supermarket display cabinet can be seen in Fig. 15.3. This wide range of temperatures explains why shelf life of produce often does not meet the sell by date. Produce loss due to wilting, drying, and not being at optimum set point is estimated at $1.00 per 30 cm of display cabinet per day. This indicates a need for innovation in this sector of the cold chain, over and above the covers that are pulled down over night. Specialized lighting can produce true colors along with less heat and radiation, thus adding less heat load to the refrigeration.

15.7.4 Home refrigerators

Keeping perishables cold in the domestic environment is essential for maintaining their quality. These refrigerators come in a variety of sizes and are usually set at a compromise temperature of between 4°C and 5°C. Sealed crisper drawers are provided in most modern units in an effort to manage a higher RH for the benefit of vegetables. An evolving

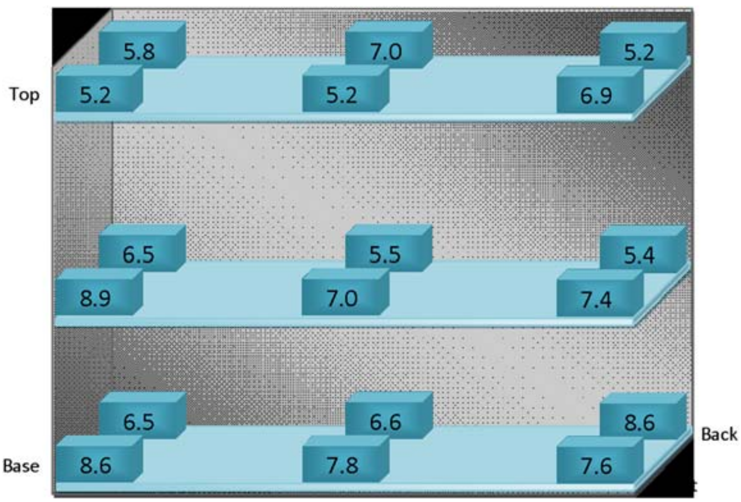


FIGURE 15.3 The range of air temperatures (°C) recorded in a typical “refrigerated open throat” display cabinet used in a supermarket. The delivery set point was 2.0°C.

technology is the fitting of RFID within the refrigerator that is linked to reusable recorders, which enables the checking of product temperatures and shelf life.

15.7.5 Summary of the cold chain

As has been illustrated, maintaining the cold chain is essential to the preservation of product quality and gaining maximum value out of the value chain. This cold chain begins on the farm when the produce is harvested and ends in the home when the produce is consumed. Overviews of fruit and vegetable storage and transport systems can be found in the *Encyclopaedia of Agriculture, Food and Biological Engineering* (Hellevang, 2003; Hellickson, 2003; Tao, 2003). In general, any procedure to reduce or eliminate breaks in the cold chain will have a positive impact by maximizing the quality and shelf life of the produce. Temperature management is the most important means of managing fresh produce quality. There is an optimum storage temperature for all products as shown in Tables 15.1 and 15.2.

15.7.5.1 Supporting technologies

In taking a systems approach to a process, it is necessary to have a view and understanding of the technologies that support the process. As such with a cold supply chain, the most important technology is that of refrigeration.

15.7.5.2 Refrigeration principles

Cooling is the removal of heat from the produce. Heat may be defined as the interaction between systems, which occurs by virtue of their temperature difference (TD) when they communicate. The temperature of produce is reduced during cooling. The magnitude of the heat interaction is measured in Joule (J) or calories (Cal). The increase or decrease in energy of a system during a change of state is numerically equal to the net heat during the process minus the network during the process.

The laws of thermodynamics are very relevant in understanding the mechanics of a refrigeration system. The first law of thermodynamics was formulated by Spalding and Cole (1978) and described as "When a system executes a cyclic process, the network is proportional to the net heat." This principle is also known as the conservation of energy, which means that energy cannot be created or destroyed. In any refrigeration system the energy in the form of heat is removed from the produce and discarded into the atmosphere. For the system to work, electrical energy is used to drive mechanical devices like compressors and fans and the sum of the work done by these devices is then also absorbed in the refrigeration system to add to the heat load.

The second law of thermodynamics states that an isolated system will spontaneously evolve toward a state of thermodynamic equilibrium. When two initially isolated systems in separate but nearby regions of space are allowed to interact, they will eventually reach a mutual thermodynamic equilibrium. This principle is applied a few times in a refrigeration system, because a refrigeration system relies on a series of heat transfers to transport the heat from the produce via packaging, air, fans, conduits, refrigerants, and compressors to be discarded into the atmosphere.

Refrigeration is a heat-removal process. The refrigeration system is the device that enables the heat-removal process. Various heat exchanges take place during the total process where heat is removed from produce and transported via different media until it is rejected elsewhere. The heat transporting media can be a fluid or a solid. The following example illustrates this.

15.7.5.3 Process

In this example the cooling cycle is described from the produce as starting point. This is a generic example to illustrate the working of a refrigeration system and can be applied to refrigeration systems in various applications, for example, a cold store, refrigerated truck, forced air-cooling tunnel, reefer vessel, refrigerated shipping container, freezer rooms, and display cabinet in shops. For the ease of discussion, the application will be described as a cooling chamber. The cooling chamber is the space where the produce is put to be cooled.

Heat in the produce needs to be removed by a transporting medium. In most cases, except for hydrocooling, the heat is removed by air flowing over the produce. The rate of cooling is determined by the following factors:

- A larger temperature gradient from the center of the produce to the skin or surface of the produce will increase the rate of cooling.
- A larger difference in temperature between the surface of the produce and the surrounding airflow will increase the rate of cooling.
- A higher rate of airflow will contribute to an increase in the rate of cooling as heat is removed at a higher rate.
- The size of the individual produce units. Heat flows to the surface of the product by conduction and a larger fruit like an apple will take longer to dissipate all the heat compared to smaller fruit such as a grape.
- The thermal characteristics of the produce, for example, a thick peel of a citrus fruit will slow down the rate of conduction.
- The immediate packaging surrounding the produce, for example, wrapping of produce acts as another insulating skin.
- Outer packaging and consolidated loads like pallets also restrict the air movement to remove the heat from the fruit, hence the importance of good carton and palletization design to improve airflow to the produce.

The cool air surrounding the produce is circulated in the cooling chamber by means of fans. The function of the airflow is to collect the heat of the produce and other heat sources and to transport the heat to the heat exchanger. More effective cooling is achieved when the airflow is directed with ducts and plenums to achieve a circular pattern between the produce and the heat exchanger. The heat exchanger in the cold room is the evaporator of the refrigeration cycle.

15.7.5.4 The refrigeration cycle

Continuous refrigeration is usually accomplished by the vapor-compression system, also known as the simple compression cycle (Van Dalfsen, 1989). Such a system has a low-pressure (evaporating) side and a high-pressure (condensing) side. The refrigerant acts as a transportation medium to move heat from the evaporator (in the cold chamber) to the condenser unit (outside) where the heat is given off to ambient air. The change of state from liquid to vapor and back to liquid allows the refrigerant to absorb and discharge large quantities of heat very efficiently.

High-pressure liquid refrigerant is fed through the liquid line toward the cold chamber. A valve controls the feed of liquid refrigerant to the evaporator and, by means of an orifice, reduces the pressure of the refrigerant to the low-pressure side. The reduction of pressure causes the refrigerant to boil or vaporize until the refrigerant is at a saturation temperature corresponding to its pressure. The low-temperature refrigerant passes through the evaporator coil where it absorbs heat from the cold room causing the refrigerant to continue boiling and vaporize.

The refrigerant vapor leaving the evaporator in the cold room travels through the suction line and accumulator and then on to the compressor inlet. The compressor takes the low-pressure vapor and compresses it, increasing both the pressure and the temperature. The hot, high-pressure gas is forced into the condenser for cooling. As the temperature of the refrigerant vapor reaches the saturation temperature corresponding to the high pressure in the condenser, the vapor condenses into a liquid and flows back to a receiver to repeat the cycle.

The basic units of a refrigeration system are given in the schematic diagram shown in Fig. 15.4.

The working of a refrigeration system is better understood when looking at the pressure—enthalpy relationship. The same cycle as described in the previous example is displayed in Fig. 15.5. Heat from the produce is transported via airflow to the evaporator coils where it is absorbed by the refrigerant between points 1 and 2 on the diagram. The temperature of the refrigerant does not increase when the heat is absorbed because the refrigerant changes phase from liquid to gas at a constant temperature and pressure. Latent heat is absorbed and the enthalpy of the refrigerant increases. The gas is then compressed by the compressor between points 2 and 3 on the diagram. The enthalpy of the refrigerant increases further when electrical energy is used via the compressor to increase the pressure and the temperature of the gas. The superheated gas is cooled in the condenser between points 3 and 4 at a constant pressure. Further heat is removed by the condenser between points 4 and 5, but with no decrease in temperature or pressure because latent heat is given off to change from gas to liquid. Between points 5 and 1 the refrigerant moves through the expansion valve with no change in enthalpy, but with a reduction in both pressure and temperature.

This cycle demonstrates the efficiency of a refrigeration system. Energy is applied to the system by the compressor with an increase in enthalpy of the refrigerant from point 2 to 3. The enthalpy is then reduced by the condenser between points 3 and 5. That leaves the refrigerant with a capacity to "pick up" enthalpy in the evaporator between points 1 and 3. The efficiency of the system is the ratio of useful enthalpy absorbed (points 1−2) and energy used for this purpose (points 2−3). This ratio is known as the coefficient of performance and for typical systems this ratio is between 3 and 5. This means that for each kW of electricity consumed by the compressor, the refrigeration system can absorb between 3 and 5 kW of heat from the produce. This is a very efficient system and further information regarding the refrigeration cycle can be found in Hung (1991).

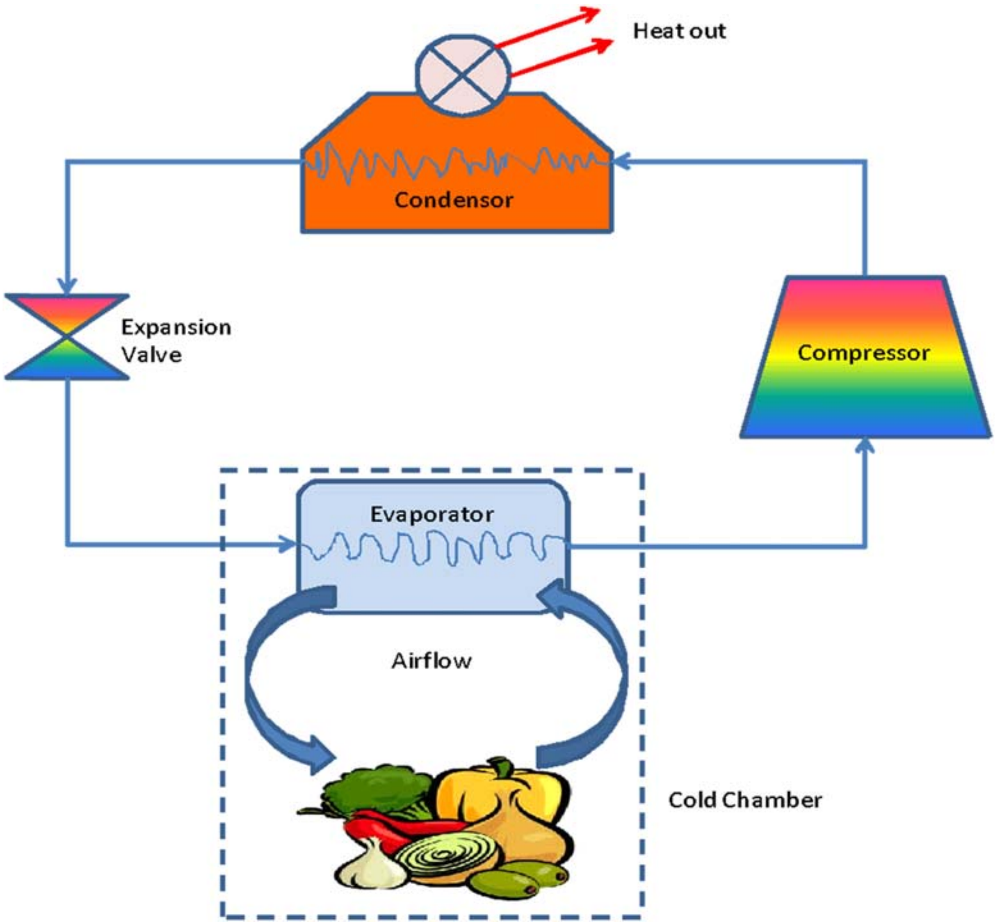


FIGURE 15.4 Diagram of the refrigeration process.

15.7.5.5 Energy efficiency in refrigeration

External energy is needed in the cold chain for refrigeration purposes. This energy is supplied as electrical energy in cold stores, or by fuel during transportation. Energy cost contributes to the cost of the product and is also a major source of carbon emissions in the cold chain. These two reasons provide enough motivation to assure that energy need to be used as efficient as possible to maintain the temperature of the produce in the cold chain.

The working of a cold room is displayed simplistically in Fig. 15.6. It shows that heat is removed from the cold store by a refrigeration plant and this heat is then discarded into the atmosphere. Energy can be used more efficiently if the following is achieved:

- reduce the heat load,
- improve the plant efficiency, and
- harvest the discarded heat and reuse.

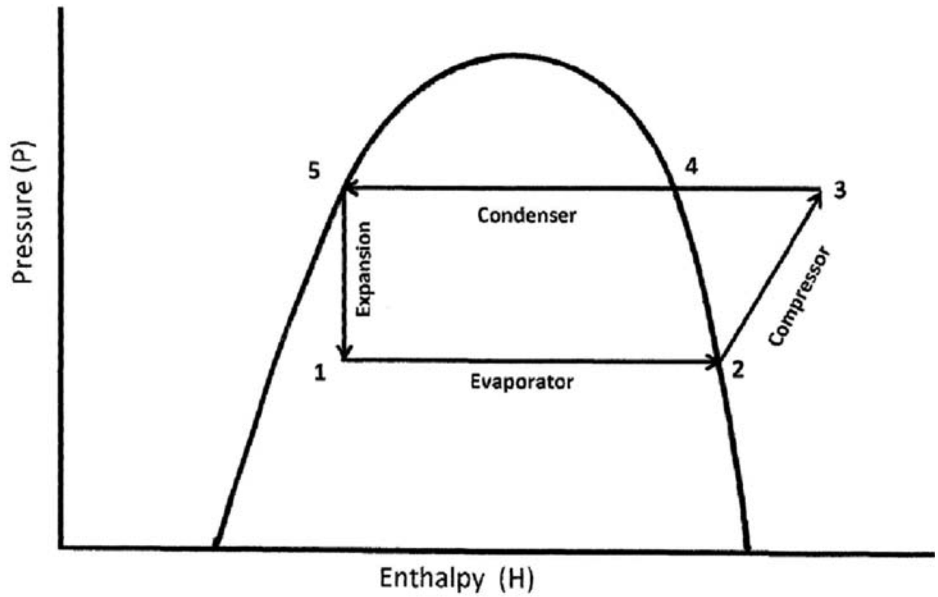


FIGURE 15.5 Enthalpy diagram.

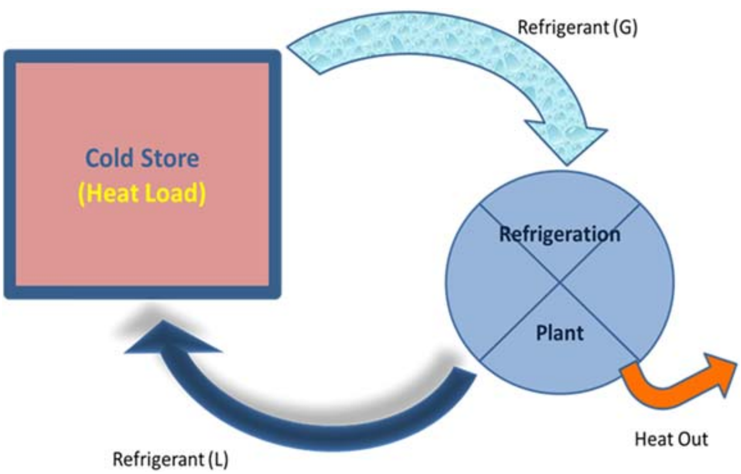


FIGURE 15.6 Refrigeration system.

These three opportunities are discussed in more detail next (Fig. 15.6).

15.7.5.5.1 Reduce the heat load

The heat load can be reduced by any of the following:

- The produce original temperature. Less energy is used for refrigeration when the original temperature of the product is closer to the target temperature. This can be

achieved by harvesting produce during the night or early mornings. Some produce types can also be stored in a natural cool place to lose some of its field heat before it is put in the cold store for further cooling to lower temperatures.
- The produce respiration heat. Respiration activity is reduced with cooling. A faster cooling rate will reduce the total respiration heat load.
- Insulation of the cold room. Heat entering the cold room through the floor, walls, ceiling, and roof adds to the heat load. Better insulation can reduce this heat load.
- Doors are a huge factor in adding to the heat load. When doors are open, warm air enters the cold room. When doors are closed, poor insulation of the doors or improper door seals may contribute to the heat load. Solutions for these are strip curtains, air curtains, automated high speed doors, or double door systems.
- Lighting is a heat source and should be reduced to the minimum. Proximity switches and energy efficient bulbs are some solutions.
- Fans are necessary for effective air circulation to transport the heat from the produce to the evaporator unit. Approximately 90% of the fan's electricity consumption is eventually transferred as heat into the cold room. Variable speed drives (VSDs) can be used to reduce the fan speed to optimum levels. Energy consumption is reduced with the cube of the ratio between speed and energy as per the affinity laws.
- People entering the cold chamber are also a heat source. Stock control or other administrative tasks should be done outside the cold chamber if possible.
- The heat of the forklift trucks adds to the heat load. Electrical forklifts are preferred previous combustion type forklifts for operating in the cold chambers.
- The nonutilization of the cold chamber space may increase the heat load when cold chambers are cooled but not utilized efficiently.

15.7.5.5.2 Improve refrigeration plant efficiency

The efficiency of the refrigeration plant can be improved by the following factors given by Wilcox (2010).

- Reducing the difference between suction and discharge pressures, also known as reducing the lift. Increasing suction pressure and/or reducing discharge pressure increases the efficiency.
- Selecting larger evaporator coils can lead to increased suction pressure.
- Increased condenser capacity may lead to reduction in discharge pressures given the effect of outdoor conditions.
- Improving the part-load performance of the refrigeration system. Although all refrigeration systems are designed to meet peak loads, many spend only a few hours at peak load. Hence, part-load operation and performance can play a large role in overall efficiency. Examples of improving the part-load performance are fan cycling, VSD on fans, improved compressor sequencing, VSD controls on compressors, and condensers.
- Upgrading the refrigeration equipment. Major refrigeration components can be retrofitted with features to improve efficiency. Examples are high-efficiency evaporator coils, more efficient fan blades, evaporator fin designs, premium-efficiency motors, and other changes to improve compressor and condenser efficiency.

- Improve the refrigeration system design. In addition to selecting the individual refrigeration components, the overall system design can be improved by features such as multistaging, subcooling, defrosting, and gas pressure pumping.
- Computer control systems can be used for controlling the refrigeration system at optimum levels for each particular operating environment.

15.7.5.5.3 Heat recovery

Heat recovery can improve the efficiency in a larger system of which the refrigeration is part of. The hot compressor discharge that is normally discarded into the atmosphere can rather be used for underfloor heating, boiler makeup or for heating plant cleanup water. This heat is then applied for a useful purpose and will save energy at another point, outside the refrigeration system.

15.7.5.6 Relative humidity

To maintain the relatively high humidity required for the storage of most fruits and vegetables, emphasis must be given to the design or capacity of the evaporators. To maintain an RH of 85%−90% at a temperature of 0°C, as recommended by Thompson (2002), the TD between the storage room temperature and the evaporator refrigerant exhaust temperature should not be greater than 3°C. Table 15.4 illustrates the effect of TD and RH that can naturally achieved. To achieve higher RHs in cold stores larger than usual, evaporator coils would be required.

15.7.5.7 The Internet of Things

Technology is moving at an ever-increasing pace and one of the benefits of this has been to the management of food safety. The ability to implement real-time supply chain temperature monitoring in conjunction with supply chain event visibility enables the proactive rather than reactive management of controls. The Internet of Things enables multiple recording devises measuring different parameters such as temperature, RH, shock loads, door openings, and dwell times to upload data in real time into the cloud. These data are then processed by algorithms into intelligence that can be retrieved on smart devises, or with the appropriate limits set warnings can be issued. Managers operating

TABLE 15.4 The relative humidity (RH) at various storage temperatures as affected by the temperature difference (TD) between the store room temperature and the evaporator refrigerant exhaust temperature.

	Minimum RH (%) at various store room temperatures		
TD (°C)	**0°C**	**1.6°C**	**3.5°C**
1	95.8	96.1	96.1
2	91.2	92.3	92.4
3	87.1	88.7	88.8
4	83.0	84.7	85.3
5	79.4	80.9	82.0

within the cold supply chain can then react appropriately to food safety concerns or the potential for the produce quality being compromised (Gogou, Katsaros, Derens, Alvarez, & Taoukis, 2015).

Considering that even a shortly sustained 2-h temperature spike can seriously affect the shelf life of strawberries (Pelletier, 2010), it is valuable to have warning of such deviation. RFID-enabled temperature devises allow for the real-time transfer of temperature within a cold supply chain. With artificial intelligence, this can be converted into intelligence on a dashboard visible on a compute or mobile devise screen. Warnings can also be sent via messaging systems to those responsible for the cold chain. Appropriate action can be taken to mitigate the risk caused to quality or value due to such thermal abuse.

15.8 Summary

Lowering the temperature of fresh produce as soon as possible after harvest and keeping it at that temperature ensures maximum storage and shelf-life quality. This allows for the maximum nutritive benefit of the produce to be maintained for the consumer. In addition, the full value of the produce will ensure that all the businesses that create the cold chain, as illustrated in Fig. 15.1, will be compensated. Cooling and keeping produce at the correct temperature is achieved with refrigeration. This is singly the most effective technology available to manage the quality of fresh produce after harvest and throughout the cold supply chain. Other technologies and processes are also involved in achieving an effective cold supply chain. Packaging design is critical and must be fit for the purpose of each produce type. Real-time supply chain temperature monitoring and visibility tools enable the anticipation of thermal abuse and the ability to rectify such an occurrence. Food safety and quality can thus be ensured resulting in consumers being able to purchase nutritious produce.

References

Anonymous. (1989). *Guide to food transport: Fruit and vegetables*. Copenhagen: Mercantila Publishers.

Ashby, H. (1995). Protecting perishable foods during transport by truck. In: *USDA handbook no. 669*.

Barger, W. R. (1962). Vacuum-cooling lettuce in commercial plants. In: *AMS-469* (9 p.). USDA Agricultural Marketing Service.

Boyette, M. D., Sanders, D. C., & Rutledge, G. A. (1996). Packaging requirements for fresh fruits and vegetables. In: *Agricultural extension publication (AG-414-8)*. North Caroline State University.

Boyhan, G. E., Purvis A.C., Wurst, W.C.torrance, R.L. and paulk, J.T. (2004). Harvest date effect on yield and controlled-atmosphere storage of short-day onions. Hortsci.39.7.1623.

Crisosto, C. H., & Mitchell, F. G. (2002). Postharvest handling systems: Stone Fruit. In: *Postharvest biology and technology: An overview. Postharvest technology of horticultural crops*. University of California, Agriculture and Natural Resources 3311.

Dehghannya, J., Ngadi, M., & Vigneault, C. (2010). Mathematical modelling procedures for airflow. Heat and mass transfer during forced convection cooling of produce: A Review. *Food Engineering Reviews*, *2*, 227–243.

Dehghannya, J., Ngadi, M., & Vigneault, C. (2012). Transport phenomena modelling during produce cooling for optimal package design: Thermal sensitivity analysis. *Biosystems Engineering*, *111*, 315–324.

Dodd, M. C. (2012). Costs in a fruit export supply chain. In: *Harvesting the sun, A profile of world horticulture* (p 32). ISHS, Scripta Horticulturae, 14.

Dodd, M. C. (2013). Identifying and rectifying temperature and humidity abuse in various fruit supply chains from South Africa to the United Kingdom. In: *World cold chain conference*, May 22–23, 2013, Impact Convention Centre, Bangkok, Thailand.

Duan, Y., Wang, G.-B., Fawole, O. A., Verboven, P., Zhang, X.-R., Wu, D., . . . Chen, K. (2020). Postharvest precooling of fruit and vegetables: A review. *Trends in Food Science and Technology*, *100*, 278–291.

FAO. *Global food losses and food waste – Extent, causes and prevention*. (2013). Available from <http://www.fao.org/docrep/014/mb060e/mb060e.pdf> Accessed 07.03.21.

Gehhardt, S. E., Cutrifelli, R., & Matthews, R. H. (1982). Composition of foods: Fruits and fruit juices, raw, processed and prepared. In: *Agriculture handbook no 8–9*. Washington, DC: US Department of Agriculture.

Gentry, J. P., & Nelson, K. E. (1964). Conduction cooling of Table grapes. *American Journal of Enology and Viticulture*, *15*, 41–46.

Gogou, E., Katsaros, G., Derens, E., Alvarez, G., & Taoukis, P. S. (2015). Cold chain database development and application as a tool for the cold chain management and food quality evaluation. *International Journal of Refrigeration*, *52*, 109–121.

Hardenburg, R. E., Watada, A. E., & Wang, C. Y. (1986). *The commercial storage of fruits, vegetables and florist and nursery stocks*. USDA/ARS, Agricultural handbook (66).

Haytowitz, D. B., & Matthews, R. H. (1984). Composition of foods: Vegetables and vegetable products, raw, processed and prepared. In: *Agriculture handbook no 8–11*. Washington, DC: US Department of Agriculture.

Hellevang, K. (2003). Vegetable storage system. In D. R. Heldman (Ed.), *The encyclopaedia of agricultural, food, and biological engineering* (pp. 1116–1123). New York: Marcel Dekker, Inc.

Hellickson, M. L. (2003). Fruit storage systems. In D. R. Heldman (Ed.), *The encyclopaedia of agricultural, food, and biological engineering* (pp. 422–424). New York: Marcel Dekker, Inc.

Holland, B. Elsie M Widdowson, I. D. Unwin, D. H. Buss, R. A. McCancePublisher:Letchworth [England] : Royal Society of Chemistry, Ministry of Agriculture, Fisheries and Food, ©1991.

Hung, Y.-C. (1991). Food freezing. In Y. H. Hui (Ed.), *Encyclopaedia of Food Science and Technology* (pp. 1041–1050). New York: John Wiley & Sons.

IIR. (2003). Refrigerated transport: Progress achieved and challenges to be met. In: *The 16th informatory note on refrigerating technologies*. Available from http://www.iifiir.org/en/doc/1014.pdf.

Jones, S. (1996). When time is of the essence. *Progressive Grocer*, *75*(2), 105.

Kader, A. A. (2002). *Postharvest biology and technology: An overview. Postharvest technology of horticultural crops*. University of California, Agriculture and Natural Resources 3311.

Kader, A. A., & Thompson, J. F. (2001). Grocery store display storage. *Perishables Handling Quarterly*, *107*, 6–7.

Katzorke, M., & Lee, B. W. (1998). Creating world class supply chains. In: *41st APICS international conference proceedings* (pp. 107–110).

McGregor, B. M. (1989). Tropical products transport handbook. In: *USDA handbook no. 668*.

Mercier, S., Villeneuve, S., Mondor, M., & Uysal, I. (2017). Time-temperature management along the food cold chain: A review of recent developments. *Comprehensive Reviews in Food Science and Food Safety*, *16*, 647–667.

Nunes, M. C. N., Nicometo, M., Emond, J. P., Melis, R. B., & Uysal, I. (2014). Improvement in fresh fruit and vegetable logistics quality: Berry logistics field studies. *Philosophical Transactions of The Royal Society A Mathematical Physical and Engineering Sciences*, *372*, 20130307.

Pelletier, W. (2010). *Air transport of horticultural products: A thermal analysis* (Ph.D. thesis). Gainesville, FL: University of Florida.

Raffo, A., Senatore, M., Monteta, E., Paoletti, F., Pepario, M., & Civitelli, E. S. (2020). Impact of different temperature abuse scenarios on sensory quality and off-odour formation in ready-to-eat salad leaves. *International Journal of Food Science & Technology*, *56*, 2345–2356. Available from http://doi.org/10.1111/ijfs.14858.

Spalding, D. B., & Cole, E. H. (1978). *Engineering thermodynamics* (3rd ed.). Edward Arnold.

Tao, Y. (2003). Fruit transport system. In D. R. Heldman (Ed.), *The encyclopedia of agricultural, food, and biological engineering* (pp. 425–430). New York: Marcel Dekker, Inc.

Tarnowski, J. (2006). The produce supply chain challenge. *Progressive grocer, executive insight series* (pp. 99–105). Available from http://www.progressivegrocer.com/progressivegrocer/mages/pdf/CH_Robinson_PG_PDF.pdf.

Thompson, J. F. (2002). Psychrometrics and perishable products. In: *Post harvest technology of horticultural crops*. University of California, Agricultural and Natural resources, Publication 3311.

Thompson, J. F., & Kader, A. A. (2004). Wholesale distribution centre storage. In: *The commercial storage of fruits, vegetables, and florist and nursery stocks (USDA agricultural handbook no. 66)*.

Thomson, J. F., Mitchell, F. G., Rumsey, T. M., Kasmire, R. F., & Crisosto, C. F. (2002). *commercial cooling of fruits, vegetables and flowers* (revised edition). University of California, Agriculture and Natural Resources Publication 21567.

Van Dalfsen, B. (1989). Refrigeration principles. *Farm structures fact sheet*. British Columbia.

Wilcox, M. E. A. (2010). Industrial refrigeration – Best practice guide. In: *Cascade energy*.

Wills, R., McGlasson, B., Graham, D., & Joyce, D. (2007). *Postharvest: An introduction to the physiology and handling of fruit, vegetables and ornamentals* (2nd ed.). Sydney: University of New South Wales Press.

CHAPTER

16

Investigating losses occurring during shipment: forensic aspects of cargo claims

Anna L. Snowdon

University of Cambridge, Wolfson College, Cambridge, United Kingdom

Abbreviations

ADR	Alternative Dispute Resolution
CA	controlled atmosphere
DCA	dynamic controlled atmosphere
FEFO	First Expired, First Out
FEU	Forty-Foot Equivalent Unit
MA	modified atmosphere
MAP	modified atmosphere packaging
QUEST system	QUality and Energy in Storage and Transport system
TEU	Twenty-Foot Equivalent Unit

16.1 Introduction

The United Nations declared 2021 as the International Year of Fruits and Vegetables. The Year aims to raise awareness of the nutritional and health benefits of consuming more fruits and vegetables as part of a diversified, balanced, and healthy diet and lifestyle as well as to direct policy attention to reducing loss and waste of these highly perishable produce items (FAO, 2020) (see also Chapter 2). Yahia (2020) presents a comprehensive review of the causes and prevention of food losses, including fruits and vegetables.

In all countries fresh produce must be transported from the growing areas to the cities, and there is great variation in losses occurring in overland supply chains. In developing countries losses tend to be high (Fabi, Cachia, Conforti, English, & Moncayo, 2021;

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00016-6

Underhill & Kumar, 2015), owing to factors such as inadequate packaging (Sibomana, Clercx, & Waal, 2019; FAO, 2017), poor roads (Pretorius & Steyn, 2019; Singh & Chauhan, 2017), and a lack of appropriate refrigeration (Kitinoja, Tokala, & Mohammed, 2019; Oberoi & Dinesh, 2019) (see also Chapter 16). Within advanced countries too, damage sustained during transport can be reduced by research into contributory causes (Fernando, Fei, & Stanley, 2019; Wills & Golding, 2016).

Beyond the subject of in-country transportation, it is horticultural exports that constitute the mainstay of the economy in many countries, including both developed and developing nations. High-value commodities may be dispatched by air (Michalský & Hooda, 2015; Pelletier, 2010; Saunders & Hayes, 2007; Thompson, Bishop, & Brecht, 2004; World Bank, 2009) in the cargo holds of passenger planes, examples being green beans from Kenya and baby sweet corn from Thailand, both of which are popular items in European supermarkets (see also Chapter 12). For larger consignments, dedicated cargo planes may be used, and this is customary for Israeli products such as tomatoes, peppers, exotic fruits, and fresh herbs. Globally, however, by far the greatest proportion of fresh produce is carried by land and sea (Ikegaya et al., 2019; LeBlanc & Hui, 2005; Tanner & Smale, 2005; Thompson, Brecht, & Hinsch, 2002; Vigneault, Thompson, Wu, Hui, & LeBlanc, 2009), and it is international maritime transport (George, 2014), which is the principal focus of the present chapter.

Transport of perishables is more complicated than storage, because of the multiple links in the chain and the many parties involved. A typical example might be a cargo of Ecuadorian bananas, insured by a German underwriter and carried in a Greek ship. The ship might have been built in Japan, registered in the Bahamas, chartered by an Italian fruit trader, and be discharging its cargo in Algiers. The vessel would probably be insured by 1 of the 13 main P&I (Protection and Indemnity) clubs (North P&I Club, 2019) that have offices in London (a great center for commercial shipping and insurance), Piraeus (Greece, with a strong maritime tradition), and the Far East, with its burgeoning trade.

In earlier years, commodities such as potatoes, onions, garlic, and citrus were often shipped in ventilated space at ambient temperature, but currently the majority of fruit and vegetable consignments are carried under refrigeration. Annual worldwide trade in refrigerated fresh fruits and vegetables was 69 million tonnes in 2002, 97 million tonnes in 2012, and 115 million tonnes in 2018 (Drewry, 2019). A little over half the total is seaborne, though with great variation between commodities; for example, only about 20% of tomato cargoes are carried by sea, compared with 48% of citrus and 99% of exported bananas.

16.2 Refrigerated maritime transport

The type of ship traditionally used in this trade is known as a specialized reefer (refrigerated) vessel, to distinguish it from freezer vessels used for fish (Lennerfors & Birch, 2019). It typically has either four or five hatch openings, each leading to three, four, or five decks. Each deck may be independently refrigerated, by delivery of cool air beneath perforated deck gratings, or the chambers may be grouped in pairs sharing a common fan system and supply of recirculated cool air, and a common fresh air ventilation system. Each deck is usually 2.2 m in height, designed to accommodate the standard pallet load of produce, leaving a few centimeters of head space above the stow (stored product) to allow the passage of return air (Handling refrigerated cargoes, 2016). Although pallet loads are generally built up to 2.1 m, the pallets themselves come in several different sizes, depending on the trade and country involved (ISO, 2009). Deck area is customarily defined in square meters, and stowage factor is expressed as square meters per pallet. Hold capacities are still given in cubic feet; not all cargoes are palletized, and stowage factor can also be expressed as cubic feet per tonne or (for the standard 20-kg banana box) cubic feet per box. The total hold capacities of these vessels are between 100,000 and 600,000 cubic feet, the average size being about 450,000 cubic feet and capable of carrying about 4000 t of cargo. During the last few years, with the scrapping of aging ships and the limited new builds, there has been a notable reduction in the specialized reefer fleet (Drewry, 2019; Lennerfors & Birch, 2019).

The reason for such a decline in specialized reefer ships is the inexorable rise in the proportion of perishable cargo carried by 40-ft reefer containers (Levinson, 2016). These are intermodal, able to be transported by road, by rail, and by sea, predominantly in purpose-built containerships but also on the weather deck of conventional vessels (Alders, 1995; Sinclair, 1999). Depending on pallet dimensions, each container can accommodate 20−28 pallets in a range of patterns with varying degrees of unused space (Berry, Defraeye, Ambaw, Coetzee, & Opara, 2018; Getahun et al., 2016). These days all are integral reefer containers, meaning that each container is equipped with its own refrigeration unit, to which electrical power is supplied at sea by the ship and on land by mains power at the port container terminal. In case of a lengthy road journey between packing station and load port, or between discharge port and final destination, power may be supplied by a clip-on diesel generator set (Maheshwar, 2008).

There are four main manufacturers of reefer units (Carrier Transicold, Thermoking, Daikin, and Maersk Container Industry) and numerous container shipping companies, of which the largest are Maersk headquartered in Denmark, MSC (Mediterranean Shipping Company) based in Switzerland, CMA-CGM of France, and COSCO of China. Since the earliest containers were 20 ft in size, the capacity of a container ship is usually measured in TEU (Twenty-foot equivalent unit) rather than FEU (Forty-foot equivalent unit); currently the largest container ships are a quarter of a mile long, with a capacity of nearly 24,000 TEU, including about 2000 electrical plugs to supply power to reefer containers.

There are a limited number of deepwater ports with the infrastructure to cope with such large vessels, and so container carriage is typified by transshipment from one vessel to another at these hub ports, smaller "feeder" vessels being required for access to more modest ports (Levinson, 2016). Again taking the example of an Ecuadorian banana shipment, the containers might be stuffed (*sic*) (filled) at the inland packing station, dispatched by road to Puerto Bolívar or Guayaquil, connected up to power at the container terminal, subsequently loaded on board a feeder vessel for the brief voyage to Panama, off-loaded at the Pacific port of Balboa, carried by rail across the isthmus (cheaper than the cost of a Canal transit for a large container ship), connected up to power at the Atlantic port of Cristóbal to await transshipment on to an ocean carrier, transshipped once more at the Spanish port of Algeciras for final carriage on feeder vessels to various ports around the Mediterranean.

Despite the frequent necessity for transshipment, there are obvious advantages in containerization, and over 80% of reefer cargo (which includes meat, poultry, and dairy products as well as fruits and vegetables) is currently carried in containers, predicted to rise to 85% by 2023 (Drewry, 2019). In the South African export trade, the proportion of fruit shipped in containers was 30% of the total in 2000 but by 2011 had risen to 90%, leaving only 10% to be exported in reefer vessels (Dodd, 2013). However, on a global scale, it is considered that specialized reefer ships will continue to play a significant role, especially in the banana trade, which involves year-round shipments of large quantities of cargo, and which benefits from direct services and hence shorter transit times than is possible with containers (Lennerfors & Birch, 2019). Other trades which may continue to prefer specialized reefers are New Zealand kiwifruit shipped to Asia, and fruit of all types imported into the Russian Federation (Drewry, 2019).

For certain commodities, a modified atmosphere (MA) or controlled atmosphere (CA) or dynamic CA is a valuable supplement to refrigeration (Kader, 2002; Lawton, 2007; Pace et al., 2020; Thompson, Prange, Bancroft, & Puttongsiri, 2018). Benefits include reduced respiration rate, reduced ethylene production, and reduced ethylene sensitivity, with the result that senescence in vegetables is delayed, and ripening of fruits is postponed (Yahia, 2009). In the early 1990s, to gain an advantage in the banana trade, the fruit company Chiquita equipped all its own reefer ships with the means of providing a CA in the holds and also started shipping bananas in CA reefer containers (Roche, 1998). Other companies followed suit, and currently a substantial proportion of bananas in international trade is carried under CA, as also are other commodities such as avocados, mangoes, apples, kiwifruit, and stone fruit (Thompson et al., 2018). By this means, physiological disorders may be alleviated, examples being chilling injury in avocados (Burdon, Billing, & Pidakala, 2017) and mangoes (Bender, Brecht, & Sargent, 2020) and superficial scald in apples (Mditshwa et al., 2017). CA can also suppress development of fungal rots (Liu et al., 2018). Modified atmosphere packaging (MAP) is a valuable alternative for a range of commodities (Muzammil Habib, Mudassir Bhat, Dar, & Wani, 2017; Sole, Henriod, Diczbalis, Stice, & Tora, 2016; Wilson, Stanley, Eyles, & Ross, 2019; Yahia, 2009; Varriano-Marston, 2010). An example of MAP is the patented Banavac bag (Badran, 1969) which is widely used for bananas destined for long voyages (3–5 weeks), in ships and containers that are not equipped to provide CA.

The container companies have promoted various technologies, including both hardware and software innovations, with the aim of saving energy while safeguarding the cargo, improving performance, and thereby reducing environmental impact. There are various ways of controlling the amount of fresh air ventilation in a refrigerated container, and each container company has its own design of automated vent management. It has also proved feasible to run the refrigeration machinery intermittently without jeopardizing the cargo (Lukasse, Baerentz, & Kramer-Cuppen, 2013), the QUEST (QUality and Energy in Storage and Transport) system having been developed through collaboration between Wageningen UR Food & Biobased Research, Maersk Line, and Carrier Transicold. Other container operators have devised their own "economy mode," which saves energy costs and also reduces greenhouse gas emissions. Meanwhile the high global warming potential of current refrigerants has triggered a major effort to find and implement more environmentally benign alternatives (McLinden, Seeton, & Pearson, 2020).

Throughout the transit period, in all reefer containers, there is automatic recording of set-point temperature, delivery air temperature (often called supply air temperature), return air temperature, and relative humidity, as well as details of the mode of operation of the reefer machinery (Maheshwar, 2008). This information may be downloaded electronically at the end of the voyage, or at any convenient time during the ensuing two years, should there be a cargo claim.

Clearly it is also valuable to be able to monitor conditions inside the container while the journey is in progress (Getahun et al., 2016; Jedermann, Geyer, Praeger, & Lang, 2013; Jedermann, Ruiz-Garcia, & Lang, 2009; LeBlanc & Vigneault, 2006; Ruiz-Garcia, Barreiro, Rodriguez-Bermejo, & Robla, 2007). Implementation of such technologies would afford a means of alerting carrier or cargo owner to potential problems that might thereby be mitigated; furthermore, information gathered could be used to minimize losses by marketing on the principle of FEFO (First Expired, First Out). Fresh fruits and vegetables are characterized by a high degree of inherent variability between batches of the same product, and prediction of storage life of individual batches can be of great value (East, Jabbar, & Heyes, 2013) (see also Chapters 5, 6, and 15). Traceability (Doyon & Lagimonière, 2006; Paul, Jacob-John, D'Souza, & Hamilton, 2016; Serem, 2011; Toussaint & Vigneault, 2006) is essential first for the health and safety of consumers, in the event of contaminated produce (Carstens, Salazar, & Darkoh, 2019; Lund & Snowdon, 2000; Mostafidi, Sanjabi, Shirkhan, & Zahedi, 2020; Watkins, 2020) (see also Chapters 11, 19, and 20), and, in the present context, can also provide vital evidence pointing toward the cause or causes of deterioration in a cargo during shipment.

16.3 Cargo claims

Whatever the method of carriage, if a consignment is discharged in poor condition, cargo interests (perhaps including the cargo underwriter) may lodge a claim against the carrier (ship owner or container operator). The carrier will normally turn to his P&I Club for assistance in defending the claim (North P&I Club, 2019; Crane, 2007b). Each party should have appointed an independent marine surveyor to assess the damage at the time of discharge and assign a cause. Specialists may also be instructed, with a view to obtaining further independent expert opinion.

The strategy is to identify the *pattern of damage*, to see whether it is related to preshipment factors (Kader, 2013; Manganaris, Vicente, & Crisosto, 2008; Valero & Serrano, 2010) or carriage factors (D. Tanner & Smale, 2005; D.J. Tanner & Amos, 2003) or both (Oke, Sobratee, & Workneh, 2013; Snowdon, 1994; Snowdon, 2007).

Preshipment factors include:

1. crop husbandry in relation to disease control (Castelan, Saraiva, Cordenunsi, & Chillet, 2013; Johnson, Malik, Malik, & Campbell, 2013; Snowdon, 1990, 1991),
2. weather during the growing season and at harvest (Paliyath, Murr, Handa, & Lurie, 2009; Rees, Farrell, & Orchard, 2012),
3. maturity of the crop at harvest (Arpaia et al., 2010; Mitra, Chakraborty, & Pathak, 2011; Moggia et al., 2018; Saeed, Thompson, & Pervez, 2007; Tchango, Achard, & Ngalani, 1999),
4. handling techniques during and after harvest (de Haan, 2008; Kader, 2013; Michaelides & Manganaris, 2009; Vicente et al., 2005; Wills & Golding, 2016),

5. postharvest treatments (Bazioli et al., 2019; Dukare et al., 2019; Haidar, Fermaud, Calvo-Garrido, Roudet, & Deschamps, 2016; Montecalvo, Opina, Dalisay, & Esguerra, 2019; Siddiq, Ahmed, Lobo, & Ozadali, 2012; Simone et al., 2020; Singh, Singh, Sane, & Nath, 2013; Streif, Kittemann, Neuwald, McCormick, & Xuan, 2010; Tomala, Malachowska, Guzek, Glabska, & Gutkowska, 2020; Wang Fei, Michailides, & Xiao, 2021; Yahia, 2011),
6. packagingtechniques (Berry, Defraeye, Ambaw, Coetzee, & Opara, 2018; Delele et al., 2013; Macnish et al., 2012; Pathare, Opara, Vigneault, Delele, & Al-Said, 2012; Rodriguez & Zoffoli, 2016; Wijeratnam, Fernando, & Hewajulige, 2018; Yahia, 2009),
7. lapse of time between harvest and establishment of cooling (de Haan, 2008; Madrid, 1998; Thompson, Mitchell, Rumsey, Kasmire, & Crisosto, 2008; Yahia, 2010), and
8. the appropriateness or otherwise of the shipper's (exporter's) carriage instructions (Alders, 1995; Crane, 2007b; Snowdon, 2010).

Carriage factors include:

1. interpretation and application of the shipper's carriage instructions (Punt & Huysamer, 2005; Reid & Serek, 1999),
2. duration of the voyage (Snowdon, 2007),
3. maintenance or otherwise of the cool chain (Maheshwar & Chanakwa, 2006; Yahia, 2010; CCQI, 2009) and atmosphere (Dodd, Bishop, & Lippert, 2018), and
4. stowage (Getahun et al., 2016; Sinclair, 1999; Thompson, Brecht, Hinsch, & Kader, 2000).

With regard to stowage, in a conventional vessel, responsibility lies with the ship owner, or sometimes with a charterer, depending on the contract of carriage (Alders, 1995; Crane, 2007b). In container carriage it is the shipper who is responsible for stowage of his goods in the container; the container operating company simply receives the closed box and applies the requested temperature and ventilation parameters (Heap & Marshall, 2003; Maheshwar, 2008).

16.4 Legal procedure

"Forensic" means "pertaining to the law" and, unless claims can be settled amicably, each party appoints a law firm. The bill of lading (signed by the ship's Master as receipt for the cargo) provides the basis for most shipping contracts that are generally governed by the Hague Rules or Hague−Visby Rules for the Carriage of Goods by Sea (Alders, 1995; Djadjev, 2017; Reynolds, 1992). Subsequent rules are the Hamburg Rules and the Rotterdam Rules (Thomas, 2010), but these have not been widely adopted. In English jurisdiction, solicitors for the claimant(s) draw up particulars of claim, alleging that the clean bill of lading (without remarks) demonstrates that the cargo was "loaded in apparent good order and condition" and, since part of it outturned in poor condition, the carrier must be responsible for the loss and should therefore pay the requested sum, with interest. Solicitors for the defendant carrier then draw up a defense, maintaining that the vessel's personnel exercised due diligence in carrying the cargo in the required manner, and pointing to Article IV of the Rules, which states that the carrier shall not be responsible for "loss or damage arising from inherent defect, quality, or vice of the goods" (Crane, 2007b).

Each party makes a request for disclosure of documents, which may illuminate the history of the consignment under dispute. Claimants and their lawyers are sometimes under the illusion that a phytosanitary certificate is sufficient proof of "fitness to load," unaware that phytosanitary inspection is designed to prevent the movement of quarantine organisms rather than to provide a statement of suitability to withstand the proposed voyage. More appropriate documents would include details of harvest dates, harvest maturity, postharvest treatments, dates of packing, code numbers of packing stations, dates and times of dispatch to the load port and loading in each deck, dates and locations of stuffing of containers, and inspections by quality control personnel in the exporting country. The shipper may also have placed independent temperature recorders on or in the stow at the time of stuffing, and retrieval of such records will provide an indication of the cargo environment during the voyage.

The carrier's lawyers would be expected to disclose bills of lading, cargo manifest, and shipper's Carriage Instructions. For a conventional vessel, relevant documents would include vessel particulars, general arrangement, hold capacities, stowage plan, statements of fact at load port(s) and discharge port(s), and a copy of the refrigeration log and deck log. For container shipments, historical tracking and tracing information is sometimes available on the container operator's website, and this can be used in conjunction with temperature data downloaded in electronic form from each container, either at the time of survey or subsequently.

In the event of a large cargo claim, it is usual for each party (generally cargo owner as claimant and carrier as defendant) to appoint two experts, one with a knowledge of postharvest biology and the other with expertise in marine engineering. It is advantageous if they are instructed in time to attend the discharge and collect evidence for themselves, working in conjunction with local marine surveyors. Frequently, however, experts are appointed by lawyers at a later stage and asked to analyze contemporary documents. In English jurisdiction, experts are required to write an unbiased report, acknowledging that their duty is to assist the court and that this duty overrides any obligation to the client; they must never assume the role of an advocate (Civil Procedure Rules, 2013; Cresswell, 1993). An expert should be willing to act for either claimant or defendant, thus displaying their professional independence and lack of bias.

Expert reports are exchanged between the parties on a given date. Opposing experts meet (in person or else by telephone) to discuss points of agreement and disagreement, and issue a joint statement; supplementary reports may also be exchanged. At this stage claimant and defendant often reach an out of court settlement, but otherwise the case may be heard before a high court judge (whose judgment will be published) or alternatively before an arbitration tribunal (whose decision will remain confidential), according to the original contract of carriage between the parties (Crane, 2007a; 2007b). Each side's case will have been prepared by a solicitor belonging to a law firm, and each firm then appoints a barrister (self-employed in "chambers") to act as advocate for that party's view of the case. Witnesses of fact give evidence in person or by way of a witness statement, and expert witnesses are cross-examined by the opposing barrister.

With a view to saving time and costs, it has become more common in recent years to attempt mediation, the principal form of alternative dispute resolution (ADR) (Kelbie, 2008). Mediation involves the use of a neutral third party as facilitator, but if agreement cannot be reached then the parties resort to arbitration or litigation (Crane, 2007a). In the United States, ADR proceeds in a similar fashion. In the event of litigation, however, American jurisdiction requires that, following the exchange of expert reports, expert witnesses make an out-of-court deposition before the opposing attorney (Federal Rules of Civil Procedure, 2010). This is an oral testimony that is taken down by a stenographer and forms part of the "discovery" process, whereby evidence is assembled. If a settlement cannot be reached then the case goes to trial and the witnesses appear before a judge. In both countries a party may occasionally contest the judge's decision by lodging an appeal; there are fewer grounds available for appealing against an arbitration decision (Crane, 2007a).

16.5 Case studies

An illustrative example (dating, however, from several years ago, and therefore not necessarily indicative of current practices) involved two containerloads of South African clementines (*Citrus reticulata* Blanco, cv. "Nules"), which arrived in poor condition in a northern European port. They had originally formed part of a consignment of seven containerloads of citrus, of which four comprised oranges and lemons and three comprised clementines. Owing to a serious labor strike in South African ports, there was a hiatus in cargo shipments and three of the containers (two, here called A and B, with clementines and one with oranges and lemons) had been "short-shipped," that is, had been shut out from the intended vessel and loaded on the next one. The total time between stuffing and unstuffing had thereby been extended from 3 to 4 weeks.

The importer claimed that the cargo was in good order and condition upon receipt by the carrier, and that the damaged arrival condition of the clementines resulted from the delay in delivery and/or the carrier's failure to take reasonable care of the cargo. The carrier argued that the hiatus arose because of the protracted dock strike, and that in any case, the observed damage to the clementines resulted from "inherent vice" in the fruit, which was not in actual good order and condition at the time of stuffing.

The importer had called in a surveyor to assess the damaged cargo on behalf of the cargo insurer; the carrier was alerted but declined to send a counter-surveyor. Examination showed that some of the clementines still had a greenish tinge rather than being fully colored, and that a few were suffering from either rind breakdown or puffiness. However, the surveyor reported that the main problem was decay, described as blister rot, blue-green mold rot, and stem-end rot. He noted that fruits of a certain size from two particular growers had an especially high incidence of rots. Though he did not distinguish between the two containerloads, it could be deduced from the packing lists that all the fruit from those two growers had been carried in Container A.

Temperature downloads showed that Container A had experienced three off-power periods, lasting 4, 6, and 3 h respectively, corresponding to the abortive sending forward for loading, the actual loading on board ship a week later, and the unloading on arrival of the vessel at the discharge port. Such breaks in the cool chain are unexceptional, and the requested delivery air temperature of 3.5°C had otherwise been well maintained. The rate at which cargo pulp temperatures rise during an off-power period depends on the respiration rate of the commodity, the pattern of stowage, the external ambient conditions, and the insulation characteristics of the container. Clementines have a low respiration rate, and furthermore, the first two off-power periods were during nighttime hours, when the external ambient temperature in the Cape Town area was between 4°C and 14°C. The clementines would have been precooled before being stowed in the containers.

Container B had experienced off-power periods of 10, 2, and 4 h and had operated in alarm mode for the whole of the first week, as the delivery air temperature was between 2°C and 3°C instead of 3.5°C. After manual intervention at the load port container terminal, the correct delivery air temperature was eventually established. The fact that the relative humidity in this container was consistently at or close to 100% suggested that fresh air ventilation had been excessive, although there was no documentation to indicate what degree of vent opening had been requested by the exporter or what setting had been used by the container operator. Despite the nonideal carriage conditions, when the cargo was surveyed on discharge, there was no indication of chilling injury, and the batches of fruit from this container reportedly showed a lower incidence of decay than the batches from Container A.

Blister rot is an early stage of green and blue mold rots caused by *Penicillium digitatum* Sacc. and *Penicillium italicum* Wehmer, respectively. One of the survey photographs suggested the possibility that sour rot might also have been involved; this type of decay is a soft wet rot caused by *Geotrichum citri-aurantii* (Ferraris) Butler, otherwise known as *Geotrichum candidum*, and is one of the main postharvest problems of citrus in South Africa (Lesar, 2007). Stem-end rot of citrus can be caused by any of several fungi, but the predominant causal organism in South Africa is *Lasiodiplodia theobromae* (Pat.) Griffon & Maubl. that causes diplodia rot. From the survey report the only certainty was penicillium rot, from which it was possible to state that some of the clementines must have sustained mechanical injuries and that postharvest fungicide treatment had been ineffective in preventing wound infection (Erasmus et al., 2011).

The fact that some fruits were greenish, and some were deep orange in color suggested that they had been degreened with ethylene to promote an attractive peel color. A disadvantage of ethylene treatment of citrus fruits is that the stem buttons may become moribund and susceptible to stem-end rot (Arpaia et al., 2010).

Rind breakdown is a limiting factor in the storage life of South African "Nules" clementines, typically appearing about 3–5 weeks after harvest. It is caused by a release of oil from collapsed oil glands in the peel, but rather than resulting from physical damage it seems to be a senescence-related physiological process; incidence increases with use of ethylene degreening, delay in cooling, and duration of storage (Cronje, Barry, & Huysamer, 2011).

Puffiness is a condition in which an air space develops between peel and pulp, making the fruit liable to split when handled. While puffiness may sometimes develop in fruit still on the tree, this disorder also occurs in storage (Burdon et al., 2007). Advancing maturity, vigor of the tree, and weather (particularly irregular water supply) may all be involved. Japanese research shows that puffiness has a dual origin: shrinking, often to near disappearance, of the albedo from undetermined causes, and swelling of the flavedo from external moisture. Preharvest sprays of growth regulators have provided significant reduction in puffiness but at the expense of poorer fruit color (Kuraoka, Iwasaki, & Ishii, 1977). On the one hand, therefore, it has been concluded that this disorder is a function of senescence. On the other hand, researchers have related puffiness to high humidity in storage.

It may be seen from the above that the arrival condition of the clementines had been determined by a multitude of interplaying factors, both preshipment and shipboard. Cargo importers had failed to provide preshipment details but packing codes on the boxes (only a few of which were legible in the photographs) indicated that at least some of the fruit had been harvested and packed more than 2 weeks before being stowed in the containers. Together with the delay in shipment, this meant that the total postharvest period was approaching the normal storage life of the fruit, leaving it with very little shelf life on return to ambient temperature for marketing. It would have been useful to have had access to outturn data for the third containerload of clementines that had been shipped on the earlier vessel, as this would have provided an instructive comparison. The fact that there was no claim on the promptly delivered load does not necessarily mean that the outturn was perfect.

The service provided by the carrier clearly left much to be desired, and the delay would have exacerbated the poor condition of the fruit. With regard to the "short-shipping," however, it was held that, according to the contract of carriage, the carrier had not undertaken to ship the goods on a particular vessel and was constrained by the situation of the protracted dock strike. The available evidence showed that some of the clementines had been unfit for the proposed voyage. Had they arrived in the discharge port a week earlier, there would already have been signs of decay, which would have continued to proliferate during marketing.

As a general point, there is often a dearth of documentation, in spite of the legal requirement for traceability (GS1 2010). Surveyors can only examine a portion of the cargo, and if patterns of damage are to be ascertained, the documents which are needed are the consignee's quality control inspection reports, since each pallet load is assigned a unique code, which incorporates information as to packing station, pack date, and location in the ship or container.

The most important perishable cargo is bananas. Bananas are shipped hard green, at a carriage temperature of 13.3°C (56°F) and must remain preclimacteric until they reach the ripening room in the country of destination. The most common cause of loss is premature ripening during the voyage (Snowdon, 2010), and the following is another case study.

The cargo (both underdeck and in reefer containers on deck) comprised Honduran and Guatemalan fruit, undergoing a month-long voyage culminating in discharge in Syria (port of Tartous). The crew had smelled ripening fruit during the Atlantic crossing, and the ship's P&I Club suggested boarding the vessel at Gibraltar to investigate the causes and attend the discharge. In Tartous, a detailed joint survey took place, by consultants and numerous local surveyors (who brought in assistants to cover the night shift), and the result was the collection of detailed information in the form of box-codes of both sound and ripened cargo discharged from each deck and each container. The cargo receiver had made a claim against the vessel for minor infringement of the carriage instructions, but the data collected by the survey teams demonstrated that the ripe and overripe fruit had come from three specific Guatemalan packing stations and with specific pack-dates. The rest of the Guatemalan cargo was in good condition, as was all of the Honduran cargo.

When faced with such evidence, the cargo owner withdrew his claim and the matter was taken no further. This demonstrates that early collaboration can lead to prompt resolution of claims.

16.6 Conclusion

Whenever a consignment of fresh produce arrives in poor condition, it is instructive to gather detailed evidence promptly. In the sophisticated supply chains pertaining in many parts of the world, the cargo receiver's quality control personnel will be present at outturn as a matter of course. However, in the event of complaint about produce quality or condition, surveyors representing either receiver or carrier can be called in to carry out a joint survey. Postharvest specialists may attend also, or be appointed at a later date by lawyers pursuing or defending a claim. Although the immediate objective is resolution of the claim, correct identification of the causes of deterioration enables recommendations to be made for avoiding similar losses in the future.

References

Alders, A.W.C. (1995). *Reefer transport and technology*, Rotterdam Marine Chartering Agents.

Arpaia, M. L., Mitcham, E., Cantwell, M., Crisosto, C., Kader, A., Reid, M., & Thompson, J. (2010). *Fruit ripening and ethylene management* (p. 130) Davis, CA: University of California, Publication no. HS9.

Badran, A. M. (1969). *'Controlled atmosphere storage of green bananas', Patent no. 3,450,548*, United States Patent Office, pp. 6.

Bazioli, J. M., Belinato, J. R., Costa, J. H., Akiyama, D. Y., Pontes, J. G., de, M., . . . Fill, T. P. (2019). Biological control of citrus postharvest phytopathogens. *Toxins*, *11*(8), 460. Available from. Available from https://www.mdpi.com/2072-6651/11/8/460/htm.

Bender, R. J., Brecht, J. K., & Sargent, S. A. (2020). Low storage temperature for tree ripe mangoes under controlled atmospheres with elevated CO_2 concentrations. *Journal of the Science of Food and Agriculture*, *101*(3), 1161–1166.

Berry, T. M., Defraeye, T., Ambaw, A., Coetzee, C., & Opara, U. L. (2018). Horticultural packaging systems of the future: Improving reefer container usage. *Acta Horticulturae, No. 1201*, 221–228.

Burdon, J., Billing, D., & Pidakala, P. (2017). Avoiding chilling damage in 'Hass' avocado fruit by controlled atmosphere storage at higher temperature. *HortScience: A Publication of the American Society for Horticultural Science*, *52*(8), 1107–1110.

Burdon, J., Lallu, N., Yearsley, C., Osman, S., Billing, D., & Boldingh, H. (2007). Postharvest conditioning of *Satsuma mandarins* for reduction of acidity and skin puffiness. *Postharvest Biology and Technology*, *43*, 102–114.

Carstens, C. K., Salazar, J. K., & Darkoh, C. (2019). Multistate outbreaks of foodborne illness in the United States associated with fresh produce from 2010 to 2017. *Frontiers in Microbiology*, *10*. Available from. Available from https://doi.org/10.3389/fmicb.2019.02667.

CCQI (2009). *Cool chain quality indicator standard: The concept of cool chain quality, version 2.2*, Germanischer Lloyd and Cool Chain Association, Hamburg, pp. 177.

Civil Procedure Rules (2013). *Part 35: Experts and assessors*, Ministry of Justice, UK Government, London.

Crane, P. (2007a). In *Arbitration v. litigation, second annual seminar on perishable product transportation* (pp. 10). Lloyds Maritime Academy, London.

Crane, P. (2007b). In *Contracts of carriage by sea and cargo claims, second annual seminar on perishable product transportation* (pp. 23). Lloyds Maritime Academy, London.

Castelan, F. P., Saraiva, L. A., Cordenunsi, B. R., & Chillet, M. (2013). Necrotic leaf removal: An effective method to limit the green life shortening effects of Sigatoka leaf spot disease in bananas. *Acta Horticulturae, No. 986*, 145–148.

Cresswell, J. (1993). The “Ikarian Reefer,”. *Lloyds Law Reports*, *2*, 81–82.

Cronje, P. J. R., Barry, G. H., & Huysamer, M. (2011). Postharvest rind breakdown of ’Nules Clementine’ mandarin is influenced by ethylene application, storage temperature and storage duration. *Postharvest Biology and Technology*, *60*, 192–201.

de Haan, H. (2008). *BMT de Beer’s consolidated manual on postharvest handling, cooling and storage of fruit and vegetables*, BMT de Beer, Rotterdam.

Delele, M. A., Ngcobo, M. E. K., Getahun, S. T., Chen, L., Mellman, J., & Opara, U. L. (2013). Studying airflow and heat transfer characteristics of a horticultural produce packaging system using a 3-D CFD model, Part II: Effect of package design. *Postharvest Biology and Technology*, *86*, 546–555.

Djadjev, I. (2017), The obligations of the carrier regarding the cargo: The Hague-Visby Rules, Springer International Publishing. DOI: 10.1007/978-3-319-62440-2.

Dodd, M. C. (2013). Managing airflow inside reefer containers benefits produce quality. *Acta Horticulturae*, *No. 1012*, 1159–1166.

Dodd, M. C., Bishop, C. F. H., & Lippert, F. (2018). Commercial benefits achieved by the removal of ethylene in a long plum supply chain with new filtration technology. *Acta Horticulturae*, *No. 1194*, 729–735.

Doyon, G., & Lagimonière, M. (2006). Traceability and quality assurance systems in food supply chains. *Stewart Postharvest Review*, *2*(3), 16.

Drewry (2019). *Reefer shipping annual review and forecast 2019/20* (pp. 166). Drewry Maritime Research, London.

Dukare, A. S., Paul, S., Nambi, V. E., Gupta, R. K., Singh, R., Sharma, K., & Vishwakarma, R. K. (2019). Exploitation of microbial antagonists for the control of postharvest diseases of fruits: A review. *Critical Reviews in Food Science and Nutrition*, *59*(9), 1498–1513.

East, A. R., Jabbar, A., & Heyes, J. A. (2013). Approaches to prediction of storage out-turn for units of fresh produce. *Acta Horticulturae*, *No. 1012*, 1303–1309.

Erasmus, A., Lennox, C. L., Jordaan, H., Smilanick, J. L., Lesar, K., & Fourie, P. H. (2011). Imazalil residue loading and green mould control in citrus packhouses. *Postharvest Biology and Technology*, *62*, 193–203.

FAO (2017). *Policy measures for managing quality and reducing post-harvest losses in fresh produce supply chains in South Asian countries*, Rome, pp. 4. <http://www.fao.org/3/a-i7954e.pdf>.

FAO (2020). ’Fruit and vegetables – Your dietary essentials’, *The international year of fruits and vegetables*, *2021*, *background paper*, Rome, pp. 73. <https://doi.org/10.4060/cb2395en>.

Federal Rules of Civil Procedure (2010). *Rule 26: Duty to disclose; general provisions governing discovery*, US Government, Washington DC, pp. 34–42.

Fabi, C., Cachia, F., Conforti, P., English, A., & Moncayo, J. R. (2021). Improving data on food losses and waste: From theory to practice. *Food Policy*, *98*. Available from https://doi.org/10.1016/j.foodpol.2020.101934.

Fernando, I., Fei, J. G., & Stanley, R. (2019). Measurement and analysis of vibration and mechanical damage to bananas during long-distance interstate transport by multi-trailer road trains. *Postharvest Biology and Technology*, *158*, 110977. Available from. Available from https://doi.org/10.1016/j.postharvbio.2019.110977.

George, R. (2014). *Deep sea and foreign going: Inside shipping, the invisible industry that brings you 90% of everything*. London: Granta Books.

Getahun, S., Ambaw, A., Delele, M., Meyer, C. & Opara, U. L. (2016). ’Numerical study of airflow in a full scale refrigerated shipping container packed with apples’. In *Proceedings of the CIGR-AgEng conference* (pp. 1–8). *26–29 June 2016*, *Aarhus*, *Denmark*. <https://www.cabdirect.org/cabdirect/abstract/20183376962>.

GS1 (2010). *Traceability for fresh fruits and vegetables implementation guide* (pp. 57). GS1 UK, London.

Haidar, R., Fermaud, M., Calvo-Garrido, C., Roudet, J., & Deschamps, A. (2016). Modes of action for biological control of *Botrytis cinerea* by antagonistic bacteria. *Phytopathologia Mediterranea*, *55*(3), 301–322.

Handling refrigerated cargoes - fresh produce (fruit and vegetables) and frozen cargo (2016). Available from: <generalcargoship.com/refrigerated-cargoes.html>.

Heap, R. & Marshall, R. (2003). ’Ventilation effects and requirements in containerised refrigerated transport’. In *Proceedings of the international congress of refrigeration* (pp. 5). Washington DC, paper ICR0472.

Ikegaya, A., Toyoizumi, T., Ohba, S., Nakajima, T., Nagafuji, A., Nakamura, S., . . . Arai, E. (2019). Quality evaluation of fruits and vegetables in mixed cargo exported by sea. *The Horticultural Journal*, *88*(4), 548–558.

ISO (2009). ’Flat pallets for intercontinental materials handling – Principal dimensions and tolerances’, *ISO Standard 6780:2003* (pp. 13). Geneva: International Organisation for Standardisation.

Jedermann, R., Geyer, M., Praeger, U., & Lang, W. (2013). Sea transport of bananas in container — Parameter identification for a temperature model. *Journal of Food Engineering*, *115*, 330—338.

Jedermann, R., Ruiz-Garcia, L., & Lang, W. (2009). Spatial temperature profiling by semi-passive RFID loggers for perishable food transportation. *Computers and Electronics in Agriculture*, *65*, 145—154.

Johnson, P., Malik, A. U., Malik, O. H., & Campbell, J. (2013). Issues and advances in commercializing sea-freight technology of mangoes. *Acta Horticulturae*, *992*, 75—85.

Kader, A.A. (ed.) (2002). *Postharvest technology of fruits and vegetables*. University of California Agriculture and Natural Resources Publication, 3311, Oakland, CA.

Kader, A. A. (2013). Postharvest technology of horticultural crops — An overview from farm to fork. *Ethiopian Journal of Applied Science and Technology*, 1—8. (Special Issue no. 1).

Kelbie, J. (2008). ADR/Mediation for recoveries, *Technical paper of the chartered institute of loss adjusters* (pp. 9).

Kitinoja, L., Tokala, V. Y., & Mohammed, M. (2019). Clean cold-chain development and the critical role of extension education. *Agriculture for Development*, *36*, 19—25.

Kuraoka, T., Iwasaki, K., & Ishii, T. (1977). Effect of GA_3 on puffing and levels of GA-like substances and ABA in the peel of satsuma mandarin (*Citrus unshiu* Marc.). *Journal of the American Society for Horticultural Science*, *102*, 651—654.

Lawton, R. (2007). *Understanding controlled atmosphere storage. 2nd annual seminar on perishable product transportation* (p. 14) London: Lloyds Maritime Academy.

LeBlanc, D., & Vigneault, C. (2006). Traceability of environmental conditions for maintaining horticultural produce quality. *Stewart Postharvest Review*, *2*(3), 10.

LeBlanc, D. I., & Hui, K. P. C. (2005). Land transportation of fresh fruits and vegetables: An update. *Stewart Postharvest Review*, *1*(1), 13.

Lennerfors, T. T., & Birch, P. (2019). *Snow in the tropics: A history of the independent reefer operators*. Leiden: Brill.

Lesar, K. H. (2007). 'The potential role of GRAS (generally regarded as safe) chemicals, alone and in combination with post-harvest fungicides, in the control of the major post-harvest citrus pathogens, *Penicillium digitatum (citrus green mould) and Geotrichum candidum* (sour rot)'. In P. Bertolini (Ed.), *Novel approaches for the control of postharvest diseases and disorders: Proceedings of the international congress* (pp. 322—326). Bologna, Italy.

Levinson, M. (2016). *The box: How the shipping container made the world smaller and the world economy bigger* (2nd ed.). Princeton University Press.

Liu, J., Sui, Y., Wisniewski, M., Xie, Z. G., Liu, Y. Q., You, Y. M., ... Wang, Q. (2018). The impact of the postharvest environment on the viability and virulence of decay fungi. *Critical Reviews in Food Science and Nutrition*, *58* (10), 1681—1687.

Lukasse, J.S., Baerentz, M.B. & Kramer-Cuppen, J.E.de (2013). 'Quest II: Reduction of CO_2 emissions of reefer containers', *Wageningen UR food and biobased research, report*, Ref. 440747 (pp. 8).

Lund, B. M., & Snowdon, A. L. (2000). Fresh and processed fruits'. In B. M. Lund, T. C. Baird-Parker, & G. W. Gould (Eds.), *The microbiological safety and quality of food* (pp. 738—758). Gaithersburg, MD: Aspen Publishers.

Macnish, A. J., Padda, M. S., Pupin, F., Tsouvaltzis, P. I., Deltsidis, A. I., Sims, C. A., ... Mitcham, E. J. (2012). Comparison of pallet cover systems to maintain strawberry fruit quality during transport. *Horttechnology*, *22*, 493—501.

Madrid, M. (1998). Cooling delays and their impact on green life of bananas. *Acta Horticulturae*, *No. 464*, 513. Available from. Available from https://doi.org/10.17660/ActaHortic.1998.464.103.

Maheshwar, C. (2008). *Container refrigeration*. Edinburgh: Witherby Publishing.

Maheshwar, C., & Chanakwa, T. S. (2006). Postharvest losses due to gaps in cold chain in India: A solution. *Acta Horticulturae*, *No. 712*, 777—783.

Manganaris, G. A., Vicente, A. R., & Crisosto, C. H. (2008). Effect of pre-harvest and post-harvest conditions and treatments on plum fruit quality. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources*, *3*(9), 10.

McLinden, M. O., Seeton, C. J., & Pearson, A. (2020). New refrigerants and system configurations for vapor-compression refrigeration. *Science (New York, N.Y.)*, *370*(6518), 791—796. Available from https://doi.org/10.1126/science.abe3692.

Mditshwa, A., Fawole, O. A., Vries, F., Merwe, K., van der, Crouch, E., & Opara, U. L. (2017). Minimum exposure period for dynamic controlled atmospheres to control superficial scald in 'Granny Smith' apples for long distance supply chains. *Postharvest Biology and Technology*, *127*, 27—34.

Michaelides, T. J., & Manganaris, G. A. (2009). Harvesting and handling effects on postharvest decay. *Stewart Postharvest Review*, *5*(2), 7.

Michalský, M., & Hooda, P. S. (2015). Greenhouse gas emissions of imported and locally produced fruit and vegetable commodities: A quantitative assessment. *Environmental Science and Policy*, *48*, 32–43.

Mitra, S. K., Chakraborty, I., & Pathak, P. K. (2011). Postharvest technology of tropical export produce: Recent developments and challenges of a future free-trade world market. *Acta Horticulturae*, *No. 906*, 115–123.

Moggia, C., González, C., Lobos, G. A., Bravo, C., Valdés, M., Lara, I., & Graell, J. (2018). Changes in quality and maturity of "Duke" and "Brigitta" blueberries during fruit development: Postharvest implications. *Acta Horticulturae*, *No. 1194*, 1495–1501.

Montecalvo, M. P., Opina, O. S., Dalisay, T. U., & Esguerra, E. B. (2019). Efficacy of postharvest treatments in reducing stem end rot of 'Carabao' mango (*Mangifera indica* L.) fruit. *Philippine Journal of Crop Science*, *44*(1), 36–43.

Mostafidi, M., Sanjabi, M. R., Shirkhan, F., & Zahedi, M. T. (2020). A review of recent trends in the development of the microbial safety of fruits and vegetables. *Trends in Food Science and Technology*, *103*, 321–332.

Muzammil Habib., Mudassir Bhat., Dar, B. N., & Wani, A. A. (2017). Sweet cherries from farm to table: A review. *Critical Reviews in Science and Nutrition*, *57*(8), 1638–1649.

North P&I Club. (2019). *An introduction to P&I insurance and loss prevention* (3rd ed.). Edinburgh: Witherby Publishing.

Oberoi, H. S., & Dinesh, M. R. (2019). Trends and innovations in value chain management of tropical fruits. *Journal of Horticultural Sciences*, *14*(2), 87–97.

Oke, M. O., Sobratee, N., & Workneh, T. S. (2013). Integrated pre- and post-harvest management processes affecting fruit and vegetable quality. *Stewart Postharvest Review*, *9*(3), 8.

Pace, B., Cefola, M., Logrieco, A. F., Sciscio, B., Sacchetti, A., Siliberti, M., ... Colelli, G. (2020). Shipping container equipped with controlled atmosphere: Case study on table grapes. *Journal of Agricultural Engineering*, *51*(1), 1–8.

Paliyath, G., Murr, D., Handa, A. K., & Lurie, S. (Eds.), (2009). *Postharvest biology and technology of fruits, vegetables, and flowers*. Ames, IA: Wiley-Blackwell.

Pathare, P. B., Opara, U. L., Vigneault, C., Delele, M. A., & Al-Said, F. A. (2012). Design of packaging vents for cooling fresh horticultural produce. *Food and Bioprocess Technology*, *5*, 2031–2045.

Pelletier, W. (2010). *Air transport of horticultural produce: A thermal analysis* (Ph.D. dissertation no. 3436418). University of Florida (pp. 248).

Paul, R., Jacob-John, J., D'Souza, D., & Hamilton, M. (2016). A cloud model for real-time fresh produce transportation management. *Acta Horticulturae*, *No. 1137*, 225–232.

Pretorius, C. J., & Steyn, W. JvdM. (2019). Quality deterioration and loss of shelf life as a result of poor road conditions. *International Journal of Postharvest Technology and Innovation*, *6*(1), 26–45.

Punt, H., & Huysamer, M. (2005). Effect of the commercial dual temperature shipping regime on pulp temperature and fruit quality in Sapphire plums, shipped in integral reefer containers. *Acta Horticulturae*, *No. 687*, 289–296.

Rees, D., Farrell, G., & Orchard, J. (Eds.), (2012). *Crop post-harvest: Science and technology, vol. 3, Perishables*. Oxford: Wiley-Blackwell.

Reid, M. S., & Serek, M. (1999). *Guide to food transport: Controlled atmosphere*. Copenhagen: Mercantila Publishers.

Reynolds, F. (1992). The hague rules, the hague-visby rules, and the Hamburg rules. *Australian and New Zealand Maritime Law Journal*, *7*, 16–34.

Roche, J. (1998). *The international banana trade*. Cambridge: Woodhead Publishing.

Rodriguez, J., & Zoffoli, J. P. (2016). Effect of sulfur dioxide and modified atmosphere packaging on blueberry postharvest quality. *Postharvest Biology and Technology*, *117*, 230–238.

Ruiz-Garcia, L., Barreiro, P., Rodriguez-Bermejo, J., & Robla, J. I. (2007). Review: Monitoring the intermodal, refrigerated transport of fruit using sensor networks. *Spanish Journal of Agricultural Research*, *5*, 142–156.

Saunders, C. & Hayes, P. (2007). 'Air freight transport of fresh fruit and vegetables', *Agribusiness & economics research unit (Lincoln University, New Zealand) research report*, no. 299 (pp. 48).

Saeed, A., Thompson, A. K., & Pervez, M. A. (2007). Effect of harvest maturity stage and position of hands on the ripening behavior and quality of banana fruit. *Acta Horticulturae*, *No. 741*, 117–123.

Serem, A. (2011). International trade opportunities for small scale horticultural production systems. *Acta Horticulturae*, *No. 911*, 53−60.
Sibomana, M., Clercx, L., & Waal, J. W. H. van der (2019). An integrated analysis of tomato supply networks in Nigeria to improve efficiency and quality. *Acta Horticulturae*, *No. 1258*, 171−182.
Siddiq, M., Ahmed, J., Lobo, M. G., & Ozadali, F. (Eds.), (2012). *Tropical and subtropical fruits: Postharvest physiology, processing and packaging*. Ames, IA: Wiley-Blackwell.
Simone, N., de, Pace, B., Grieco, F., Chimiento, M., Tyibilika, V., Santoro, V., . . . Russo, P. (2020). *Botrytis cinerea* and table grapes: A review of the main physical, chemical, and bio-based control treatments in post-harvest. *Foods*, *9*(9). Available from. Available from https://doi.org/10.3390/foods9091138.
Sinclair, J. (1999). *Refrigerated transportation* (2nd ed.). London: Witherby Publishing.
Singh, S., & Chauhan, S. K. (2017). Post harvest losses in marketing of vegetables in Himachal Pradesh. *Indian Journal of Agricultural Marketing*, *31*(2), 1−11.
Singh, Z., Singh, R. K., Sane, V. A., & Nath, P. (2013). Mango − postharvest biology and biotechnology. *Critical Reviews in Plant Sciences*, *32*, 217−236.
Snowdon, A. L. (1990). *A colour atlas of post-harvest diseases and disorders of fruits and vegetables, vol. 1, General introduction and fruits*. London: Wolfe Scientific.
Snowdon, A. L. (1991). *A colour atlas of post-harvest diseases and disorders of fruits and vegetables, vol. 2, Vegetables*. London: Wolfe Scientific.
Snowdon, A. L. (1994). 'Diagnosing the causes of out-turn problems in imported tropical fruits', In B. R. Champ, E. Highley & G. I. Johnson (Eds.) *Postharvest handling of tropical fruits: Proceedings of an international conference held at Chiang Mai* (pp. 94−101). *Thailand, 19−23 July 1993*, ACIAR proceedings, no. 50.
Snowdon, A. L. (2007). *From cargo claims to loss prevention: Fresh fruits and vegetables in transit*. *2nd annual seminar on perishable product transportation* (p. 6) London: Lloyds Maritime Academy.
Snowdon, A. L. (2010). Carriage of bananas (*Musa* spp.) in refrigerated ships and containers: Pre-shipment and shipboard factors influencing cargo out-turn condition. *Acta Horticulturae*, *No. 879*, 375−383.
Sole, D., Henriod, R., Diczbalis, Y., Stice, K. N., & Tora, L. (2016). Modified atmosphere packaging effects on the postharvest quality of papaya fruit. *Acta Horticulturae*, *No. 1111*, 119−124.
Streif, J., Kittemann, D., Neuwald, D. A., McCormick, R., & Xuan, H. (2010). Pre- and post-harvest management of fruit quality, ripening and senescence. *Acta Horticulturae*, *No. 877*, 55−68.
Tanner, D., & Smale, N. (2005). Sea transportation of fruits and vegetables: An update. *Stewart Postharvest Review*, *1*(1), 9.
Tanner, D. J., & Amos, N. D. (2003). Temperature variability during shipment of fresh produce. *Acta Horticulturae*, *No. 599*, 193−203.
Tchango, J. T., Achard, R., & Ngalani, J. A. (1999). Study of harvesting stages for exportation to Europe, by ship, of three plantain cultivars grown in Cameroon. *Fruits (Paris)*, *54*, 215−224.
Thomas, R. (Ed.), (2010). *The carriage of goods by sea under the Rotterdam Rules*. London: Informa Law, Routledge.
Thompson, A. K., Prange, R. K., Bancroft, R. D., & Puttongsiri, T. (2018). *Controlled atmosphere storage of fruit and vegetables* (3rd ed.). Wallingford: CAB International.
Thompson, J. F., Bishop, C. F. H., & Brecht, P. E. (2004). *Air transport of perishable products* (p. 22) Oakland, CA: University of California Agriculture and Natural Resources Publication no. 21618.
Thompson, J. F., Brecht, P. E., & Hinsch, T. (2002). *Refrigerated trailer transport of chilled perishable produce* (p. 28) Oakland, CA: University of California Agriculture and Natural Resources Publication no. 21614.
Thompson, J. F., Brecht, P. E., Hinsch, T., & Kader, A. A. (2000). *Marine container transport of chilled perishable produce* (p. 32) Oakland, CA: University of California Agriculture and Natural Resources Publication no. 21595.
Thompson, J. F., Mitchell, F. G., Rumsey, T. R., Kasmire, R. F., & Crisosto, C. H. (2008). *Commercial cooling of fruits, vegetables, and flowers* (p. 61) Oakland, CA: University of California Agriculture and Natural Resources Publication 21567.
Tomala, K., Malachowska, M., Guzek, D., Glabska, D., & Gutkowska, K. (2020). The effects of 1-methylcyclopropene treatment on the fruit quality of 'Idared' apples during storage and transportation. *Agriculture*, *10*(11).
Toussaint, V., & Vigneault, C. (2006). Fresh horticultural produce quality and safety: The importance of traceability from the field to the consumer. *Stewart Postharvest Review*, *2*(3), 6.
Underhill, S. J. R., & Kumar, S. (2015). Quantifying postharvest losses along a commercial tomato supply chain in Fiji: A case study. *Journal of Applied Horticulture (Lucknow)*, *17*(3), 199−204.

Valero, D., & Serrano, M. (2010). *Postharvest biology and technology for preserving fruit quality*. Boca Raton, FL: CRC Press.

Varriano-Marston, E. (2010). 'Method for controlling banana and plantain quality by packaging', *Patent no. EP 2197750/A1*, European Patent Register (pp. 38).

Vicente, A. R., Civello, P. M., Martinez, G. A., Powell, A. L. T., Labavitch, J. M., & Chaves, A. R. (2005). Control of postharvest spoilage in soft fruit. *Stewart Postharvest Review*, *1*(4), 11.

Vigneault, C., Thompson, J., Wu, S., Hui, K. P. C., & LeBlanc, D. I. (2009). Transportation of fresh horticultural produce. In N. Benkeblia (Ed.), *Postharvest technologies for horticultural crops* (2, pp. 1–24). Trivandrum: Research Signpost.

Wang Fei, S. S., Michailides, T. J., & Xiao, C. L. (2021). Postharvest use of natamycin to control Alternaria rot on blueberry fruit caused by *Alternaria alternata* and *A. arborescens*. *Postharvest Biology and Technology*, *172*. Available from. Available from https://doi.org/10.1016/j.postharvbio.2020.111383.

Watkins, C. (2020). *Advances in postharvest management of horticultural produce*. Cambridge: Burleigh Dodds Science Publishing.

Wijeratnam, R. S. W., Fernando, K., & Hewajulige, I. G. N. (2018). Models adopted for commercializing new post-harvest technology for minimizing postharvest loss of fruits in Sri Lanka. *Acta Horticulturae*, *No. 1201*, 177–182.

Wills, R. B. H., & Golding, J. B. (2016). *Postharvest: An introduction to the physiology and handling of fruit and vegetables*. Wallingford: CAB International.

Wilson, M. D., Stanley, R. A., Eyles, A., & Ross, T. (2019). Innovative processes and technologies for modified atmosphere packaging of fresh and fresh-cut fruits and vegetables. *Critical Reviews in Food Science and Nutrition*, *59*(3), 411–422.

World Bank. (2009). *Air freight: A market study with implications for landlocked countries*. *Transport paper TP-26* (p. 95) Washington, DC: International Trade Department, The World Bank.

Yahia, E. M. (Ed.), (2009). *Modified and controlled atmospheres for the storage, transportation, and packaging of horticultural commodities*. Boca Raton, FL: CRC Press.

Postharvest biology and technology of tropical and subtropical fruits. In E. M. Yahia (Ed.), *Woodhead Publishing series in food science, technology and nutrition, nos. 206–209* (1–4). Cambridge: Woodhead Publishing.

Yahia, E. M. (2010). Cold chain development and challenges in the developing world. *Acta Horticulturae*, *No. 877*, 127–132.

Yahia, E. M. (2020). *Preventing food losses and waste to achieve food security and sustainability*. Cambridge: Burleigh Dodds Science Publishing.

PART 4

Perceptions

CHAPTER

17

Consumer eating habits and perceptions of fresh produce quality

Amy Bowen and Alexandra Grygorczyk

Vineland Research and Innovation Centre, Vineland, ON, Canada

Abbreviations

1-MCP	1-methylcyclopropene
CA	controlled atmosphere storage

17.1 Introduction

Public health agencies around the world have been promoting increased consumption of fruits and vegetables for many years. Human decision-making is complex, and over the years, reviews of public health campaigns have found that increasing knowledge of the benefits of a diet high in fruits and vegetables alone is not enough to motivate sustained consumption across the population. As the research on this subject has progressed, it has shed light on the many external factors (e.g., access, quality) and internal (i.e., psychological) factors that ultimately lead to a meaningful increase in fruit and vegetable intake. These factors play a foundational role in explaining overall trends in fruit and vegetable consumption. Therefore this chapter will begin with an overview of factors that moderate overall fruit and vegetable consumption habits.

In addition to factors that moderate overall intake, understanding consumption also requires an exploration of another area of research which examines the factors that lead a consumer to choose one fruit or vegetable over another or even one variety of produce over another. While quality is an important element in increasing overall fruit and vegetable consumption, the public health benefits of increased produce consumption are typically viewed as a secondary benefit by fruit and vegetable marketers when aiming for high-quality produce. It's been said that consumer acceptability of a product is reflected in the sales figures, with repeat purchase being a key indicator of quality (Fandos & Flavián,

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00017-8

2006; Rao, 2005). Therefore consumer-related quality attributes are what drive the success of individual cultivars, thereby fueling competition, innovation, and ultimately driving economic growth and sustainability of the sector.

The quality of produce is generally determined prior to harvest by deciding what to grow and when to pick the crop. Subsequently, postharvest protocols are essential for preserving the quality of the crop until it reaches the consumer. Postharvest handling standards frequently monitor quality by means of visual cues at the expense of flavor, nutritional, and functional product attributes (Kyriacou & Rouphael, 2018). However, a comprehensive depiction of the caliber of a product as viewed by consumers requires teasing through the complexities of quality that include both inherent product features and external factors and how these relate to the preferences of a diverse population.

This chapter will elaborate on consumer-focused produce quality attributes by discussing the connection between perceived quality and produce features. Consumption quality, sometimes referred to as intrinsic quality, includes inherent properties of the product such as appearance, taste, and texture. These are influenced by genotypic, agro-environmental, and postharvest factors. Meanwhile purchase quality, sometimes referred to as extrinsic quality, includes features that are external to the product such as pricing, socioeconomics, and marketing (Schreiner, Korn, Stenger, Holzgreve, & Altmann, 2013). In particular, this chapter will focus on marketing-based features such as organic, local, and waste reduction initiatives.

17.2 Factors impacting overall fruit and vegetable consumption

17.2.1 An evolution in public health recommendations

Diets rich in fruits and vegetables have repeatedly been shown to contribute to reduced risk of cardiovascular diseases and various cancers such as colorectal and renal (Aune et al., 2017; Lee et al., 2009). A metaanalysis of the risk of cardiovascular disease, cancer, and all-cause mortality estimated that inadequate fruit and vegetable consumption may have been attributable to between 5.6 and 7.8 million premature deaths worldwide in 2013 (Aune et al., 2017). Clearly, fruits and vegetables are recognized as an important part of a healthy diet. As a result, many public health agencies around the world have been tasked with initiatives to increase the public's consumption of this food category (Health Canada, 2019; National Health Services UK, 2020; USDA, 2016; World Health Organization, 2013).

The way in which public health agencies communicate the need to increase fruit and vegetable consumption is undergoing a radical shift. Since the 1940s foods have typically been categorized into four to six food groups, and specific amounts were recommended for consumption within each category (Health Canada, 2020; USDA, 2020). Some public health agencies recommended amounts by weight while others by the number of servings, such as the emblematic five-a-day campaign encouraging consumption of at least five portions of fruits or vegetables per day (National Health Services UK, 2020). These consumption recommendations, produced by public health agencies around the world, laid the foundation for what was taught about nutrition to children in schools and to the public by dieticians. In many countries these recommendations also served as a framework for menu development in food service environments such as school cafeterias, hospitals, and nursing homes. Thus such recommendations have broad-reaching impacts particularly for vulnerable populations in institutionalized care and have a pervasive influence on the public consciousness regarding what constitutes a "healthy" diet.

Since 2018, many agencies around the world have been revamping their dietary recommendations with increased focus on lifestyle factors, eating a varied diet and added emphasis on plant-based foods. Many no longer recommend specific amounts for consumption. For example, the Canada Food Guide recommends filling "half your plate" with fruits and vegetables, without specifying portion sizes (Health Canada, 2019). Additionally, despite the name of the report, the food guide contains a number of guidelines that are not directly tied to the contents of a diet, such as eating with others, enjoying your food and cooking more.

The evolution of these guidelines can be linked back to advances in our understanding of the factors that motivate healthy eating. It's been observed that increasing knowledge about the importance of healthy eating and the benefits of a diet high in fruits and vegetables does not, alone, motivate a substantial increase in consumption of fruits and vegetables (Prelip, Kinsler, Thai, le, Erausquin, & Slusser, 2012; Rekhy & McConchie, 2014). Rather, factors that address the underlying psychological, behavioral, and physical barriers to consumption have been found to be more important than intellectual (i.e. knowledge) barriers. The following section will expand on factors that have been linked to changes in fruit and vegetable consumption behavior.

17.2.2 Factors affecting consumption habits

Many studies have examined demographic profiles that are associated with increased or decreased fruit and vegetable consumption and some trends have emerged from these studies. It is often found that higher fruit and vegetable consumption is associated with being female, having higher educational status, higher socioeconomic status, having children in the home, and a larger family (Azagba & Sharaf, 2011; Baker & Wardle, 2003; Dehghan, Akhtar-Danesh, & Merchant, 2011; Kiadaliri, 2013; Rasmussen et al., 2006). However, it's understood that many of these characteristics are not the underlying cause behind consumption trends. Rather these generic criteria group together individuals with similar access, lifestyles, and behaviors that explain the resulting consumption patterns.

17.2.2.1 The link between access and consumption

Access to high-quality fruits and vegetables has been shown to be a contributing factor in consumption. Consumers' food environment can be qualified in four dimensions: geographic food access (proximity, retail density, travel time), food availability (quantity and variety on store shelves), food quality (freshness, bruising), and affordability (price relative to income) (Health Canada, 2013). "Food deserts" and "food swamps" are terms frequently used to describe geographic areas that score low on the four dimensions of the food environment, indicating poor access to healthy foods such as fruits and vegetables. The main distinction between food deserts and swamps is that food deserts are areas with very limited access to retail outlets selling healthy food (e.g., supermarkets), whereas food swamps have retail outlets selling healthy food; however, the areas are dominated by retail outlets selling unhealthy food options (e.g., corner stores, fast food outlets) (Cooksey-Stowers, Schwartz, & Brownell, 2017; Hager et al., 2017). Despite the access to healthy food options in food swamps, the high proportion of unhealthy food outlets to healthy food outlets has been shown to be associated with higher consumption of unhealthy food among individuals living in those areas (Cooksey-Stowers et al., 2017; Hager et al., 2017). Communities in food deserts and food swamps have been shown to be characterized by low-income residents (Beaulac, Kristjansson, & Cummins, 2009; Hager et al., 2017; Sushil, Vandevijvere, Exeter, & Swinburn, 2017) and living in areas with low access to healthy foods may be associated with lower consumption of fruits and vegetables and higher reliance on less nutritious offerings (Caspi, Sorensen, Subramanian, & Kawachi, 2012).

In some cases, food deserts or food swamps may also occur in high income communities, such as in metropolitan centers. Interestingly, in these cases where income levels are higher, fruit and vegetable consumption is not reduced. Research suggests that despite living in a poor food environment, higher income individuals' access to fruit and vegetables is less impacted due to their higher likelihood to own a car, enabling more convenient longer distance trips and the ability to transport heavy loads of groceries with greater ease (Aggarwal et al., 2014; Zhang, 2016). Conversely, lower income residents living in poor food environments are more often limited to public transit, bicycling, or walking, making it difficult to carry heavy loads of fruits and vegetables, particularly if they are found at longer distances from the home (Zhang, 2016). Lack of access to a vehicle can especially be a hurdle to accessing healthy food for individuals who work evening or night shifts. It has been found that access to healthy food within a given area varies with time of day due to nighttime closures of many grocery stores and access is further limited for individuals who rely on public transit where transit schedules in the night and early morning hours are restrictive (Widener et al., 2017).

Considering these findings, postharvest fruit and vegetable handling has an important role to play in increasing access to fruits and vegetables among populations that currently have poor food environments. Extending the shelf-life of fruits and vegetables may make them more profitable to stock in retail stores operating in food deserts due to being more attractive to customers and reducing waste at the store level. Furthermore, offering fruits and vegetables in convenient, low−weight, and durable formats (e.g., small and lightweight packaging formats) can make it easier for those without easy modes of transport to bring fruits and vegetables home in good condition.

17.2.2.2 The link between psychological factors and consumption

Although access to fruits and vegetables is an important first step toward increasing consumption, access alone is often insufficient to induce behavior change. Research has found mixed results when examining the association between the food environment and fruit and vegetable consumption. Some studies showed that increased access to grocery stores was associated with increased fruit and vegetable consumption (Menezes, Costa, Oliveira, & Lopes, 2017) while others found that there was no association when the study controlled for the ratio, rather than count, of healthy and unhealthy food outlets (Gustafson et al., 2013; Minaker et al., 2013). Therefore other factors clearly play an important role in mediating whether or not consumers act on their ability to access fruits and vegetables.

A study by Zhang (2016) examined the characteristics of successful and unsuccessful public health intervention programs aiming to increase fruit and vegetable consumption. Intervention programs included a wide range of approaches such as coupons, fresh fruit and vegetable basket delivery, motivational interviews, consumption diaries, food skill building, personalized reminders, nutrition education, and others, including combinations of these. The analysis determined that programs that focused on psychological factors by applying principles of behavioral theories through motivational interviews, counseling, and self-trackers to stimulate and maintain increases in fruit and vegetable consumption had the highest success, resulting in the highest increases in the number of servings of fruits and vegetables consumed daily. Other interventions that focused mainly on education, food skill building, or increasing access without a behavioral change component had lower success levels.

While motivational interviews and other approaches used in public health studies are difficult, if not impossible, to implement on a population scale, some changes can be made to induce behavioral change. Broers, de Breucker, van den Broucke, and Luminet (2017) conducted a metaanalysis of "nudge" research that aimed to increase fruit and vegetable consumption. According to the authors, nudging is defined as "any aspect of the choice architecture that alters peoples' behavior in a predictable way without forbidding any options or significantly changing their economic incentives." Simple examples include placing fruits and vegetables on shelving at closer proximity to consumers than unhealthy options in a cafeteria or market-style restaurant setting or serving salads at a hot dishes table rather than only at a salad bar (Lassen, Thorsen, Trolle, Elsig, & Ovesen, 2004). It has been found that altering placement has a medium significant effect (effect size $d = 0.39$) on choice, sales, or servings of fruits and vegetables purchased. Considering that in both scenarios, fruits and vegetables were available to shoppers, this indicates that behavioral interventions such as prominent placement can be combined with fruit and vegetable availability to increase consumption (Broers et al., 2017).

In another study by Wansink, Just, Hanks, and Smith (2013), it was observed that when apples were made available presliced rather than whole in school cafeterias, the percentage of students that purchased and proceeded to eat more than half an apple increased by 73%. A survey of a sample of the students indicated that they were more likely to purchase and consume presliced apples because they were more convenient and tidier to eat. Therefore preconceived notions that apple sales in the school cafeteria were low because of cost and food preference were incorrect and instead it was shown that behavioral reasons were in fact underlying causes of this trend. These observations have important implications for the role of postharvest fruit and vegetable treatments and packaging in influencing consumption as these technologies can be applied to maintain a high-quality appearance, eye-catching packaging designs, and convenient, mess-reducing formats to increase consumption.

Research focused on developing healthy eating behavior in children indicates that teaching children about the pleasure of eating is an important element in developing healthy future dietary habits. Children as young as 1-year old learn to eat foods from their own culture by observing and imitating family and peers during eating occasions (Birch, Savage, & Ventura, 2007). In a comparison of different strategies to encourage children to eat new vegetables, among the most effective approaches is modeling eating the vegetable and its enjoyment by a sibling or peer (Birch, 1980; Cullen et al., 2001; Holley, Farrow, & Haycraft, 2017). Children learn to associate healthy foods with pleasure through experiences of consuming these foods in positive, social environments. Parents or caregivers talking about the favorable taste of healthy foods have been shown to impact children's enjoyment of healthy meals (Haines et al., 2019). Interestingly, telling children the food is healthy has been shown to be counter-productive as they associate the term "healthy" with unpleasant taste (Wardle & Huon, 2000). Therefore emphasis should be placed on hedonics rather than on practical benefits. Presenting fruits in a more visually attractive display can also influence consumption. When 4—7-year-old children were offered a mix of grapes, strawberries and apples pierced with cocktail sticks and stuck onto a watermelon, consumption of fruit was significantly higher compared with when the same mix of fruits were simply presented on a white plate (Jansen, Mulkens, & Jansen, 2010). Similar effects have been observed in adults where enjoyment is associated with increased consumption of fruits and vegetables (Duthie et al., 2018; Mc Morrow, Ludbrook, Macdiarmid, & Olajide, 2016; Pollard, Kirk, & Cade, 2002).

Considering the mounting evidence that enjoyment of healthy foods is a key component of healthy diets that include increased consumption of fruits and vegetables, it's no mystery that public health organizations have changed the approach in their recommendations. Many agencies now extend recommendations to include eating in social environments, enjoying meals and giving examples of healthy foods that reflect current food trends and changing cultural norms such as the inclusion of more plant-based alternatives and foods from diverse cultures. Despite the evidence that a key component to developing healthy eating habits centers around food enjoyment and social aspects, such as regular family meals, these goals may be difficult to achieve for disadvantaged groups. Families with lower socioeconomic status may experience economic and physical barriers to accessing fruits and vegetables as well logistical constraints due work hours (e.g., shift work) (Bowen, Brenton, & Elliott, 2019). Food quality has a large impact on food enjoyment; therefore postharvest technology is an important element in ensuring that people can access fruits and vegetables that will be a pleasure to consume and convenient to access, thereby ultimately impacting produce consumption levels.

17.3 Factors impacting fruit and vegetable choice

While factors such as access, knowledge, and, particularly motivation, influence total fruit and vegetable consumption, a different set of factors determines which fruits and vegetables are selected by consumers. Thus the ensuing section will shift attention to these factors and discuss both consumption quality and purchase quality attributes that drive consumer preferences among fruits and vegetables and determine product choice.

17.3.1 Consumption quality

Sensory properties of a fruit or vegetable are at the core of consumer perceived produce quality. While purchase qualities can enhance the perception of sensory quality, if sensory properties fail to meet consumer expectations, no amount of purchase quality will be able to adequately compensate for those shortcomings. A consumer's first impression of fruits or vegetables is based on appearance, pricing, and marketing elements; however, repeat purchasing and consumption is driven by flavor and texture (Beaulieu, 2006; Waldron, Parker, & Smith, 2003). Flavor and texture are often cited as a top reason for purchasing specific types of produce (Barrett, Beaulieu, & Shewfelt, 2010). For this reason, it's also a key deciding factor in selecting cultivars for commercialization and frequently dictates how new introductions are marketed. Before examining the taste and texture factors related to quality, this section will begin by examining the link between product appearance and consumer quality perception. As the culinary adage goes, "You eat with your eyes first," and it is known that product appearance can influence perception of taste.

17.3.1.1 Appearance

Visual appearance is a consumers' first impression of a product's quality. A quick glance at an array of produce in the grocery store sets off a cascade of associations between the products' appearances and how they will relate to other sensory characteristics such as aroma, taste, and texture. When shown images of different colored apples, consumers have immediate reactions based on the color of the skin; a green apple is thought of as tart, a red apple is considered sweet, and a yellow apple elicits impressions of soft texture. These initial visual cues also form impressions of price, freshness, and quality. As such it is not surprising that visual appearance has been used as a key criterion for postharvest fruit and vegetable quality evaluation (Kyriacou & Rouphael, 2018). In addition to color, the visual appearance also refers to the size, shape, sheen, consistency, and absence of blemishes, wilt, or rot (Barrett et al., 2010).

Although flavor and texture dominate preference in most products, color has been found to be a key driver of liking in certain produce. With the recent increase in consumption of sweet potato fries in Canada, a sensory and consumer acceptance study set out to identify the best sweet potato varieties for fries from a sweet potato breeding trial (Bowen, Flemming, Turecek, & Blake, 2015). Sensory profiles were completed by a trained sensory panel followed by consumer acceptance testing with 209 consumers. Although the fries were found to differentiate for texture properties such as crispness, firmness, and chewiness, these attributes were not associated with consumer liking. Instead it was found that irrespective of texture, consumers most liked fries that were bright orange in color with little darkening and least liked light orange fries. Therefore it was concluded that in the case of sweet potato fries, the color had to be "right" above all and only when the color was right would consumers be likely to consider other parameters such as texture. Thus despite the great importance of flavor and texture, appearance must also be considered in studies of consumer acceptance of produce.

Color is derived from the natural pigments in fruits and vegetables and it sets consumer expectations as it is linked to taste, maturity, and nutritional content. Green and brightly colored fruits and vegetables are associated with health and higher nutrition due to higher concentrations of antioxidants and other health promoting nutraceuticals (Isabelle et al., 2010; Katz, 2004). Color is also an indicator of ripeness and maturity that consumers can related to the flavor experience. As a banana turns from green to yellow it becomes sweeter, softer, and less astringent (Barrett et al., 2010). A similar progression occurs in tomatoes as they change from green to red either on the vine or postharvest. This lends to why vibrant colors signal freshness and ripeness for many fruits and vegetables.

Freshness is a multidimensional property and it is often listed as the most important attribute associated with minimally processed foods (Ragaert, Verbeke, Devlieghere, & Debevere, 2004). Consumers' concept of freshness can arise from a variety of influences. For example, consumers with experience working in fruit and vegetable production, such as those who grew up on a farm, are more likely to relate freshness to nonsensory characteristics such as location, time, or handling compared to more urban consumers who relate freshness to sensory properties such as appearance and flavor (Péneau, Linke, Escher, & Nuessli, 2009). The concept of freshness is subjective, connected to the consumers' environment and experiences. The true definition of "fresh" by consumers is not fully understood and may be product-specific. In carrots and strawberries, glossiness and absence of bruising were the best predictors of freshness perception (Péneau, Brockhoff, Escher, & Nuessli, 2007). Similarly, in a Swiss study of 559 participants, appearance was the most frequently listed sensory cue used by consumers when describing what makes a food fresh, with fruits and vegetables being the top food products described by the term "freshness" (Péneau, Hoehn, Roth, Escher, & Nuessli, 2006). Luminance distribution has shown to be used by consumers to differentiate product freshness when shown images of cabbage leaves (Arce-Lopera, Masuda, Kimura, Wada, & Okajima, 2013).

Ripeness of fruits is first assessed by color as evaluated through the progression from underripe (green), ripe (e.g., red or yellow), to overripe (discoloring or decay), and forms the first impression which sets expectations for taste, aroma, and texture (Wei, Ou, Luo, & Hutchings, 2012). Bananas are picked green and found on grocery store shelves in various stages of ripeness and purchasing is based on this appearance. Banana ripeness can be classified into seven stages from (1) totally green, (3) more green than yellow, (5) yellow with green edges to (7) yellow with brown spots (von Loesecke, 1950). Consumers given bananas at ripening stage 7 had lower overall expected liking and purchase intent than when presented with bananas at ripening stage 5, even though overall liking of the unpeeled bananas at both stages was not significantly different (Symmank, Zahn, & Rohm, 2018). These findings highlight the importance of color and visual cues in sensory expectation, since bananas at ripening stage 7 were expected to be too high in banana flavor and sweetness and too low in firmness.

Another aspect of ripeness to consider is the difference in ripening between climacteric and nonclimacteric fruit and the impact on consumer acceptance of quality. Many consumers are unaware of these differences in ripening and as a result do not know how to properly store their produce which results in reduced acceptability and repeat purchasing as well as increased waste. Based on the appearance, consumers will make an assessment of ripeness and then store fruit accordingly, even though many of these fruits, such as berries, do not ripen further after harvest. Increased consumer education may be needed to promote proper postharvest storage in the home.

Changes in the color of a new variety can impact consumer expectation and liking but not always in the same way because consumers may react differently to products based on familiarity, expectation, and food neophobia. When introducing a new yellow-fleshed kiwifruit variety in New Zealand, researchers found two distinct segments of consumers. One segment of consumers (46%) disliked and rejected the new and different yellow-fleshed variety while the second segment of consumers (54%) liked the yellow and green-fleshed varieties equally (Jaeger, Rossiter, Wismer, & Harker, 2003). Food neophobia is a term used to describe an individuals' aversion to trying new foods. Approximately 40%–50% of the US population has been identified as being food neophobic (Meiselman, King, & Gillette, 2010). Thus it is not uncommon to uncover segments of consumers who are excited by the proposition of a new, different-looking variety while also identifying another segment of the overall population that experiences feelings of disgust when presented with an unfamiliar color of a familiar product (Paakki, Sandell, & Hopia, 2016; Tesini et al., 2015; Zellner, Lankford, Ambrose, & Locher, 2010). The diversity of consumer preferences should be acknowledged to set realistic sales targets and develop successful business strategies for introducing new cultivars.

Regions around the world exhibit different norms in produce expectations according to their food culture. For example, different varieties of a product may have different levels of familiarity across geographic areas. The flesh color of sweet potatoes has been shown to impact consumer acceptability and familiarity. In North America, orange-fleshed sweet potatoes are most familiar and liked by consumers (Bowen et al., 2015; Leksrisompong, Whitson, Truong, & Drake, 2012) while in Africa the same is true for white-fleshed sweet potatoes (Laurie et al., 2013). Efforts to introduce orange-fleshed sweet potatoes in Africa because of their increased nutritional benefits (i.e., β-carotene, a precursor to vitamin A) have only been successful when flavor aligned with African consumers' sensory expectations (Sugri, Nutsugah, Wiredu, Johnson, & Aduguba, 2012). Even within the same color category, changes in color shades can impact liking. Another study on sweet potatoes using Canadian consumers found that color was correlated to consumer acceptance with consumers preferring products with uniform color and light orange hues and small changes in visual cues significantly impacted liking (Bowen, Blake, & Tureček, 2019a).

Research has found that when consumers are presented with brightly colored solutions, they expect them to taste fruity (Zampini, Sanabria, Phillips, & Spence, 2007). Thus color is intimately linked to fruits and vegetables in the public mind. An attractive, vibrant appearance is an important first step that can trigger a consumer's desire to purchase the product and consume it. However, flavor and texture must subsequently meet the expectations set by appearance to earn consumer acceptance and repeat purchasing.

17.3.1.2 Flavor

Flavor, the combination of taste and olfaction, is often considered the main factor for consumer acceptance. Consumers can forgive the appearance of some fruits and vegetables, such as Bosc pears, as long as they taste great. Flavor is therefore important for repeat purchasing and in creating the habit of buying a particular fruit or vegetable because its flavor profile is preferred. Within sensory science, it is more common to refer to the distinct modalities of taste and olfaction rather than flavor. There are six basic tastes: sweet, acid, bitter, salty, umami, and oleogustus (fat). These basic tastes are perceived by receptors on your tongue, whereas there are thousands of volatiles that lead to olfaction (both retronasal and orthonasal) that are perceived by receptors on the olfactory mucosa and processed in the brain. Ultimately to a consumer, these distinctions do not exist (or matter) as they talk about taste and olfaction interchangeably. Thus for the sake of simplicity, the term flavor will be used in the context of this chapter.

Improved flavor and differentiated flavor are the cornerstones to many new cultivar introductions. In the past, new cultivar selection by breeders was based predominately on appearance, firmness, and yield because these were easy to select for and to evaluate postharvest (Kader, 2008; Klee, 2010). Fortunately, consumer pull for more flavorful fruits and vegetables has shifted tides and now breeding programs around the world are trying to gain a competitive advantage through introduction of flavorful cultivars such as apples (Bowen, Blake, Tureček, & Amyotte, 2019b; Hampson et al., 2000), tomatoes (Tieman et al., 2012), kiwifruit (Jaeger et al., 2003; Wismer et al., 2005), and may others (Folta & Klee, 2016). With this shift comes the expectation that with the improved new cultivars consumers will be willing to pay more for these value-added traits.

What is it that drives consumers' acceptance of fruits and vegetables? In tender fruit varieties such as peaches, nectarines, and plums, consumer acceptance of cultivars was found to increase with increasing concentration of soluble solids until saturation of sweetness perception was reached. Once this upper threshold of sweetness perception was reached, further increases in soluble solids did not correlate with increased liking in ripe fruit (Crisosto, Crisosto, & Garner, 2005). Interestingly in the same study, in the plum variety "Blackamber" consumer liking was linked with acidity concentration once the plum reached the acceptable level of sweetness, demonstrating the importance of the interaction between sweetness and acidity on consumer liking. The role of sweetness is also key to understanding consumer acceptance in tomatoes, particularly how it interacts with volatiles present in tomatoes to increase sweetness perception, thereby improving flavor for consumers (Tieman et al., 2012). Using transgenic tomatoes with specific apocarotenoid volatile compounds knocked out, researchers were able to show that consumer liking was driven by a combination of sweetness and flavor, whereby apocarotenoid deficient tomatoes with the same sugar concentration were significantly less liked by consumers.

The apple market has become very competitive with new cultivars being introduced annually and increasing pull from the consumer for more flavorful apples (Yue & Tong, 2011). Much research has focused on identifying what constitutes preferred flavor in apples. It has been found that consumer acceptance is correlated with sweetness, acidity, fresh apple aromas, juiciness, and crunchiness (Amyotte, Bowen, Banks, Rajcan, & Somers, 2017; Bonany et al., 2013; Cliff, Stanich, Lu, & Hampson, 2016; Endrizzi et al., 2015). A recent study looking at consumer preference within a diverse set of over 70 apple varieties found that while all consumers wanted their apples to be crisp and juicy, what segmented consumers into liking clusters was their preference for different flavor profiles; sweet apples with fresh red apple aromas (89%) versus those consumers (11%) that like apples with more acidity and fresh green aromas. Soft or mealy apples and oxidized apple aromas were found to be detractors of liking for all consumer segments (Amyotte et al., 2017).

Sweetness and acidity are present in most fruits and vegetables and can be measured instrumentally and often correlated with sensory panels. Their relationship to consumer acceptance is well established in the literature. Salt and fat (oleogustus) are not naturally occurring in most fruits and vegetables; however, bitter and umami perceptions are both present and impact consumer acceptance. Umami is found mainly in vegetables such as mushrooms, carrots, potatoes, and Chinese cabbage and fruits such as tomatoes but concentrations are low when compared to other food groups such as meats and dairy (Zhang, Venkitasamy, Pan, & Wang, 2013). Umami boosts the flavor perception in savory foods but not in sweet or fruity foods and is more prominent in cooked than in raw vegetables (Yamaguchi, 1998). Foods higher in umami are associated with increased consumer liking (Poelman, Delahunty, & de Graaf, 2017) even though it is a taste that is not as easily identifiable to all consumers (Cecchini et al., 2019). Bitterness by contrast is generally found to be a detractor from liking and the main reason for dislike of vegetables and low vegetable consumption (Poelman et al., 2017).

Breeding programs and the food industry have gone to great lengths to reduce bitter compounds such as glucosinolates, terpenes, phenols, and flavonoids in foods (Drewnowski & Gomez-Carneros, 2000). Glucosinolates, sinigrin, and progoitrin are responsible for the bitter taste in Brussels sprouts with consumer acceptance decreasing in cultivars with higher levels of these compounds (Fenwick, Curl, Griffiths, Heaney, & Price, 1990). Similarly, a study looking at the cultivar differences among Chinese broccoli and cauliflowers found sweetness, juiciness, and overall broccoli/cauliflower flavor to be attributes that described the most liked cultivars. By contrast cultivars described as intensely bitter, pungent, and with green grassy notes had significantly lower consumer liking scores (Brueckner, Schonhof, Kornelson, & Schrodter, 2005).

Understanding the impact of flavor on consumer liking of fruits and vegetables is essential to ensure high-quality produce is available and consumer satisfaction is achieved. Since many consumers do not differentiate between flavor (taste and olfaction) and texture, understanding the impact of texture to consumer eating quality is necessary to fully understand the role that sensory characteristics play in postharvest quality.

17.3.1.3 Texture

When asked, consumers generally cite flavor as the most important quality attribute for produce and they often don't immediately notice texture in many foods. However, it has been observed that when the texture does not meet expectations, the food will be rejected regardless of the quality of the flavor (Harker, Gunson, & Jaeger, 2003). Therefore texture quality is critical for a fruit or vegetable to be deemed acceptable.

Fruit and vegetable texture arises from the strength and rigidity of the cell wall, the extent of bonding between cells in the middle lamella as well as the osmotic pressure exerted from inside the protoplast cells against the cell wall (i.e. turgor) (Toivonen & Brummell, 2008). In the early stages of maturation, fruit texture remains constant and as the fruit matures and transitions to the ripening phase the texture begins to soften. Senescence accelerates as soon as produce are harvested and softening is further accelerated in fresh-cut products where the cutting process causes wounding and damage to tissues (Toivonen & Brummell, 2008).

According to Bourne (1979), fruits can be categorized into two groups based on their softening behavior:

1. Fruits that exhibit soft, melting texture, and soften greatly during ripening (e.g., most berries, most stone fruit, kiwi, European pears). The firmness of these fruits decreases by 78%−97% during ripening.
2. Fruits that tend to have crisp texture, and soften moderately during ripening (e.g., apples, Asian pears, bell pepper, and watermelon). The firmness of these fruits decreases by only approximately 20% during ripening.

TABLE 17.1 Definitions of texture attributes commonly encountered in fruits and vegetables.

Attribute	Definition
Crisp	Breaks apart in a single step due to formation of a free-running crack. Associated with a higher-pitched sound
Firm/Hard	Force required for teeth to compress and/or shear through fruit or vegetable flesh
Juicy	Amount of liquid released on first bite or when chewing
Mealy	Soft, dry, and granular flesh
Skin toughness	Amount of force required to bite through the skin

Vegetables tend to have a higher proportion of cells with thickened and lignified cell walls and as a result tend to be much firmer and have tougher tissues in their raw state compared to fruit (Toivonen & Brummell, 2008).

A number of texture attributes are commonly encountered across a diversity of fruits and vegetables including crispness, firmness/hardness, juiciness, mealiness, and skin toughness. Table 17.1 lists definitions of these common attributes.

Although segmentation is quite common in terms of the types of flavors consumers prefer in produce, nearly all consumers seem to agree that juicy, nonmealy, and low skin thickness are important drivers of liking in most fruits and vegetables including apples, peaches, tomatoes, kiwis, pears, melons, and carrots among others (Bowen et al., 2019b; Bugaud, Maraval, Daribo, Leclerc, & Salmon, 2016; Cliff et al., 2016; Crisosto, 2002; Escribano, Sánchez, & Lázaro, 2010; Hampson et al., 2000; Harker et al., 2003; Jaeger et al., 2006, 2003; Kiraci & Padem, 2016; Sinesio et al., 2010). Additionally, crispness has also been found to be an important positive attribute in produce that soften moderately during ripening such as apples, carrots, lettuce, and cucumbers (Cliff et al., 2016; Hampson et al., 2000; Kiraci & Padem, 2016; Munoz & Vance Civille, 1987).

While the previously cited attributes positively contribute to consumer liking with increasing intensity (i.e., the juicier the better, the less mealy the better), firmness tends to have an optimal range where produce must exhibit a certain amount of firmness without being too firm (Bugaud et al., 2016; Ding et al., 2020; Jaeger et al., 2003; Jaeger, Lund, Lau, & Harker, 2006). The degree of firmness that is preferred also tends to vary by consumer segment. For example, it has been found that tomato liking for some consumer segments is positively associated with firmness, whereas it is negatively associated with firmness for others (Sinesio et al., 2010). Similarly, the degree of firmness preferred in kiwifruit also varied among assessors (Stec, Hodgson, Macrae, & Triggs, 1989). Since fruits and vegetables tend to soften as they ripen, the variability in preferred firmness among consumers may partly explain why consumers vary in the level of ripeness they deem optimal for consumption in products such as bananas (Symmank et al., 2018). There is evidence also that as consumers age and acquire dental deficiencies preference shifts toward softer product (Roininen, Fillion, Kilcast, & Lahteenmaki, 2003).

One attribute that merits additional discussion is mealiness. As mentioned above, it has been repeatedly shown that mealiness is a key detractor of liking for consumers across various types of produce. The perception of mealiness relies on the interaction between fruit cell walls and the middle lamella, which is found between fruit cells and acts as a "glue" holding the cells together. In fresh fruits, the middle lamella is typically stronger than the cell walls thus when pressure is applied (e.g. biting), the fruit fractures through the cell, releasing juices from inside the cells (Allan-Wojtas, Sanford, McRae, & Carbyn, 2003; Harker & Hallett, 1992). As fruits undergo senescence, the pectin in the middle lamella breaks down and weakens the middle lamella. When the middle lamella becomes weaker than the cell walls, when a force is applied, the fruit fractures through the middle lamella, thus leaving cells intact and not allowing juices to be released (Allan-Wojtas et al., 2003; Harker & Hallett, 1992). The combination of reduced force required to fracture the fruit structure, the lack of juice release from inside the cells, and the large gritty clumps of intact cells, together produce the perception of fruit mealiness.

Despite its importance, this attribute has historically been difficult to monitor instrumentally as techniques such as the penetrometer and acoustic resonance have produced inconsistent or poor correlations with this sensory property (Barreiro et al., 1998; Ioannides et al., 2007; Mehinagic et al., 2003; Zdunek, Cybulska, Konopacka, & Rutkowski, 2011). As is evident from the definition provided in Table 17.1, mealiness is a multicomponent attribute that overlaps with other texture properties such as juiciness and hardness/firmness which are often evaluated in addition to mealiness. Thus mealiness ratings from sensory panels frequently correlate with ratings for juiciness or hardness/firmness as these are components of the definition of this attribute (Ioannides et al., 2007; Kim et al., 2020).

When attempts have been made to correlate mealiness to instrumental measures, generally the instrumental measures are unidimensional and capture only one aspect of mealiness. For example, the penetrometer only captures firmness. Therefore if the product set evaluated happens to exhibit firmness that varies in parallel to juiciness and graininess (sometimes referred to as grittiness or granularity), the penetrometer will produce a strong correlation with mealiness. If, however, the product set happens to include products in which samples with equivalent firmness exhibit a range of juiciness or graininess, penetrometer measurements will fail to correlate with mealiness. Recently, friction measurements were shown to correlate strongly with apple mealiness (Kim et al., 2020). This technique shows promise for monitoring mealiness as friction is produced by the combination of hardness, lubrication, and surface roughness, all of which are also factors in the perception of mealiness. Further work is needed to determine if the technique will be similarly successful in other crops.

Various postharvest factors can impact texture quality by impacting the rate of senescence, accelerating moisture loss, enhancing defects or causing chilling injury (Gast, 2001; Hadad, 2016). Chilling injury, which occurs when produce is stored below its optimal temperature, causes tissue damage and can lead to softening and increased mealiness (Giné-Bordonaba, Cantín, Echeverría, Ubach, & Larrigaudière, 2016; Verlinden, de Smedt, & Nicolaï, 2004). On the opposite end of the spectrum, temperatures that are too high can accelerate senescence and moisture loss, particularly when the relative humidity is insufficient (Gast, 2001). Temperature fluctuations are another factor that can lead to texture deterioration. It has been found that texture deteriorates more quickly in peaches that undergo temperature fluctuations during storage compared with those that are held at a constant temperature (Pan et al., 2019). Therefore postharvest storage and handling has a major role to play in the maintenance of acceptable texture in fruits and vegetables and new postharvest technologies should be evaluated for their impact on texture throughout supply chains.

17.3.1.4 Challenges with achieving consumption quality targets

Fruit and vegetable sensory properties are arguably the most influential attributes determining preference and purchase intents. However, these sensory targets must be balanced against the practical challenges of providing only the most flavorful fruit and vegetable cultivars for the consumer market.

Through much of the 20th century, fruit and vegetable breeding programs aimed to produce products that were easier to grow and distribute and hence more profitable in a commodity market: higher yields, greater pest and disease resistance, longer postharvest shelf-life, and resistance to bruising during transport. Because flavor and texture were not prioritized, cultivars were not intentionally enriched with these traits during breeding and the traits fell by the way-side in many modern cultivars (Folta & Klee, 2016). If products did not have high-quality sensory properties to start, postharvest handling techniques could only preserve the mediocre existing sensory properties of those cultivars. However, in recent decades as the produce market became more competitive and most modern cultivars already had a "base" of superior agronomic attributes bred into them, the priorities began to shift. An increasing number of breeding programs are now making conscious efforts to include flavor and texture properties as high priority breeding targets as they have been recognized as a key value-proposition in new cultivars (Folta & Klee, 2016). This has also driven the shift toward branded produce in an increasing number of categories. Up until the 1980s, a typical North American grocery store had a very limited selection of apple cultivars and included primarily apples such as Red Delicious, Golden Delicious, and McIntosh (Seabrook, 2011; Yager, 2014). Today even discount grocery chains boast at least one row of different apple cultivars, with higher end grocery outlets selling up to 10–15 cultivars at any given time. Apples and tomatoes are currently the most diversified categories with products being frequently sold under cultivar and/or brand names. However, this trend is expanding into other categories such as pears and kiwis and will likely continue to expand in the future.

The trend toward selling produce with the variety name specified or branded produce is beneficial to both the sector and to consumers. For the sector, branded varieties that are made available to a limited number of growers (sometimes called "club varieties" in the apple market) prevent flooding the market with an oversupply of product that would drive down pricing. Thus controlling the supply can help maintain profitable pricing and make this low-margin sector more economically sustainable. For consumers, the ability to buy branded products or those that are sold by variety name means they can choose the product that best matches their sensory preferences and therefore provides more consistent, pleasing quality.

Although consumers are typically unaware of this, different cultivars of fruits and vegetables are frequently sold under the same banner throughout the season. For example, many different cultivars of peaches will be sold simply as "peaches" throughout the peach season even though they are a mixture of early, mid, and late season cultivars. At the same time, cultivars exhibiting similar characteristics as a popular consumer-facing variety such as Redhaven may be sold under that name even if genotypically they are different. Thus consumers, typically unaware of this change-over in cultivars throughout the season, may be frustrated at the lack of consistency in sensory quality from week to week.

Failure to meet consumer expectations of quality may be devastating to an entire industry as well as to a particular cultivar. The impacts of a poor eating experience can be significant. In an Australian study on apples, it was found that following a bad eating experience 58% of consumers indicated they would change cultivars, 31% would purchase fewer fruit, 24% would switch to other types of fruit, 17% would stop buying apples for a while, 10% would change to higher priced apples, 5% would switch brands, and <1% would change to lower priced apples (Batt & Sadler, 1998). Therefore the shift toward named fruits and vegetables can make significant contributions toward ensuring the products that are purchased by consumers will consistently meet their expectations and create repeat customers.

Breeding is an important element in creating fruits and vegetables with desirable starting sensory properties. However, in some crops, the superior sensory properties come at a cost. The production of volatile flavor compounds in melons is dictated by ethylene-dependent pathways. This association between volatile production and ethylene also means that melons with higher volatile production are associated with the phenotype of shorter shelf-life (Pech, Bouzayen, & Latché, 2008). In other cases, crops with improved flavor or texture may also have lower yield. Lower yield may be a feature of the cultivar or it may also be influenced by cultural practices such as more aggressive pruning to provide increased sun exposure and reduced vegetative growth which makes more sugars available to developing fruit (Wilson, 2000). Adoption of cultural practices by producers that will improve flavor quality but slightly reduce yield may be compensated for by the willingness of buyers to pay a higher price for the products, accounting for the loss in yield (Kader, 2008). However, to reap these benefits, these improved practices must be made evident to consumers via quality associations with specific brands.

While breeding and growing practices dictate the starting sensory qualities, appropriate postharvest handling is essential for enabling the product to maintain its qualities until it reaches the consumer. This is where postharvest technological developments have enabled consumers to expect a year-round supply of fruits, such as apples, through storage in controlled atmosphere (CA) environments (Kupferman, 2003) and treatment with 1-methylcyclopropene (1-MCP) to delay ripening (Watkins, Nock, & Whitaker, 2000). However, both CA and 1-MCP have been shown to impair the development of flavor in fruit with negative impacts on consumer acceptance (Fan & Mattheis, 1999). Thus the desire for highly flavorful fruits and vegetables must be balanced against the desire to be able to make these products available at all. A threshold must be set to determine at which level of quality decline the increase in storability becomes not worth the trade-off.

This brings us to the final point of discussion with regards to challenges of providing produce with high consumption quality: Once a quality target is established based on consumer preferences, how does one detect when that target has been achieved through breeding or cultural practices and subsequently, how can the quality be monitored through supply chains? First, it should be underscored that what is defined as "good" quality will be dependent on the segment of the population that is being targeted as different segments vary in their sensory preferences. Once this target is established, product profiling by a trained sensory panel is considered the gold standard for determining when consumption quality attributes have met the target. Although analytical instruments, such as the penetrometer, are frequently used to guide breeding and postharvest decisions, they should be used with caution. As discussed in the texture section, penetrometers are a unidimensional measure of fruit firmness, which is but one aspect of produce texture and does not capture other important elements such as mealiness, juiciness, or flavor.

Furthermore, analytical instruments measure products under highly controlled conditions and often measure only one dimension at a time. In contrast, oral processing is a multidimensional experience with interactions between taste and texture attributes dictating the final perception. Instrumental volatile analysis is typically completed on cubed pieces of sample from which headspace volatiles are extracted at a constant temperature (Aprea et al., 2011). In contrast, during oral processing foods are broken down at an uneven pace until they are macerated into a bolus and throughout this process experience a change in temperature as they equilibrate to body temperature. The dynamic breakdown and temperature change in the mouth will impact flavor release and volatilization (Harker & Johnston, 2008) which is difficult to accurately reproduce instrumentally.

Furthermore, interactions between volatiles, tastants, and texture will impact perceived flavor. In sensory science, flavor is understood to be the combined effect of taste (e.g., sweet, sour) and aroma volatiles (Banerjee, Tudu, Bandyopadhyay, & Bhattacharyya, 2016). As a result, it is often found that Brix (soluble solids measurement) alone does not correlate with perceived sweetness in the mouth as volatiles can enhance or detract from the perception of sweetness (Aprea et al., 2017). Volatiles have also been shown to impact texture perception. For example, delivering creamy odors retronasally to study participants via tubes in the nose, increased the perception of thickness and creamy texture of milk-like foods compared to when the same samples were consumed without additional retronasal aroma delivery (Bult, de Wijk, & Hummel, 2007). Therefore it's conceivable that certain aroma compounds in fruits and vegetables may also enhance or suppress the perception of produce texture attributes such as crispness or mealiness, an effect which would not be taken into account in instrumental analyses.

Similar to flavor, instrumental measures of structural properties of produce also often encounter challenges preventing accurate prediction of in-mouth texture perception. In the mouth, foods are sheared at constantly changing speeds and as a solid food is processed into a flowing mass, it experiences extensional and turbulent flow in the oral cavity (van Vliet, 2002; van Vliet, van Aken, de Jongh, & Hamer, 2009). Conversely, analytical instruments used to measure structural and mechanical properties of fruits and vegetables frequently operate at constant speeds (or constant rates of acceleration/deceleration) and take measurements on the food in a single state (i.e., solid or first fracture) which may induce differences in mechanical behavior of the product compared to in-mouth.

Furthermore, analytical measures are most often completed in the absence of saliva. Salivary components interact with food in the mouth and can increase lubrication or change their properties. For example, interaction between salivary mucins and food components (i.e., tannins or proteins) can lead to particle sedimentation on the tongue and generate a sensation of roughness, such as with astringency (Chen, 2009). Furthermore, salivary enzymes may also act on foods to change their consistency. For example, in starch containing foods, such as many fruits and vegetables, salivary α-amylases quickly break down starch and can lead to a decrease in viscosity within seconds (Evans, Haisman, Elson, Pasternak, & McConnaughey, 1986). While saliva or substances mimicking saliva are sometimes added during instrumental analysis (Bongaerts, Rossetti, & Stokes, 2007; Laguna & Sarkar, 2017), this is typically only done in research settings and is still an infrequent practice due to the associated logistical challenges.

Although trained sensory panels are the gold standard for monitoring sensory properties of foods, they can be expensive due to labor costs, time-intensive, and require specialized skillsets to operate and produce and analyze robust data. For this reason, a great deal of research has been completed to identify instrumental measures that correlate with specific sensory attributes in a wide range of fruits and vegetables. These measures are typically unidimensional and must be validated with sensory panels for each new cultivar and sometimes also for different growing locations. Ultimately, they can provide a good approximation of sensory quality for specific attributes and can be used for quality control in an efficient manner. However, it is highly improbable that an instrument will be developed any time in the foreseeable future that will be able to accurately mimic the complex in-mouth sensory experience of a human being. For this reason, major decisions such as final selections for commercialization or establishing new instrumental quality measures should ideally be validated using a trained sensory panel or via large-scale consumer acceptance tests, as appropriate for the project objective. As explained in greater detail in Chapter 21, Measuring Consumer Acceptance of Vegetables, consumer acceptance tests are used to determine how much consumers like or dislike a product, whereas sensory profiling by a trained panel is a more analytical process that strives to eliminate the hedonic (i.e., personal preference) aspects and focus attention instead on describing the intensities of various sensory attributes including appearance, flavor, and texture. By applying certain statistical methods, the data from both types of analyses may also be used in tandem to explain which sensory attributes are responsible for differences in consumer preference. Based on the stage of the product lifecycle, appropriate sensory, and/or consumer tests can be selected to ensure high-quality produce is reaching the market and to support successful introductions of new cultivars.

17.3.2 Purchase quality cues

While consumption quality cues are essential for eating pleasure and a desire to repeatedly purchase fruits and vegetables, purchase quality cues have an important influence on produce selection in the shopping context. These cues include attributes such as organic, local, genetic engineering status, and waste reduction features.

Fruits and vegetables are the leading category in organic products, accounting for approximately 40% of organic product sales (Organic Trade Association, 2019; Organic Trade Association Canada, 2013). It is known that there is a wide range of variability among consumers with regards to their interest in organic products. A consumer survey on organic food purchasing found that approximately one-third of consumers do not typically purchase organic products, another third buys organic products occasionally and the last third purchases organic products regularly with 50% or more of their purchases consisting of organic items (Mintel, 2017). This is in line with previous studies that found that organic labeling is the driving factor in product choice for approximately 24%−32% of the population, depending on the product and country under investigation (Grygorczyk, Turecek, & Lesschaeve, 2014; Meixner, Haas, Perevoshchikova, & Canavari, 2014; Skreli et al., 2017). While this segment of the population exists across many different product categories, the segment tends to be larger for foods. For example, when comparing the segment size of organic product purchasers among greenhouse tomato purchasers and purchasers of an ornamental crop (chrysanthemums), it was found that the segment of organic purchasers was nearly twice as large in the study on tomatoes (24% of the population vs 13.5%) (Grygorczyk et al., 2014). Therefore the organic designation is an important purchase quality attribute for produce.

Interestingly, it has been found that organic labels can impact consumers' perception of sensory properties. An online study of Portuguese consumers found that consumers expected organic fruits and vegetables (e.g., lettuce, zucchini, strawberries, apples, grapes) to taste better than their conventional counterparts (Prada, Garrido, & Rodrigues, 2017). A study on apples found that consumers who had strongly held beliefs about the superiority of organic farming rated apples higher for taste when the apples were presented with an organic label compared to without (Bernard, Bernard, & Liu, 2017). Note that in the context of consumer studies, taste is generally used by consumers to describe the overall product acceptability meaning when something "tastes better" this refers to liking the flavor, and often the texture, not just the basic taste sensations (e.g., sweet or sour).

In the early 2000s, around the same time that organic foods began to proliferate in mainstream supermarkets, the local food movement also quickly grew in popularity. For example, the USDA recorded a rapid growth in the number of farmers market listings in their directory between the years 2000 and 2012 with nearly threefold growth from 2863 to 7864 markets, after which point the growth began to plateau (USDA, 2019). Today many mainstream supermarkets, particularly upscale outlets, structure their produce supply chains to prioritize sourcing of local product to better align with consumer demand.

Studies that aimed to understand the consumer drive for local product have indicated that the most often cited reasons for purchasing local products was for perceived superior quality and taste. This expected quality was linked to perceived freshness, healthiness, and wholesomeness (Feldmann & Hamm, 2015). Similarly to organic labeling, studies completed on apples (Bernard et al., 2017) and strawberries (He, Gao, Sims, & Zhao, 2015) have shown that consumer beliefs that local products will have superior taste can ultimately modify taste experiences. In these studies, consumers were served the same fruit either with or without a local label and it was found that the fruits had higher ratings for appearance and taste when a "local" label was present. The effect of beliefs was underscored in this study as those consumers who were not local product seekers did not experience an improvement in taste when a local label was present (Bernard et al., 2017).

Attributes such as organic and local have had an important influence on consumer choice in the past couple of decades. More recently, other attributes such as genetic engineering status and waste reduction features have also accelerated in relevance for consumer fruit and vegetable selection.

Up until recently, the only genetically engineered foods that could be found in grocery stores were soybeans, corn, canola, papaya, and a variety of squash (Fernandez-Cornejo, Wechsler, Livingston, & Mitchell, 2014). Despite this, a 2013 survey of US consumers found that approximately 40%–50% of consumers believed that there were genetically engineered tomatoes, oranges, and apples on the market. This was a surprising finding as genetically engineered apples were not released in the market until several years later and the remainder of the fruits do not have genetically engineered varieties on the market to this day (Hallman, Cuite, & Morin, 2013). A study of Polish consumers found that over 60% believed there were genetically engineered tomatoes on the market and over 40% believed there were genetically engineered strawberries, cucumbers, lettuce, apples, grapes, and bananas on grocery store shelves (Jabłońska, Żuchowski, & Olewnicki, 2016). Therefore, although genetically engineered products are rarely found in the produce aisle, perceptions of genetic engineering continue to impact consumer choice of fruits and vegetables. Consumers often perceive unusually large and pristine appearances of fruits and vegetables as being unnatural. Because many consumers are not familiar with plant breeding (Grygorczyk, Jenkins, Deyman, Bowen, & Turecek, 2017) and are often not aware that produce is graded and sorted, some consumers incorrectly attribute the large, uniform, and "perfect" appearance of fruits and vegetables to genetic engineering.

The importance of genetic engineering perceptions is becoming particularly relevant to the produce industry with the recent launch of the genetically modified nonbrowning apple. The Arctic Apple was launched in some US grocery stores in 2017 and continues to expand its reach annually. What makes the launch of the Arctic apple particularly interesting is that the producer clearly states on the packaging that the apples are genetically engineered (Okanagan Specialty Fruits, 2020). This is a subject that researchers will surely follow in the years to come to examine how the transparent marketing of this genetically engineered product will influence its market success and how its commercial availability will impact quality perceptions of other products in the produce aisle.

In opposition to the beautiful fruit that is associated with modern food manufacturing and genetic engineering, a new "ugly fruit" trend has also found a place in the market. However, this trend is largely driven by a public desire to reduce food waste. In 2014 Intermarché, France's third-largest supermarket chain, became the first major retailer to address the issue of food waste in a consumer-facing way by selling imperfect produce through its "inglorious fruits and vegetables" campaign. The campaign launched a series of light-hearted television and print advertisements to highlight the imperfect produce along with dedicated shelf-space in produce aisles where the products were sold at a 30% discount. The initiative caught on in other parts of the world, for example, Canadian retailer, Safeway, launched imperfect produce in their stores later the same year and Canada's largest grocery chain, Loblaws, followed suit in 2016 with the launch of their "Naturally Imperfect" line of produce. The British retailer, Tesco, also jumped on-board in 2016 with their "Perfectly Imperfect" line.

Consumer research on perceptions of imperfect produce showed that consumers are more accepting of imperfect produce if they have proenvironmental views as well as when they are shopping in the context of a farmers market (Yuan, Yi, Williams, & Park, 2019). Consumers who regularly engage in grocery shopping and cooking are also more inclined to purchase imperfect produce (de Hooge et al., 2017). Conversely, consumers who have children are less likely to purchase imperfect produce as they perceive imperfect produce to have an increased food safety risk (Yuan et al., 2019). Interestingly, research has indicated that there appears to be a "sweet spot" for the degree of imperfection needed for a mishappen product to be acceptable. Fruits and vegetables marketed as imperfect produce that were only slightly mishappen and those that were heavily mishappen had lower perceived quality ratings than those that were moderately mishappen (Lombart et al., 2019).

The recent excitement about waste reduction among consumers has also led to another, more significant trend that has gained a great deal of attention in the produce industry: environmentally friendly packaging. The produce sector uses a small proportion of the world's plastic. For example, in Canada, it has been estimated that the fresh produce sector accounts for 5.1% of plastic used in packaging and 2% of overall plastic used in the Canadian economy annually (Gooch, Bucknell, Laplain, & Whitehead, 2019b). However, because the produce section is highly visible, typically located at the entrance of grocery stores, and because there is a consumer perception that packaging is unnecessary for most fruits and vegetables, the produce industry has faced a disproportionate amount of consumer backlash for packaging waste. Many consumers not only erroneously believe that packaging is unnecessary for products such as cucumbers, but they also believe that packaging causes produce to sweat thus reducing shelf-life (Icaro Consulting, 2012). This has put producers in a difficult spot as past research has demonstrated that packaging does indeed reduce produce waste by extending shelf-life and reducing physical damage (Gooch et al., 2019a).

In recent years, many retailers have been moving to packaging for produce that was historically sold in bulk, such as apples and pears, to reduce food waste and improve the quality of product that consumers bring home. However, currently there are few eco-friendly packaging alternatives, particularly ones that are compostable, that have been proven to be suitable for produce supply chains. Therefore producers must balance the desire to reduce food waste with the desire to reduce packaging waste. Another consideration is how eco-friendly packaging impacts perception of produce quality. It's known that the tactile qualities of packaging can impact consumer perceptions of the product contained within (Krishna & Morrin, 2008).

Many packaging producers are developing technologies enabling them to reduce the volume of plastic used in packaging in an effort to reduce overall plastic use. However, it has been observed in a variety of product categories that reducing packaging weight is correlated with a reduction in perceived monetary value of the product (Spence, 2016). Thus, as eco-friendly packaging materials are developed, it will be important for manufacturers to keep in mind the sensory qualities of the packaging itself to ensure that the tactile properties of the packaging add, rather than detract, from the perceived product quality. The trend for eco-friendly, and particularly compostable, packaging is still in its early days and much more research is needed before the industry can adequately respond to the trend while maintaining consumer expectations of fruit and vegetable quality and reducing food waste.

17.4 Summary

Purchase decisions are moderated by price fluctuation, perceived value, reason for use, marketing, nutritional, and functional properties as well as taste, aroma, texture, and appearance (Lange, Issanchou, & Combris, 2000). Quality plays a pervasive role in all of these aspects.

Consumers' product choices are influenced by the buying context. In the absence of being able to sample products, consumers tend to be more decisive and less influenced by sensory characteristics than when given the opportunity to taste the products (Harker et al., 2003). However, tasting at point of sale is rarely an option, and therefore the market must rely on effective pre- and postharvest practices to deliver consistent high-quality produce that will generate return customers.

Delivering products that meet quality expectations requires an understanding of the factors that moderate consumer perceived quality and must consider both product consumption (e.g. sensory) quality as well as purchase quality such as marketing labels. A periodic reevaluation of consumer definitions of quality should be completed as fruit quality is not an absolute nor constant element. Harker et al. (2003) summarized it well by stating that fruit quality "is a concept that changes dynamically across time as consumers' expectations change. As new products are released and new postharvest technologies developed, there will be a corresponding impact on the lifecycle of existing products." These will lead to changes in consumer habits, product familiarity, and preferences. Therefore, consumer perceptions of quality must be periodically reexamined and postharvest practices must be adapted over time to continue to align with consumer quality expectations and contribute to continued produce enjoyment and consumption.

References

Aggarwal, A., Cook, A. J., Jiao, J., Seguin, R. A., Moudon, A. V., Hurvitz, P. M., & Drewnowski, A. (2014). Access to supermarkets and fruit and vegetable consumption. *American Journal of Public Health*, *104*, 917–923. Available from https://doi.org/10.2105/AJPH.2013.301763.

Allan-Wojtas, P., Sanford, K. A., McRae, K. B., & Carbyn, S. (2003). An integrated microstructural and sensory approach to describe apple texture. *Journal of the American Society for Horticultural Science*, *128*(3), 381–390. Available from https://doi.org/10.21273/jashs.128.3.0381.

Amyotte, B., Bowen, A. J., Banks, T., Rajcan, I., & Somers, D. J. (2017). Mapping the sensory perception of apple using descriptive sensory evaluation in a genome wide association study. *PLoS One*, *12*(2), e0171710. Available from https://doi.org/10.1371/journal.pone.0171710.

Aprea, E., Gika, H., Carlin, S., Theodoridis, G., Vrhovsek, U., & Mattivi, F. (2011). Metabolite profiling on apple volatile content based on solid phase microextraction and gas-chromatography time of flight mass spectrometry. *Journal of Chromatography A*, *1218*, 4517–4524. Available from https://doi.org/10.1016/j.chroma.2011.05.019.

Arce-Lopera, C., Masuda, T., Kimura, A., Wada, Y., & Okajima, K. (2013). Luminance distribution as a determinant for visual freshness perception: Evidence from image analysis of a cabbage leaf. *Food Quality and Preference*, *27*(28), 202–207. Available from https://doi.org/10.1016/j.foodqual.2012.03.005.

Aune, D., Giovannucci, E., Boffetta, P., Fadnes, L. T., Keum, N. N., Norat, T., ... Tonstad, S. (2017). Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality—A systematic review and dose–response *meta*-analysis of prospective studies. *International Journal of Epidemiology*, *46*(3), 1029–1056. Available from https://doi.org/10.1093/ije/dyw319.

Azagba, S., & Sharaf, M. F. (2011). Disparities in the frequency of fruit and vegetable consumption by socio-demographic and lifestyle characteristics in Canada. *Nutrition Journal*, *10*(1), 118. Available from https://doi.org/10.1186/1475-2891-10-118.

Baker, A. H., & Wardle, J. (2003). Sex differences in fruit and vegetable intake in older adults. *Appetite*, *40*(3), 269–275. Available from https://doi.org/10.1016/s0195-6663(03)00014-x.

Banerjee, R., Tudu, B., Bandyopadhyay, R., & Bhattacharyya, N. (2016). A review on combined odor and taste sensor systems. *Journal of Food Engineering*, *190*, 10–21. Available from https://doi.org/10.1016/j.jfoodeng.2016.06.001.

Barreiro, P., Ortiz, C., Ruiz-Altisent, M., Schotte, S., Andani, Z., Wakeling, I., & Beyt, P. K. (1998). Comparison between sensory and instrumental measurements for mealiness assessment in apples. A collaborative test. *Journal of Texture Studies*, *29*(5), 509−525. Available from https://doi.org/10.1111/j.1745-4603.1998.tb00180.x.

Barrett, D. M., Beaulieu, J. C., & Shewfelt, R. (2010). Color, flavor, texture, and nutritional quality of fresh-cut fruits and vegetables: Desirable levels, instrumental and sensory measurement, and the effects of processing. *Critical Reviews in Food Science and Nutrition*, *50*(5), 369−389. Available from https://doi.org/10.1080/10408391003626322.

Batt, P., & Sadler, C. (1998). Consumer attitudes towards the labelling of apples. *Food Australia*, *50*(9), 449−450.

Beaulac, J., Kristjansson, E., & Cummins, S. (2009). A systematic review of food deserts, 1966−2007. *Preventing Chronic Disease*, *6*(3), 1−10.

Beaulieu, J. C. (2006). Effect of cutting and storage on acetate and nonacetate esters in convenient, ready-to-eat fresh-cut melons and apples. *HortScience: A Publication of the American Society for Horticultural Science*, *41*, 65−73. Available from https://doi.org/10.21273/hortsci.41.1.65.

Bernard, J. C., Bernard, J. C., & Liu, Y. (2017). Are beliefs stronger than taste? A field experiment on organic and local apples. *Food Quality and Preference*, *61*, 55−62. Available from https://doi.org/10.1016/j.foodqual.2017.05.005.

Birch, L. L. (1980). Effects of peer models' food choices and eating behaviors on preschoolers' food preferences. *Child Development*, *51*(1), 489−496. Available from https://doi.org/10.2307/1129283.

Birch, L., Savage, J. S., & Ventura, A. (2007). Influences on the development of children's eating behaviours: From infancy to adolescence. *Canadian Journal of Dietetic Practice and Research : A Publication of Dietitians of Canada*, *68*(1), s1−s56.

Bonany, J., Buehler, A., Carbó, J., Codarin, S., Donati, F., Echeverria, G., Egger, S., Guerra, W., Hilaire, C., Höller, I., Iglesias, I., Jesionkowska, K., Konopacka, D., Kruczyńska, D., Martinelli, A., Pitiot, C., Sansavini, S., Stehr, R., & Schoorl, F. (2013). Consumer eating quality acceptance of new apple varieties in different European countries. *Food Quality and Preference*, *30*(2), 250−259. Available from https://doi.org/10.1016/j.foodqual.2013.06.004.

Bongaerts, J. H. H., Rossetti, D., & Stokes, J. R. (2007). The lubricating properties of human whole saliva. *Tribology Letters*, *27*(3), 277−287. Available from https://doi.org/10.1007/s11249-007-9232-y.

Bourne, M. C. (1979). Texture of temperate fruits. *Journal of Texture Studies*, *10*(1), 25−44. Available from https://doi.org/10.1111/j.1745-4603.1979.tb01306.x.

Bowen, A., Flemming, C., Turecek, J., & Blake, A. (2015). All in the eyes. Consumer preference for sweet potato fries. In: *Paper presented at the 11th Pangborn sensory science symposium*, Gothenburg, Sweden.

Bowen, A. J., Blake, A., & Tureček, J. (2019a). Development and validation of a color evaluation process for sweet potato preference characterization. *Journal of Sensory Studies*, *34*(5), e12524. Available from https://doi.org/10.1111/joss.12524.

Bowen, A. J., Blake, A., Tureček, J., & Amyotte, B. (2019b). External preference mapping: A guide for a consumer-driven approach to apple breeding. *Journal of Sensory Studies*, *34*(1), e12472. Available from https://doi.org/10.1111/joss.12472.

Bowen, S., Brenton, J., & Elliott, S. (2019). *Pressure cooker: Why home cooking won't solve our problems and what we can do about it*. Oxford University Press.

Broers, V. J. V., de Breucker, C., van den Broucke, S., & Luminet, O. (2017). A systematic review and *meta*-analysis of the effectiveness of nudging to increase fruit and vegetable choice. *European Journal of Public Health*, *27*(5), 912−920. Available from https://doi.org/10.1093/eurpub/ckx085.

Brueckner, B., Schonhof, I., Kornelson, C., & Schrodter, R. (2005). Multivariate sensory profile of broccoli and cauliflower and consumer preference | Request PDF. *Italian Journal of Food Science*, *17*(1), 17−31.

Bugaud, C., Maraval, I., Daribo, M. O., Leclerc, N., & Salmon, F. (2016). Optimal and acceptable levels of sweetness, sourness, firmness, mealiness and banana aroma in dessert banana (Musa sp.). *Scientia Horticulturae*, *211*, 399−409. Available from https://doi.org/10.1016/j.scienta.2016.09.016.

Bult, J. H. F., de Wijk, R. A., & Hummel, T. (2007). Investigations on multimodal sensory integration: Texture, taste, and ortho- and retronasal olfactory stimuli in concert. *Neuroscience Letters*, *411*(1), 6−10. Available from https://doi.org/10.1016/j.neulet.2006.09.036.

Caspi, C. E., Sorensen, G., Subramanian, S. V., & Kawachi, I. (2012). The local food environment and diet: A systematic review. *Health and Place*, *18*(5), 1172−1187. Available from https://doi.org/10.1016/j.healthplace.2012.05.006.

Cecchini, M. P., Knaapila, A., Hoffmann, E., Boschi, F., Hummel, T., & Iannilli, E. (2019). A cross-cultural survey of umami familiarity in European countries. *Food Quality and Preference*, *74*, 172−178. Available from https://doi.org/10.1016/j.foodqual.2019.01.017.

Chen, J. (2009). Food oral processing—A review. *Food Hydrocolloids*, *23*(1), 1−25. Available from https://doi.org/10.1016/j.foodhyd.2007.11.013.

Cliff, M. A., Stanich, K., Lu, R., & Hampson, C. R. (2016). Use of descriptive analysis and preference mapping for early-stage assessment of new and established apples. *Journal of the Science of Food and Agriculture*, *96*(6), 2170–2183. Available from https://doi.org/10.1002/jsfa.7334.

Cooksey-Stowers, K., Schwartz, M., & Brownell, K. (2017). Food swamps predict obesity rates better than food deserts in the United States. *International Journal of Environmental Research and Public Health*, *14*(11), 1366. Available from https://doi.org/10.3390/ijerph14111366.

Crisosto, C. H. (2002). 'How do we increase peach consumption? In C. H. Crisosto, & R. Scott Johnson (Eds.), *Acta horticulturae 592: V international peach symposium* (pp. 601–605). Davis, CA: International Society for Horticultural Science. Available from https://doi.org/10.17660/ActaHortic.2002.592.82.

Crisosto, C. H., Crisosto, G. M., & Garner, D. (2005). Understanding tree fruit consumer acceptance. In F. Mencarelli, & P. Tonutti (Eds.), *Acta horticulturae 682: V international postharvest symposium* (pp. 865–870). Verona: International Society for Horticultural Science. Available from https://doi.org/10.17660/ActaHortic.2005.682.112.

Cullen, K. W., Baranowski, T., Rittenberry, L., Cosart, C., Hebert, D., & de Moor, C. (2001). Child-reported family and peer influences on fruit, juice and vegetable consumption: Reliability and validity of measures. *Health Education Research*, *16*(2), 187–200. Available from https://doi.org/10.1093/her/16.2.187.

de Hooge, I. E., Oostindjer, M., Aschemann-Witzel, J., Normann, A., Loose, S. M., & Almli, V. L. (2017). This apple is too ugly for me!: Consumer preferences for suboptimal food products in the supermarket and at home. *Food Quality and Preference*, *56*(Part A), 80–92. Available from https://doi.org/10.1016/j.foodqual.2016.09.012.

Dehghan, M., Akhtar-Danesh, N., & Merchant, A. T. (2011). Factors associated with fruit and vegetable consumption among adults. *Journal of Human Nutrition and Dietetics*, *24*(2), 128–134. Available from https://doi.org/10.1111/j.1365-277X.2010.01142.x.

Ding, C., Wu, H., Feng, Z., Wang, D., Li, W., & Cui, D. (2020). Online assessment of pear firmness by acoustic vibration analysis. *Postharvest Biology and Technology*, *160*, 111042. Available from https://doi.org/10.1016/j.postharvbio.2019.111042.

Drewnowski, A., & Gomez-Carneros, C. (2000). Bitter taste, phytonutrients, and the consumer: A review. *American Journal of Clinical Nutrition*, *76*(6), 1424–1435.

Duthie, S. J., Duthie, G. G., Russell, W. R., Kyle, J. A. M., Macdiarmid, J. I., Rungapamestry, V., Stephen, S., Megias-Baeza, C., Kaniewska, J. J., Shaw, L., Milne, L., Bremner, D., Ross, K., Morrice, P., Pirie, L. P., Horgan, G., & Bestwick, C. S. (2018). Effect of increasing fruit and vegetable intake by dietary intervention on nutritional biomarkers and attitudes to dietary change: A randomised trial. *European Journal of Nutrition*, *57*(5), 1855–1872. Available from https://doi.org/10.1007/s00394-017-1469-0.

Endrizzi, I., Torri, L., Corollaro, M. L., Demattè, M. L., Aprea, E., Charles, M., Biasioli, F., & Gasperi, F. (2015). A conjoint study on apple acceptability: Sensory characteristics and nutritional information. *Food Quality and Preference*, *40*(PA), 39–48. Available from https://doi.org/10.1016/j.foodqual.2014.08.007.

Escribano, S., Sánchez, F. J., & Lázaro, A. (2010). Establishment of a sensory characterization protocol for melon (*Cucumis melo* L.) and its correlation with physical–chemical attributes: Indications for future genetic improvements. *European Food Research and Technology*, *231*(4), 611–621. Available from https://doi.org/10.1007/s00217-010-1313-8.

Evans, I., Haisman, D., Elson, E., Pasternak, P., & McConnaughey, W. (1986). The effect of salivary amylase on viscosity behaviour of gelatinised starch suspensions and the mechanical properties of gelatinised starch granules. *Journal of the Science of Food and Agriculture*, *37*(6), 573–590. Available from https://doi.org/10.1002/jsfa.2740370611.

Fan, X., & Mattheis, J. P. (1999). Impact of 1-methylcyclopropene and methyl jasmonate on apple volatile production. *Journal of Agricultural and Food Chemistry*, *47*(7), 2847–2853. Available from https://doi.org/10.1021/jf990221s.

Fandos, C., & Flavián, C. (2006). Intrinsic and extrinsic quality attributes, loyalty and buying intention: An analysis for a PDO product. *British Food Journal*, *108*(8), 648–662. Available from https://doi.org/10.1108/00070700610682337.

Feldmann, C., & Hamm, U. (2015). Consumers' perceptions and preferences for local food: A review. *Food Quality and Preference*, *40*(Part A), 152–164. Available from https://doi.org/10.1016/j.foodqual.2014.09.014.

Fenwick, G., Curl, C., Griffiths, N., Heaney, R., & Price, K. (1990). Bitter principles in food plants. *Developments in Food Science*, *25*, 205–250.

Fernandez-Cornejo, J., Wechsler, S., Livingston, M., & Mitchell, L. (2014). *Genetically engineered crops in the United States*. Available from <https://www.ers.usda.gov/webdocs/publications/45179/43668_err162.pdf> Accessed 31.03.20.

Folta, K. M., & Klee, H. J. (2016). Sensory sacrifices when we mass-produce mass produce. *Horticulture Research*, *3*, 16032. Available from https://doi.org/10.1038/hortres.2016.32.

Gast, K. L. B. (2001). *Bulletin #4135, storage conditions: Fruits and vegetables – Cooperative extension publications*. University of Maine Cooperative Extension. Available from <https://extension.umaine.edu/publications/4135e/> Accessed 10.05.20.

Giné-Bordonaba, J., Cantín, C. M., Echeverría, G., Ubach, D., & Larrigaudière, C. (2016). The effect of chilling injury-inducing storage conditions on quality and consumer acceptance of different Prunus persica cultivars. *Postharvest Biology and Technology*, *115*, 38–47. Available from https://doi.org/10.1016/j.postharvbio.2015.12.006.

Gooch, M., Bucknell, D., Laplain, D., Dent, B., Whitehead, P., & Felfel, A. (2019a). *The avoidable crisis of food waste: Technical report*. Available from <https://secondharvest.ca/wp-content/uploads/2019/01/Avoidable-Crisis-of-Food-Waste-Technical-Report-January-17-2019.pdf> Accessed 08.03.20.

Gooch, M., Bucknell, D., Laplain, D., & Whitehead, P. (2019b). *A landscape review of plastics in the Canadian fresh produce sector*. Available from <https://cpma.ca/docs/default-source/corporate/2019/cpma-executive-summary-of-technical-report.pdf> Accessed 09.03.20.

Grygorczyk, A., Jenkins, A., Deyman, K., Bowen, A. J., & Turecek, J. (2017). Applying appeal ratings and CATA for making word choices in messaging about food technology. *Food Quality and Preference*, *62*. Available from https://doi.org/10.1016/j.foodqual.2017.06.002.

Grygorczyk, A., Turecek, J., & Lesschaeve, I. (2014). Consumer preferences for alternative pest management practices used during production of an edible and a non-edible greenhouse crop'. *Journal of Pest Science*, *87*(2), 249–258. Available from https://doi.org/10.1007/s10340-013-0544-4.

Gustafson, A., Lewis, S., Perkins, S., Wilson, C., Buckner, E., & Vail, A. (2013). Neighbourhood and consumer food environment is associated with dietary intake among Supplemental Nutrition Assistance Program (SNAP) participants in Fayette County, Kentucky. *Public Health Nutrition*, *16*(7), 1229–1237. Available from https://doi.org/10.1017/S1368980013000505.

Hadad, R. (2016). *Cold storage chart and reference guide to commercial vegetable storage: Cornell cooperative extension*. Available from <https://cvp.cce.cornell.edu/submission.php?id = 411> Accessed 10.05.20.

Hager, E. R., Cockerham, A., O'Reilly, N., Harrington, D., Harding, J., Hurley, K. M., & Black, M. M. (2017). Food swamps and food deserts in Baltimore City, MD, USA: Associations with dietary behaviours among urban adolescent girls. *Public Health Nutrition*, *20*(14), 2598–2607. Available from https://doi.org/10.1017/S1368980016002123.

Haines, J., Haycraft, E., Lytle, L., Nicklaus, S., Kok, F. J., Merdji, M., Fisberg, M., Moreno, L. A., Goulet, O., & Hughes, S. O. (2019). Nurturing children's healthy eating: Position statement. *Appetite*, *137*, 124–133. Available from https://doi.org/10.1016/j.appet.2019.02.007.

Hallman, W. K., Cuite, C. L., & Morin, X. (2013). *Public perceptions of labeling genetically modified foods*. RUcore: Rutgers University Community Repository. Available from <https://doi.org/10.7282/T33N255N> Accessed 09.03.20.

Hampson, C. R., Quamme, H. A., Hall, J. W., MacDonald, R. A., King, M. C., & Cliff, M. A. (2000). Sensory evaluation as a selection tool in apple breeding. *Euphytica*, *111*(2), 79–90. Available from https://doi.org/10.1023/A:1003769304778.

Harker, F. R., & Hallett, I. C. (1992). Physiological changes associated with development of mealiness of apple fruit during cool storage. *HortScience: A Publication of the American Society for Horticultural Science*, *27*(12), 1291–1294. Available from https://doi.org/10.21273/hortsci.27.12.1291.

Harker, F. R., & Johnston, J. W. (2008). Importance of texture in fruit and its interaction with flavour. In B. Brückner, & S. G. Wyllie (Eds.), *Fruit and vegetable flavour: Recent advances and future prospects* (pp. 132–149). Woodhead Publishing. Available from https://doi.org/10.1533/9781845694296.2.132.

Harker, R., Gunson, A., & Jaeger, S. (2003). The case for fruit quality: An interpretive review of consumer attitudes, and preferences for apples. *Postharvest Biology and Technology*, *28*(3), 333–347. Available from https://doi.org/10.1016/S0925-5214(02)00215-6.

He, C., Gao, Z., Sims, C., & Zhao, X. (2015). Does local label bias consumer taste bud and choice behavior: Evidence of a strawberry sensory experiment. In: *Paper presented at the southern agricultural economics association annual meeting*, Atlanta, GA.

Health Canada. *Measuring the food environment in Canada*. (2013). <https://www.canada.ca/en/health-canada/services/food-nutrition/healthy-eating/nutrition-policy-reports/measuring-food-environment-canada.html> Accessed 02.03.20.

Health Canada. *Canada's food guide*. (2019). <https://food-guide.canada.ca/en/> Accessed 02.03.20.

Health Canada. *History of Canada's food guides from 1942 to 2007*. (2020). <https://www.canada.ca/en/health-canada/services/canada-food-guide/about/history-food-guide.html> Accessed 02.04.20.

Holley, C. E., Farrow, C., & Haycraft, E. (2017). A systematic review of methods for increasing vegetable consumption in early childhood. *Current Nutrition Reports*, *6*(2), 157–170. Available from https://doi.org/10.1007/s13668-017-0202-1.

Icaro Consulting. *Consumer attitudes to food waste and food packaging*. (2012). <http://www.wrap.org.uk/sites/files/wrap/Report%20-%20Consumer%20attitudes%20to%20food%20waste%20and%20packaging_0.pdf>.

Ioannides, Y., Howarth, M. S., Raithatha, C., Defernez, M., Kemsley, E. K., & Smith, A. C. (2007). Texture analysis of Red Delicious fruit: Towards multiple measurements on individual fruit. *Food Quality and Preference*, *18*(6), 825–833. Available from https://doi.org/10.1016/j.foodqual.2005.09.012.

Isabelle, M., Lee, B. L., Lim, M. T., Koh, W. P., Huang, D., & Ong, C. N. (2010). Antioxidant activity and profiles of common vegetables in Singapore. *Food Chemistry*, *120*(4), 993–1003. Available from https://doi.org/10.1016/j.foodchem.2009.11.038.

Jabłońska, L., Żuchowski, S., & Olewnicki, D. (2016). GMOs in the Polish fruit and vegetables consumer awareness'. *Journal of Agribusiness and Rural Development*, *40*(2), 271–279. Available from https://doi.org/10.17306/jard.2016.31.

Jaeger, S., Lund, C. M., Lau, K., & Harker, F. (2006). In search of the "Ideal" pear (Pyrus spp.): results of a multidisciplinary exploration. *Journal of Food Science*, *68*(3), 1108–1117. Available from https://doi.org/10.1111/j.1365-2621.2003.tb08296.x.

Jaeger, S. R., Rossiter, K. L., Wismer, W. V., & Harker, F. R. (2003). Consumer-driven product development in the kiwifruit industry. *Food Quality and Preference*, *14*(3), 187–198. Available from https://doi.org/10.1016/S0950-3293(02)00053-8.

Jansen, E., Mulkens, S., & Jansen, A. (2010). How to promote fruit consumption in children. Visual appeal vs restriction. *Appetite*, *54*(3), 599–602. Available from https://doi.org/10.1016/j.appet.2010.02.012.

Kader, A. A. (2008). Flavor quality of fruits and vegetables. *Journal of the Science of Food and Agriculture*, *88*(11), 1863–1868. Available from https://doi.org/10.1002/jsfa.3293.

Katz, F. (2004). The natural color of health: Product developers are looking at natural sources of color for their incidental health benefits. *Food Processing*, *65*(4), 54.

Kiadaliri, A. A. (2013). Demographic and socioeconomic differences in fruit and vegetables consumption, 2007–2009: A province-level study in Iran. *International Journal of Preventive Medicine*, *4*(7), 831–840.

Kim, M. S., Walters, N., Martini, A., Joyner, H., Duizer, L., & Grygorczyk, A. (2020). Adapting tribology for use in sensory studies on hard food: The case of texture perception in apples. *Food Quality and Preference*, *86*. Available from https://doi.org/10.1016/j.foodqual.2020.103990.

Kiraci, S., & Padem, H. (2016). Determination of the chemical and sensory characteristics of some carrot varieties grown in Turkey. *Acta Scientiarum Polonorum. Hortorum cultus*, *15*, 139–147.

Klee, H. J. (2010). Improving the flavor of fresh fruits: Genomics, biochemistry, and biotechnology. *New Phytologist*, *187*(1), 44–56. Available from https://doi.org/10.1111/j.1469-8137.2010.03281.x.

Krishna, A., & Morrin, M. (2008). Does touch affect taste? The perceptual transfer of product container haptic cues. *Journal of Consumer Research*, *34*(6), 807–818. Available from https://doi.org/10.1086/523286.

Kupferman, E. (2003). Controlled atmosphere storage of apples and pears. In H. W. Peppelenbos, & J. Oosterhaven (Eds.), *Acta horticulturae 600: VIIi international controlled atmosphere research conference* (pp. 729–735). Rotterdam: International Society for Horticultural Science. Available from https://doi.org/10.17660/ActaHortic.2003.600.111.

Kyriacou, M. C., & Rouphael, Y. (2018). Towards a new definition of quality for fresh fruits and vegetables. *Scientia Horticulturae*, *234*, 463–469. Available from https://doi.org/10.1016/j.scienta.2017.09.046.

Laguna, L., & Sarkar, A. (2017). Oral tribology: Update on the relevance to study astringency in wines. *Tribology – Materials, Surfaces and Interfaces*, *11*(2), 116–123. Available from https://doi.org/10.1080/17515831.2017.1347736.

Lange, C., Issanchou, S., & Combris, P. (2000). Expected vs experienced quality: Trade-off with price. *Food Quality and Preference*, *11*(4), 289–297. Available from https://doi.org/10.1016/s0950-3293(99)00074-9.

Lassen, A., Thorsen, A. V., Trolle, E., Elsig, M., & Ovesen, L. (2004). Successful strategies to increase the consumption of fruits and vegetables: Results from the Danish '6 a day' Work-site Canteen Model Study. *Public Health Nutrition*, *7*(2), 263–270. Available from https://doi.org/10.1079/phn2003532.

Laurie, S. M., Faber, M., Calitz, F. J., Moelich, E. I., Muller, N., & Labuschagne, M. T. (2013). The use of sensory attributes, sugar content, instrumental data and consumer acceptability in selection of sweet potato varieties. *Journal of the Science of Food and Agriculture*, *93*(7), 1610–1619. Available from https://doi.org/10.1002/jsfa.5932.

Lee, J. E., Männistö, S., Spiegelman, D., Hunter, D. J., Bernstein, L., van den Brandt, P. A., Buring, J. E., Cho, E., English, D. R., Flood, A., Freudenheim, J. L., Giles, G. G., Giovannucci, E., Håkansson, N., Horn-Ross, P. L., Jacobs, E. J., Leitzmann, M. F., Marshall, J. R., McCullough, M. L., Miller, A. B., Rohan, T. E., Ross, J. A., Schatzkin, A., Schouten, L. J., Virtamo, J., Wolk, A., Zhang, S. M., & Smith-Warner, S. A. (2009). Intakes of fruit, vegetables, and carotenoids and renal cell cancer risk: A pooled analysis of 13 prospective studies. *Cancer Epidemiology and Prevention Biomarkers*, *18*(6), 1730−1739. Available from https://doi.org/10.1158/1055-9965.EPI-09-0045.

Leksrisompong, P. P., Whitson, M. E., Truong, V. D., & Drake, M. A. (2012). Sensory attributes and consumer acceptance of sweet potato cultivars with varying flesh colors. *Journal of Sensory Studies*, *27*(1), 59−69. Available from https://doi.org/10.1111/j.1745-459X.2011.00367.x.

Lombart, C., Millan, E., Normand, J. M., Verhulst, A., Labbé-Pinlon, B., & Moreau, G. (2019). Consumer perceptions and purchase behavior toward imperfect fruits and vegetables in an immersive virtual reality grocery store. *Journal of Retailing and Consumer Services*, *48*, 28−40. Available from https://doi.org/10.1016/j.jretconser.2019.01.010.

Mc Morrow, L., Ludbrook, A., Macdiarmid, J. I., & Olajide, D. (2016). Perceived barriers towards healthy eating and their association with fruit and vegetable consumption. *Journal of Public Health*, *39*(2), 330−338. Available from https://doi.org/10.1093/pubmed/fdw038.

Mehinagic, E., Royer, G., Bertrand, D., Symoneaux, R., Laurens, F., & Jourjon, F. (2003). Relationship between sensory analysis, penetrometry and visible−NIR spectroscopy of apples belonging to different cultivars. *Food Quality and Preference*, *14*(5), 473−484. Available from https://doi.org/10.1016/S0950-3293(03)00012-0.

Meiselman, H. L., King, S. C., & Gillette, M. (2010). The demographics of neophobia in a large commercial US sample. *Food Quality and Preference*, *21*(7), 893−897. Available from https://doi.org/10.1016/j.foodqual.2010.05.009.

Meixner, O., Haas, R., Perevoshchikova, Y., & Canavari, M. (2014). Consumer attitudes, knowledge, and behavior in the Russian market for organic food. *International Journal on Food System Dynamics*, *5*(2), 110−120. Available from https://doi.org/10.18461/ijfsd.v5i2.525.

Menezes, M. C., Costa, B. V. L., Oliveira, C. D. L., & Lopes, A. C. S. (2017). Local food environment and fruit and vegetable consumption: An ecological study. *Preventive Medicine Reports*, *5*, 13−20. Available from https://doi.org/10.1016/j.pmedr.2016.10.015.

Minaker, L. M., Raine, K. D., Wild, T. C., Nykiforuk, C. I. J., Thompson, M. E., & Frank, L. D. (2013). Objective food environments and health outcomes. *American Journal of Preventive Medicine*, *45*(3), 289−296. Available from https://doi.org/10.1016/j.amepre.2013.05.008.

Mintel. *Produce tops grocery list for organic food shoppers in the US*. (2017). <https://www.mintel.com/press-centre/food-and-drink/produce-tops-grocery-lists-for-organic-food-shoppers> Accessed 31.03.20.

Munoz, A. M., & Vance Civille, G. (1987). Factors affecting perception and acceptance of food texture by American consumers. *Food Reviews International*, *3*(3), 285−322. Available from https://doi.org/10.1080/87559128709540817.

National Health Services (UK). *Why 5 a day?*. (2020). <https://www.nhs.uk/live-well/eat-well/why-5-a-day/> Accessed 10.03.20.

Okanagan Specialty Fruits. *Where to find Arctic® apples*. (2020). <https://www.arcticapples.com/find-our-apples/> Accessed 02.04.20.

Organic Trade Association (Canada). *The national organic market*. (2013). <https://ota.com/sites/default/files/indexed_files/COTA_NationalOrganicMarketSummary.pdf> Accessed 31.03.20.

Organic Trade Association. *U.S. organic industry survey*. (2019). <https://ota.com/resources/organic-industry-survey> Accessed 02.04.20.

Paakki, M., Sandell, M., & Hopia, A. (2016). Consumer's reactions to natural, atypically colored foods: An investigation using blue potatoes. *Journal of Sensory Studies*, *31*(1), 78−89. Available from https://doi.org/10.1111/joss.12193.

Pan, Y., Li, X., Jia, X., Zhao, Y., Li, H., & Zhang, L. (2019). Storage temperature without fluctuation enhances shelf-life and improves postharvest quality of peach. *Journal of Food Processing and Preservation*, *43*(3), e13881. Available from https://doi.org/10.1111/jfpp.13881.

Pech, J. C., Bouzayen, M., & Latché, A. (2008). Climacteric fruit ripening: Ethylene-dependent and independent regulation of ripening pathways in melon fruit. *Plant Science*, *175*(1-2), 115−119. Available from https://doi.org/10.1016/j.plantsci.2008.01.003.

Péneau, S., Brockhoff, P. B., Escher, F., & Nuessli, J. (2007). A comprehensive approach to evaluate the freshness of strawberries and carrots. *Postharvest Biology and Technology*, *45*(1), 20–29. Available from https://doi.org/10.1016/j.postharvbio.2007.02.001.

Péneau, S., Hoehn, E., Roth, H. R., Escher, F., & Nuessli, J. (2006). Importance and consumer perception of freshness of apples. *Food Quality and Preference*, *17*(1-2), 9–19. Available from https://doi.org/10.1016/j.foodqual.2005.05.002.

Péneau, S., Linke, A., Escher, F., & Nuessli, J. (2009). Freshness of fruits and vegetables: Consumer language and perception. *British Food Journal*, *111*(3), 243–256. Available from https://doi.org/10.1108/00070700910941453.

Poelman, A. A. M., Delahunty, C. M., & de Graaf, C. (2017). Vegetables and other core food groups: A comparison of key flavour and texture properties. *Food Quality and Preference*, *56*, 1–7. Available from https://doi.org/10.1016/j.foodqual.2016.09.004.

Pollard, J., Kirk, S. F. L., & Cade, J. E. (2002). Factors affecting food choice in relation to fruit and vegetable intake: A review. *Nutrition Research Reviews*, *15*(2), 373–387. Available from https://doi.org/10.1079/nrr200244.

Prada, M., Garrido, M., & Rodrigues, D. (2017). Lost in processing? Perceived healthfulness, taste and caloric content of whole and processed organic food. *Appetite*, *114*, 175–186. Available from https://doi.org/10.1016/j.appet.2017.03.031.

Prelip, M., Kinsler, J., Thai, C., le, Erausquin, J. T., & Slusser, W. (2012). Evaluation of a school-based multicomponent nutrition education program to improve young children's fruit and vegetable consumption. *Journal of Nutrition Education and Behavior*, *44*(4), 310–318. Available from https://doi.org/10.1016/j.jneb.2011.10.005.

Ragaert, P., Verbeke, W., Devlieghere, F., & Debevere, J. (2004). Consumer perception and choice of minimally processed vegetables and packaged fruits. *Food Quality and Preference*, *15*(3), 259–270. Available from https://doi.org/10.1016/S0950-3293(03)00066-1.

Rao, A. R. (2005). The quality of price as a quality cue. *Journal of Marketing Research*, *42*(4), 401–405. Available from https://doi.org/10.2307/30162389.

Rasmussen, M., Krølner, R., Klepp, K. I., Lytle, L., Brug, J., Bere, E., & Due, P. (2006). Determinants of fruit and vegetable consumption among children and adolescents: A review of the literature. Part I: Quantitative studies. *International Journal of Behavioral Nutrition and Physical Activity*, 3. Available from https://doi.org/10.1186/1479-5868-3-22.

Rekhy, R., & McConchie, R. (2014). Promoting consumption of fruit and vegetables for better health. Have campaigns delivered on the goals? *Appetite*, *79*, 113–123. Available from https://doi.org/10.1016/j.appet.2014.04.012.

Roininen, K., Fillion, L., Kilcast, D., & Lahteenmaki, L. (2003). Perceived eating difficulties and preferences for various textures of raw and cooked carrots in young and elderly subjects. *Journal of Sensory Studies*, *18*(6), 437–451. Available from https://doi.org/10.1111/j.1745-459X.2003.tb00399.x.

Schreiner, M., Korn, M., Stenger, M., Holzgreve, L., & Altmann, M. (2013). Current understanding and use of quality characteristics of horticulture products. *Scientia Horticulturae*, *163*, 63–69. Available from https://doi.org/10.1016/j.scienta.2013.09.027.

Seabrook, J. (2011). Building a better apple. *The New Yorker*.

Sinesio, F., Cammareri, M., Moneta, E., Navez, B., Peparaio, M., Causse, M., & Grandillo, S. (2010). Sensory quality of fresh French and Dutch market tomatoes: A preference mapping study with Italian consumers. *Journal of Food Science*, *75*(1), S55–S67. Available from https://doi.org/10.1111/j.1750-3841.2009.01424.x.

Skreli, E., Imami, D., Chan, C., Canavari, M., Zhllima, E., & Pire, E. (2017). Assessing consumer preferences and willingness to pay for organic tomatoes in Albania: A conjoint choice experiment study – Dialnet. *Spanish Journal of Agricultural Research*, *15*(3), 137–156, e0114–e0114.

Spence, C. (2016). *Integrating the packaging and product experience in food and beverages. A road-map to consumer satisfaction*. Duxford: Woodhead Publishing.

Stec, M. G. H., Hodgson, J. A., Macrae, E. A., & Triggs, C. M. (1989). Role of fruit firmness in the sensory evaluation of kiwifruit (*Actinidia deliciosa* cv Hayward). *Journal of the Science of Food and Agriculture*, *47*(4), 417–433. Available from https://doi.org/10.1002/jsfa.2740470404.

Sugri, I., Nutsugah, S. K., Wiredu, A. N., Johnson, P. N. T., & Aduguba, D. (2012). Kendall's concordance analysis of sensory descriptors influencing consumer preference for sweet potatoes in Ghana. *American Journal of Food Technology*, *7*(3), 142–150. Available from https://doi.org/10.3923/ajft.2012.142.150.

Sushil, Z., Vandevijvere, S., Exeter, D. J., & Swinburn, B. (2017). Food swamps by area socioeconomic deprivation in New Zealand: A national study. *International Journal of Public Health*, *62*(8), 869–877. Available from https://doi.org/10.1007/s00038-017-0983-4.

Symmank, C., Zahn, S., & Rohm, H. (2018). Visually suboptimal bananas: How ripeness affects consumer expectation and perception. *Appetite*, *120*, 472–481. Available from https://doi.org/10.1016/j.appet.2017.10.002.

Tesini, F., Laureati, M., Palagani, R., Mandrioli, M., Pagliarini, E., & Toschi, T. (2015). Children preferences of coloured fresh cheese prepared during an educational laboratory. *Italian Journal of Food Science*, *27*(4), 521–526.

Tieman, D., Bliss, P., McIntyre, L. M., Blandon-Ubeda, A., Bies, D., Odabasi, A. Z., Rodríguez, G. R., van der Knaap, E., Taylor, M. G., Goulet, C., Mageroy, M. H., Snyder, D. J., Colquhoun, T., Moskowitz, H., Clark, D. G., Sims, C., Bartoshuk, L., & Klee, H. J. (2012). The chemical interactions underlying tomato flavor preferences. *Current Biology*, *22*(11), 1035–1039. Available from https://doi.org/10.1016/j.cub.2012.04.016.

Toivonen, P. M. A., & Brummell, D. A. (2008). Biochemical bases of appearance and texture changes in fresh-cut fruit and vegetables. *Postharvest Biology and Technology*, *48*(1), 1–14. Available from https://doi.org/10.1016/j.postharvbio.2007.09.004.

USDA. *Fruit and vegetable recommendations can be met for $2.10 to $2.60 per day*. (2016). <https://www.ers.usda.gov/amber-waves/2016/march/fruit-and-vegetable-recommendations-can-be-met-for-210-to-260-per-day/> Accessed 10.03.20.

USDA. *National count of farmers market directory listings*. (2019). <https://www.ams.usda.gov/sites/default/files/media/NationalCountofFarmersMarketDirectoryListings082019.pdf> Accessed 02.04.20.

USDA. *A brief history of USDA food guides*. (2020). <https://www.choosemyplate.gov/eathealthy/brief-history-usda-food-guides> Accessed 02.04.20.

van Vliet, T. (2002). On the relation between texture perception and fundamental mechanical parameters for liquids and time dependent solids. *Food Quality and Preference*, *13*(4), 227–236. Available from https://doi.org/10.1016/S0950-3293(01)00044-1.

van Vliet, T., van Aken, G. A., de Jongh, H. H. J., & Hamer, R. J. (2009). Colloidal aspects of texture perception. *Advances in Colloid and Interface Science*, *150*(1), 27–40. Available from https://doi.org/10.1016/j.cis.2009.04.002.

Verlinden, B. E., de Smedt, V., & Nicolaï, B. M. (2004). Evaluation of ultrasonic wave propagation to measure chilling injury in tomatoes. *Postharvest Biology and Technology*, *32*(1), 109–113. Available from https://doi.org/10.1016/j.postharvbio.2003.11.006.

von Loesecke, H. (1950). *Bananas; chemistry, physiology, technology*. New York: Interscience Publishers Inc.

Waldron, K. W., Parker, M. L., & Smith, A. C. (2003). Plant cell walls and food quality. *Comprehensive Reviews in Food Science and Food Safety*, *2*(4), 128–146. Available from https://doi.org/10.1111/j.1541-4337.2003.tb00019.x.

Wansink, B., Just, D. R., Hanks, A. S., & Smith, L. E. (2013). Pre-sliced fruit in school cafeterias: Children's selection and intake. *American Journal of Preventive Medicine*, *44*(5), 477–480. Available from https://doi.org/10.1016/j.amepre.2013.02.003.

Wardle, J., & Huon, G. (2000). An experimental investigation of the influence of health information on children's taste preferences. *Health Education Research*, *15*(1), 39–44. Available from https://doi.org/10.1093/her/15.1.39.

Watkins, C. B., Nock, J. F., & Whitaker, B. D. (2000). Responses of early, mid and late season apple cultivars to postharvest application of 1-methylcyclopropene (1-MCP) under air and controlled atmosphere storage conditions. *Postharvest Biology and Technology*, *19*(1), 17–32. Available from https://doi.org/10.1016/S0925-5214(00)00070-3.

Wei, S. T., Ou, L. C., Luo, M. R., & Hutchings, J. B. (2012). Optimisation of food expectations using product colour and appearance. *Food Quality and Preference*, *23*(1), 49–62. Available from https://doi.org/10.1016/j.foodqual.2011.07.004.

Widener, M. J., Minaker, L., Farber, S., Allen, J., Vitali, B., Coleman, P. C., & Cook, B. (2017). How do changes in the daily food and transportation environments affect grocery store accessibility? *Applied Geography*, *83*, 46–62. Available from https://doi.org/10.1016/j.apgeog.2017.03.018.

Wilson, K. (2000). *Pruning fruit trees: Ontario Ministry of Agriculture, Food and Rural Affairs Factsheet*. Available from: <http://www.omafra.gov.on.ca/english/crops/facts/00-005.htm> Accessed 10.05.20.

Wismer, Wv, Harker, F. R., Gunson, F. A., Rossiter, K. L., Lau, K., Seal, A. G., Lowe, R. G., & Beatson, R. (2005). Identifying flavour targets for fruit breeding: A kiwifruit example. *Euphytica*, *141*(1–2), 93–104. Available from https://doi.org/10.1007/s10681-005-5891-7.

World Health Organization. *Global action plan for the prevention and control of noncommunicable diseases 2013–2020*. (2013). <https://www.who.int/publications/i/item/9789241506236> Accessed 02.03.20.

Yager, S. (2014, 10 September). The awful reign of the red delicious. *The Atlantic*.

Yamaguchi, S. (1998). Basic properties of umami and its effects on food flavor. *Food Reviews International*, *14*(2–3), 139–176. Available from https://doi.org/10.1080/87559129809541156.

Yuan, J. J., Yi, S., Williams, H. A., & Park, O. H. (2019). US consumers' perceptions of imperfect "ugly" produce. *British Food Journal*, *121*(11), 2666−2682. Available from https://doi.org/10.1108/BFJ-03-2019-0206.

Yue, C., & Tong, C. (2011). Consumer preferences and willingness to pay for existing and new apple varieties: Evidence from apple tasting choice experiments. *Horttechnology*, *21*(3), 376−383. Available from https://doi.org/10.21273/horttech.21.3.376.

Zampini, M., Sanabria, D., Phillips, N., & Spence, C. (2007). The multisensory perception of flavor: Assessing the influence of color cues on flavor discrimination responses. *Food Quality and Preference*, *18*(7), 975−984. Available from https://doi.org/10.1016/j.foodqual.2007.04.001.

Zdunek, A., Cybulska, J., Konopacka, D., & Rutkowski, K. (2011). Evaluation of apple texture with contact acoustic emission detector: A study on performance of calibration models. *Journal of Food Engineering*, *106*(1), 80−87. Available from https://doi.org/10.1016/j.jfoodeng.2011.04.011.

Zellner, D. A., Lankford, M., Ambrose, L., & Locher, P. (2010). Art on the plate: Effect of balance and color on attractiveness of, willingness to try and liking for food. *Food Quality and Preference*, *21*(5), 575−578. Available from https://doi.org/10.1016/j.foodqual.2010.02.007.

Zhang, P. C. (2016). *Developing consumer driven strategies for imparting fruit and vegetable consumption* (Ph.D. thesis). University of Guelph. Available from: The Atrium Accessed 03.03.20 http://hdl.handle.net/10214/9694.

Zhang, Y., Venkitasamy, C., Pan, Z., & Wang, W. (2013). Recent developments on umami ingredients of edible mushrooms − A review. *Trends in Food Science and Technology*, *33*(3), 78−92. Available from https://doi.org/10.1016/j.tifs.2013.08.002.

This page intentionally left blank

CHAPTER

18

What mining the text tells about minding the consumer: the changing fruit and vegetable consumption patterns and shifting research focus

Wojciech J. Florkowski[1] *and István Takács*[2]

[1]Department of Agricultural and Applied Economics, College of Agricultural and Environmental Sciences, University of Georgia, Athens, GA, United States [2]Keleti Faculty of Business and Management, Institute of Economics and Social Sciences, Óbuda University, Budapest, Hungary

Abbreviations

CAB Commonwealth Agricultural Bureau (now called the Centre for Agriculture and Biosciences International)
MCP 1-methylcyclopropene
USDA United States Department of Agriculture

18.1 Introduction

The benefits of eating adequate amounts of fruits and vegetables have been a focus of ongoing efforts of public health officials and a subject of public education campaigns (see also Chapter 19). Considerably less attention has been paid to the changes in what fruits and what vegetables are actually eaten and in what form. The basket of vegetables and fruits consumed currently is much different from a similar basket several decades ago, even disregarding the total consumed volume. Such changes directly impact the volume and type of fiber, vitamins, and other key nutrients directly affecting consumer health (see also Chapters 19 and 21). This chapter describes changes in fresh fruit and vegetable consumption using an illustration from the developed economy of the United

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00018-X

States. Consumer preferences exert a major influence on observed outcomes, and preferences are shaped by numerous factors and ultimately reflected in the market demand for fresh fruits and vegetables.

Besides the role of demand, the suppliers of fruits and vegetables actively pursue opportunities for sustained profits and continually adjust their offerings. What is being offered fresh, or what is available to consumers, results from the massive efforts in breeding (see Chapter 9 and 23), production (see Chapter 7), processing (see also Chapters 14 and 17), and logistics (see also Chapters 13, 16, and 18). Whether consciously or not, the actual efforts create value chains that result in what a consumer can find on the shelf in a retail outlet, realize in purchase, and eat at home. Enabled by the technique of text mining, this chapter supplements the illustration in changes of fresh fruit and vegetable consumption by examining the research focus of breeders, horticulturalists, physiologists, storage experts, and related fields through the analysis of keywords and phrases used in published research studies. On a limited scale, this approach attempts to find out if and to what extent factors that matter in consumer purchase and sustained consumption of fresh fruits and vegetables are addressed by researchers.

The vast scope of the research required narrowing the choice of examined topics to those that were identified in the Commonwealth Agricultural Bureau (CAB) database and only publications in that database could be taken into account, leaving potential gaps in some areas (e.g., locally important produce or research conducted in institutions with constrained resources). The limited length of the chapter restricted the number of individual fruits and vegetables, but fruits from both temperate and tropical areas have been included. Whereas various fruits are traded internationally, only a handful of vegetables (e.g., onion, tomato) are subject to trade on a large scale. However, the primary focus is changing consumer choices and the implications for postharvest research, or perhaps, the changing postharvest research and its implications for what and how much consumers eat.

Establishing the causal effect between postharvest research and consumption of fruits and vegetables is outside the scope of this chapter. Specifically, the description of per capita consumption changes of selected fresh fruits and vegetables is followed by the results of mining the content of abstracts of several thousand published studies in the CAB database. The text mining analysis is split into two periods, 2010–14 and 2015–19, that correspond to the periods between the second and third editions of this book and the third edition and the year in which the fourth edition is being prepared. The choice of the periods does not imply the immodest views of the importance of the subsequent revised editions but creates well-defined periods with a manageable, relevant number of studies that can be analyzed. Graphic color analysis that is an integral part of presenting the text mining analysis results and corresponds to the colors assigned to each of the four main parts of the book (see Table of Contents). The assignment of various keywords to a specific category is arbitrary (see the Appendix), but that simplified approach permitted the graphic summary of the results. Ultimately, the established relative importance of keywords selected by researchers in the published studies and the links among them depict the emphasis of research in the two periods. That emphasis indicates what issues, important to consumers directly or indirectly, were addressed leaving the question of what is missing and why to the reader.

18.2 Changing fresh fruit and vegetable consumption

Individual consumers choose the fruit or vegetable they eat guided by their personal preferences. Monitoring individual consumption is nearly impossible, forcing the use of approximations based on available data. In this section, individual changes in consumption are tracked by per capita consumption data generated by the United States Department of Agriculture (USDA). Since data collection is expensive and the chapter length is finite, the illustration of changing per capita consumption involves only a few fruits and vegetables. The purpose of the exercise is to show that there is a constant change in the volume of consumed fruits and vegetables and it is consumer choice that requires a continuous adjustment in postharvest research.

18.2.1 Per capita fruit consumption

Figs. 18.1–18.5 show per capita consumption of 20 fruits in the United States. The presented changes show that the basket of fresh fruits eaten in the United States has been changing over time. It is specific to a single country, but the specific fruit and volume consumed has been subject to change in many other countries.

Citrus fruits have been popular with consumers for decades. Fig. 18.1 shows that per capita consumption of oranges decreased by about one half between 1970 and 2018. Since oranges were among the fruits eaten in the largest quantities, the 50% drop in consumption is a major issue for the industry, but the decrease in grapefruit consumption has been even larger. Grapefruit consumption may have suffered due to the increase in high blood pressure cases in the United States because grapefruit nutrients adversely affect medication to treat high blood pressure (e.g., Kiani & Imam, 2007). The growth in per capita tangerine consumption (includes mandarins and other similar fruits) took off after 2000 and accelerated since about 2010. The popularity of that citrus category results from breeding

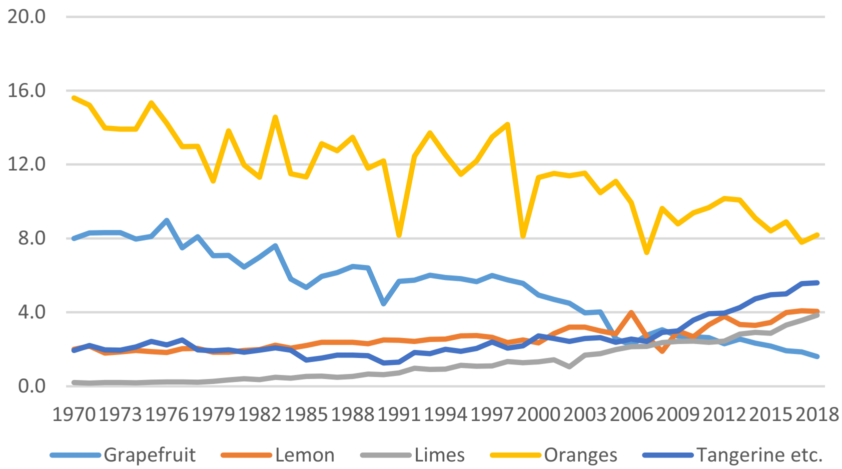


FIGURE 18.1 Per capita grapefruit, lemon, lime, orange, and tangerine consumption in the United States, 1970–2018. Source: *Based on USDA data.*

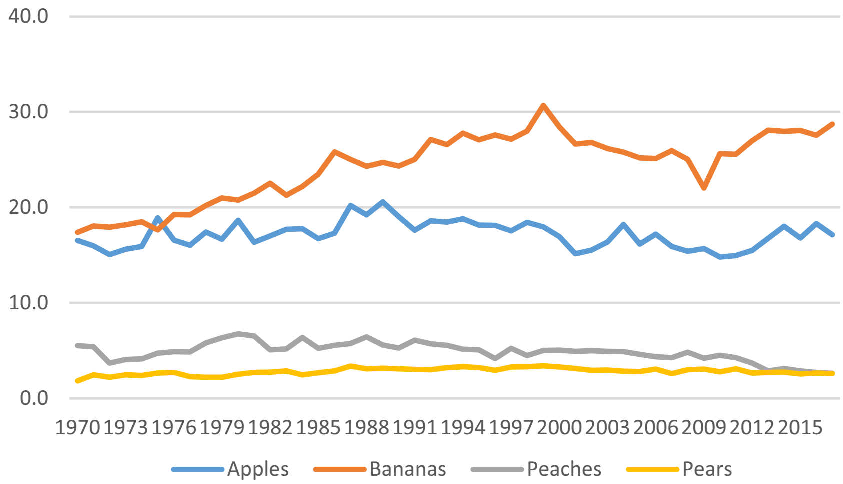


FIGURE 18.2 Per capita apple, banana, peach, and pear consumption in the United States, 1970–2018. Source: *Based on USDA data.*

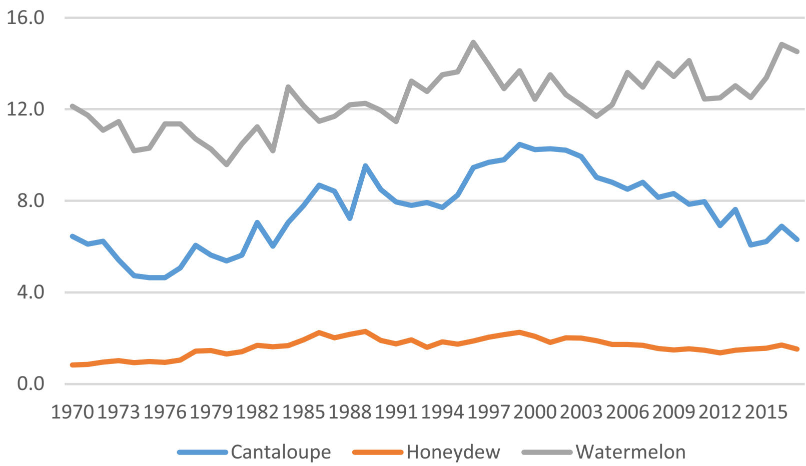


FIGURE 18.3 Per capita cantaloupe, honeydew, and watermelon consumption in the United States, 1970–2018. Source: *Based on USDA data.*

and postharvest research that permitted the supply of fruit meeting consumer expectations regarding convenience and flavor, two features contrasting with orange and grapefruit. The size and ease of pealing may encourage children to eat fresh fruit (Kurzer, Bechtel, & Ginard, 2019). The increase in lemon and, especially, lime consumption is influenced by the changing ethnic composition of American society.

Fig. 18.2 shows changes in per capita consumption of apples and bananas, two leading fresh fruits in terms of the annual volume consumed. Apple consumption remains relatively stable, but the figure does not capture the fundamental change in the varieties offered to today's consumer. Maintaining the apple consumption level has been associated with major breeding and postharvest research. The flavor of apples is specific to a variety.

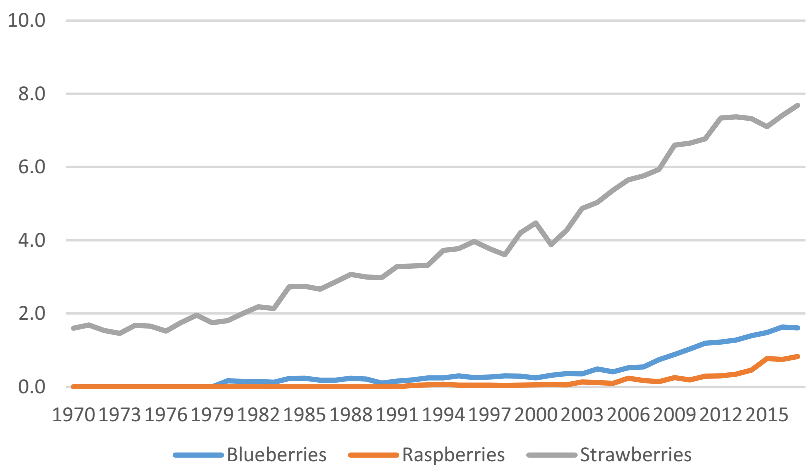


FIGURE 18.4 Per capita blueberries (1980–2018), raspberries, and strawberries consumption in the United States, 1970–2018. Source: *Based on USDA data.*

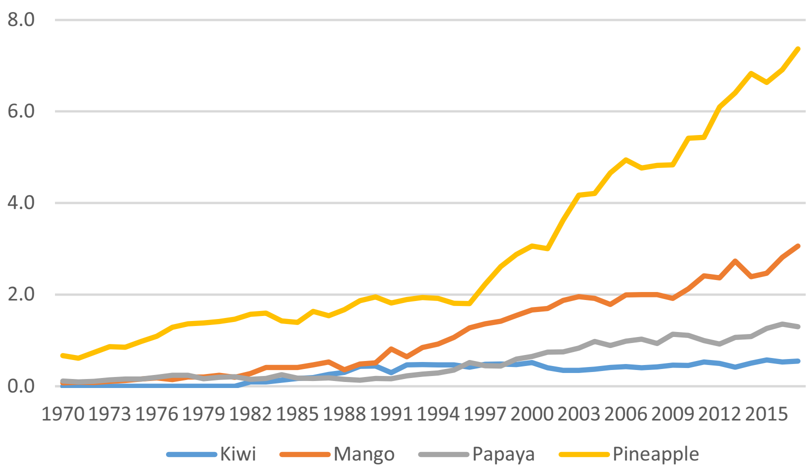


FIGURE 18.5 Per capita kiwi, mango, papaya, and pineapple consumption in the United States, 1970–2018. Source: *Based on USDA data.*

Bananas, the most popular fresh fruit, has been consumed in a steadily increasing volume. The postharvest handling of the fruit assures a consistent, predictable eating quality. The growth occurs with virtually no change in the type of fruit found at retail worldwide although the growth may be decelerating in the developed countries (Evans, Bollen, & Siddiq, 2020).

Fig. 18.2 also shows per capita consumption of two other temperate zone fruits: peaches and pears. Pear consumption has been fairly steady, but the offered variety has increased with new varieties expanding that category and likely a result of breeding and postharvest research. Per capita peach consumption, in turn, has shown a gradual but steady decline (Fig. 18.2). Canned peach consumption has declined, but domestic fresh peach production has been decreasing as well. Peach eating quality varies because of the number of different cultivars in commercial orchards and postharvest handling challenges. Production has been limited by the requirements to shift orchards due to soil pest buildup. Postharvest research has been focused on delivering the aromatic, tasty fruit, while breeding efforts continue to improve disease and pest resistance. Flat fruit and white flesh peach varieties have broadened that fruit category, but their effect on per capita consumption is yet to be confirmed.

Melon consumption has grown since 1970 (Fig. 18.3), but growth periods are different for each type of melon. Only watermelon consumption has shown an increasing tendency, while cantaloupe and honeydew per capita consumption has decreased or stalled since 2000. It is plausible that inconsistent eating quality of cantaloupe and honeydew contributed to that decline as well as incidences of illness outbreaks (Walsh, Bennett, Mahovic, & Gould, 2014). Both types of melon eaten outside the season are imported and appear to underperform. Breeding for consistent eating quality may be needed to reverse the tendency but requires resources. Watermelon in particular has been a focus of breeding efforts due to its economic importance in developing and developed countries (e.g., Huh, Choi, & Kim, 2014). The timing of harvesting is crucial, while placing the melons on the retail shelf is also critical. Melons are used in freshcut fruit salads because their colors are attractive, but freshcut fruit is a niche market item.

Per capita melon consumption contrasts with another fresh fruit category, berries. Fig. 18.4 shows the steady increase in strawberry consumption that more than quadrupled since 1970. The growth accelerated since 2000 and was supported by the progress in breeding, production practices, and postharvest handling. Currently retailed strawberries are not only visually appealing but have a fairly consistent eating quality that meets consumer expectations. However, in terms of per capita consumption, blueberries have registered even more impressive gains (Fig. 18.4). Their consumption was not reported until 1980, but the tremendous progress in breeding highbush and rabbiteye varieties combined with improvement in production practices led to the expansion of the domestic industry and the subsequent transfer of that expertise to countries across the world. Consumers whose demand for the fruit has yet to be fully met have noticed the combination of convenience, consistent flavor, and absence of spoilage (see also Chapters 17 and 20). Similarly, the breeding progress of raspberry varieties into firmer and tastier fruit that is also convenient to eat has produced fast growth in per capita consumption in the last decade. Postharvest handling, including cooling and short-term storage, heavily contributed to the growth of berry consumption (see also Chapters 5 and 11). Health-protecting compounds in berry crops are an important feature (e.g., Franck et al., 2020; Basu, Nguyen, Betts, & Lyons, 2014; Rocha, Silva Caldas, Pereira da Silva, Hermsdorff, & de Cássia Gonçalves Alfenas, 2018) in this fruit category popularity (see also, Chapters 19 and 21).

Fig. 18.5 shows per capita consumption of fruits that are mostly imported to the United States. The consumption of all four fruits shows a growing tendency albeit at different rates. Kiwi consumption has been increasing steadily and its flavor and internal appearance continue to appeal to consumers. The growing consumption of papaya and mango results from the improvement in postharvest handling of new cultivars as well as the increasingly diverse ethnicity of consumers. Pineapple consumption as a fresh, not canned, fruit has increased once the new varieties assured consumers of consistent flavor. Consumer preference for all four fruits is driven by their flavor and growing familiarity with the fruit.

Overall, per capita consumption of fruits has been undergoing substantial changes that can be summed up in the statement that “your fruits are not your grandfather’s fruits.”

Apples and bananas remain the most consumed fresh fruits, but competition from berries and tropical fruits has been increasing. A factor such as the chemical composition in the case of grapefruit may contribute to the consumption decline. Grapefruit compounds can interfere with the metabolization of drugs as well as the absorption of drugs resulting in adverse effects in humans. With the lengthening of life expectancy and growing number of older individuals managing their chronic diseases through drug therapy, the consumption of grapefruit has declined in some groups of consumers.

18.2.2 Per capita vegetable consumption

Minute changes in consumption may go unnoticed over time. The changes affect individual products and occur within the categories. From a standpoint of a fresh vegetable marketer, the individual product sales decline may not imply a decline of the category sales. Fig. 18.6 shows the slow decline in cabbage consumption and the tendency to increase consumption of broccoli until 2014 (the year the third edition of this book was published) when the average American ate more broccoli than cabbage. In 2018, the combined consumption of both was roughly equal to the consumption of cabbage alone in 1960. The steady decline in cabbage consumption was offset by the increase in broccoli consumption suggesting that as a category, Brassica fresh vegetables remained important. However, in terms of the postharvest, each vegetable posed a different challenge, including storage, appearance, and handling in distribution. Broccoli can be stored for shorter periods of time, its appearance matters more, and handling requires more attention than cabbage. Therefore broccoli is costlier. More importantly, from a consumer standpoint, broccoli is easier in preparation to eat at home than cabbage and preparation generates less waste. Consumer choice of what to eat has profound consequences on the volume of specific nutrients. Both raw *Brassica* vegetables supply major water-soluble vitamins and dietary fiber, and broccoli is higher in calories.

Fig. 18.7 shows per capita consumption of carrots and cucumbers. Carrots supply a precursor of vitamin A, a vitamin often undersupplied in the diet with severe consequences

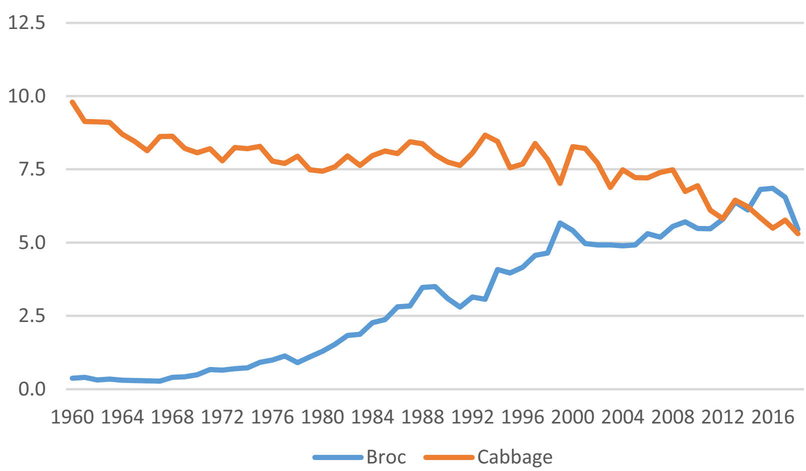


FIGURE 18.6 Per capita broccoli and cabbage consumption in the United States, 1960–2017. Source: *Based on USDA data*.

for human development and health. Until the late 1980s, consumption changes little, but the development of technology enabling the production of "baby carrots" led to a rapid increase by the mid-1990s. In recent years, consumption remains fairly steady at a level observed in the late 1980s. "Baby carrots" are intended to be eaten raw and sold as ready-to-eat responding to the consumer preference for convenience. Cucumber consumption began to increase in the mid-1970s and continues to grow. It is possible that cucumber popularity results from the lack of microbial contamination issues observed in the case of several other common vegetables. In recent years, a new variety of cucumbers produced in greenhouses has been offered at retail at a higher price than conventional cucumbers. In the United States, consumers buy cucumbers to eat as a salad ingredient since home pickling has largely ceased. The category of salad vegetables has been trending upward in the volume consumed as the lifestyle and eating habits place premium on convenience, avoidance of cooking, and speed of serving.

Major consumption changes have been associated with the introduction of Romaine lettuce and result from breeding and production developments and effective postharvest handling. The USDA statistics did not report Romaine lettuce until 1985, just before per capita iceberg lettuce reached its peak (Fig. 18.8). After years of little change in the category of lettuce, the appearance of Romaine lettuce and its ease in handling compared with iceberg lettuce (less waste) has found appeal with consumers. As the decade of the 1990s began, iceberg lettuce consumption started to decrease. By 2016 the consumption of both types of lettuce was about equal as the iceberg lettuce trended downward and Romaine continued to grow despite the latter being more expensive. There are other varieties of lettuce also sold at retail in the United States but are sold in smaller volumes and may be available only intermittently.

The rapidly growing per capita consumption of spinach was observed between 1995 and 2005 (Fig. 18.9). Since then, per capita spinach consumption initially declined but has stabilized in recent years. Per capita radish consumption seems to be holding relatively

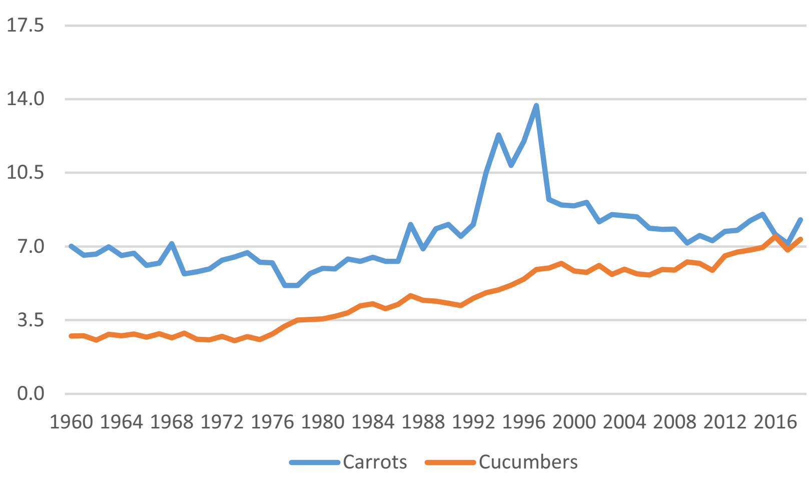


FIGURE 18.7 Per capita carrots and cucumbers consumption in the United States, 1960–2017. Source: *Based on USDA data.*

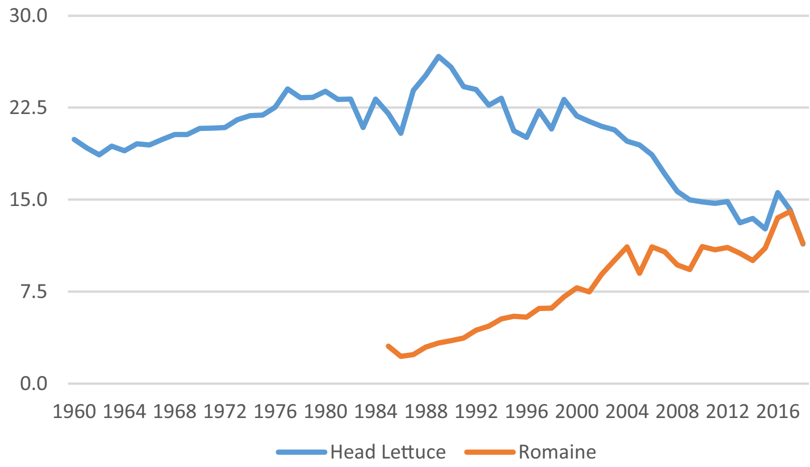


FIGURE 18.8 Per capita head lettuce (1960–2017) and Romaine lettuce (1985–2017) consumption in the United States. Source: *Based on USDA data.*

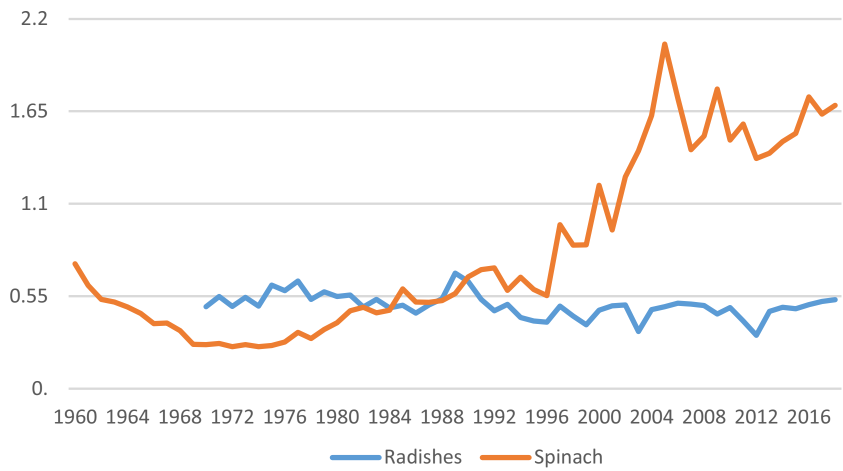


FIGURE 18.9 Per capita radishes (1969–2017) and spinach (1960–2017) consumption in the United States. Source: *Based on USDA data.*

steady. It is not a major vegetable in the United States and is now consumed mainly as a raw salad ingredient rather than cooked vegetable.

The major salad trio, tomatoes, peppers, and onions (Fig. 18.10), are eaten in the largest quantities. Tomatoes and onions in particular are probably the most popular vegetables across the world and eaten both fresh and cooked. The available data show an upward tendency in per capita tomato consumption that is less than that of onions. Per capita onion consumption showed some wide fluctuations, especially after 2000. Onions have become a category because there is a variety of onions offered at retail but the available data do not distinguish between yellow, red, white sweet, and other onion varieties.

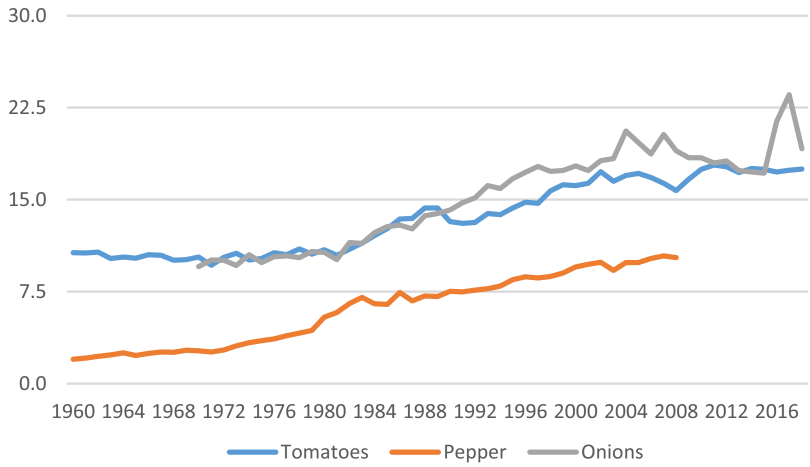


FIGURE 18.10 Per capita tomato (1960–2017), pepper (1960–2009), and onion (1969–2017) consumption in the United States. Source*: Based on USDA data.*

Only among sweet onions, there are several different varieties on sale at American supermarkets, differentiated mostly by the place of origin. The available data for per capita pepper consumption show fairly consistent growth. In recent years, the variety of peppers offered at retail in the United States has markedly increased, possibly due to the increasing ethnic diversity of consumers and the resulting multiplicity of uses.

18.3 Selection of fresh produce

The discussion of per capita consumption of selected fruits and vegetables is driven by the availability of data. Since such data were available for an extended period from publicly available sources, they are used to illustrate the steady dynamic changes in consumption. A number of economic and noneconomic factors induce the changes. However, a major force is the ability of postharvest value chains to provide fresh produce that meets consumer eating preferences on a sustained basis.

The number of factors and their interactions in the market of fresh produce prevents clear distinctions of causal relationships over a protracted period because the tracked data lack sufficient detail. Therefore the conducted analysis serves as an illustration of the possible relationships between research relevant to postharvest and the implicit source of changes in the consumption of fruits and vegetables. The selected produce can be eaten fresh or processed, but since the share of fresh consumption varies across specific produce and may vary seasonally and over time, it is assumed that the focus of research is primarily fresh consumption.

18.4 Application of text mining to postharvest research analysis

Research is communicated through written means, primarily through articles in peer-refereed journals. An essential element of a journal article is an abstract that succinctly informs the reader about the objective, method, data, and results of research. Publication in a scientific journal is preferred to other written forms because its short character permits faster publication than the book format. Publication requirements force knowledge resulting from research to be subjected to the process of critical review. In addition, the common system of researcher evaluation requires publishing, making refereed journal articles a primary goal of researcher efforts.

Information in the form of text accounts for the estimated 85% of all business information. Assuming that the research related to postharvest research of fruits and vegetables is also primarily contained in journal articles, this chapter focuses on discerning the relevance of such research to issues relevant to the consumer, the ultimate recipient of fruit and vegetable value chains.

The choice of research topics and objectives are made by the researcher and this chapter is exploratory in nature because it is limited to a single database and search for keywords constraining its scope. The purpose is to extract information and search for patterns in abstracts of refereed journal articles. Such patterns may be hidden and reflect the research objectives of the published articles. The extracted information focuses on identifying articles that address an issue related to postharvest. The search of patterns widens the objective by linking keywords and concepts showing the association of postharvest-relevant research directions. This structured approach allows the use of color figures to visualize the relative importance of selected words and concepts providing insights about what was of interest in past research but also indicates what words and concepts were absent, reflecting the lack of research in some areas pertinent to postharvest. The results of the search for patterns follow in the graphic portrayal of identified links showing usage frequency of specific words and concepts and their association in the form of clusters. The graphic representation indicates the direction between words providing insights whether the directional effects are consistent with postharvest research.

The list of keywords focused on their postharvest relevance. The list prepared initially by the authors was reviewed by two coeditors of this edition prior to the search. The final list contained 341 words (see Appendix) divided into groups corresponding to the four main parts of the book (Part I Whole system—group 1, Part II Product—group 2, Part III Processes—group 3, and Part IV Perceptions—group 4). Since every part encompasses closely related topics reflecting the systems thinking approach, each was assigned a specific color:

whole system—yellow
product—orange
processes—red
perceptions—green

The colors of each part correspond to the illustration on the book's cover capturing the systems approach that originates and ends with focus on the fresh produce consumer. Group "0" lists words and expressions that could be relevant to more than one of the four identified groups and its word color is black. The words identified from each group assume the group color in the graphic presentation summarizing the text mining. The word size on a figure indicates its relative importance in the examined postharvest research, while the word color provides an additional dimension signaling the area of postharvest research and its relative placement within the four areas or parts of the book.

18.4.1 Selected fruits and vegetables as the focus of the published postharvest research

There is an upward trend in the number of postharvest research publications on fruits and vegetables in CAB database indicated by the 11.4% increase in the published abstracts between 2009–14 and 2015–19. The upward trend coincides with the growing global fresh produce production and consumption. However, a close examination of the publications in the CAB database suggests that the amount of interest in performing research on produce depends on the category of fruits or vegetables considered in Table 18.1. For example, the category of citrus fruit shows a decreasing trend in the number of publications, while the category of berries is characterized by a strong increase in research interest. Furthermore, the number of publications pertaining to a specific fruit or vegetable can buck the overall trend in a category. For example, the number of publications on the postharvest of grapefruit increased (41.1%) between the two periods, although the number of publications in the category has been decreasing. Similarly, the number of publications on postharvest of cabbage increased by 40.7%, considerably more than those on broccoli (increase of 22.2%). Both grapefruit and cabbage per capita consumption have been steadily decreasing in the United States, but not necessarily in the world as a whole. This distinction should be kept in mind when reading the rest of this chapter, which focuses on illustrating the link between consumer choice (per capita consumption in the United States), the fruit and vegetable postharvest research (the number of publications), its focus

TABLE 18.1 Number of studies about selected fruits and vegetables in the periods 2010–14 and 2015–19 identified for the text reviewing analysis.

Fruits				**Vegetables**			
Fruit	2010–14	2015–19	Percentage change	Vegetable	2010–14	2015–19	Percentage change
Apples	752	722	−4	Artichoke	22	9	−59
Bananas	320	288	−10	Broccoli	108	132	+ 22
Blueberries	81	119	+ 47	Cabbage	54	76	+ 41
Cherries	149	272	+ 83	Freshcut	17	13	−24
Grapefruit	41	55	+ 25	Iceberg lettuce	27	21	−22
Grapes	302	353	+ 17	Kale	13	19	+ 46
Kiwi	129	158	+ 22	Onion	119	111	−7
Oranges	329	326	−1	Potatoes	287	338	+ 18
Peaches	334	332	−1	Radishes	24	31	+ 29
Pears	283	353	+ 25	Romaine lettuce	19	20	+ 5
Strawberry	252	328	+ 30	Spinach	54	74	+ 37
Tangerines	161	123	−24	Sweet onion	2	1	−50
–	–	–	–	Tomatoes	495	599	+ 21

(the frequency of words and terms), and examples of groups of researchers publishing their postharvest results. The observed tendencies indicate the continuing change in the relative importance of fruit and vegetable categories and their individual species, the shifting focus of research stimulating consumption, or of research aimed at reversing decline in consumption, and the location or geographical scope of postharvest research. The final outcome of those interacting forces is the improvement in handling fresh produce and enhanced quality, even if the initial objective of the research was not explicitly to satisfy the consumer.

Apples have been the most frequent subject of the published postharvest research (Table 18.1). The number of published articles shows the largely sustained effort in researching apples between the two time periods. The research interest reflects the widespread consumption of apples not only among consumers in Europe, Australasia, and North America, but increasingly in Asia and Africa, including tropical countries where apple production is unlikely (see, e.g., Florkowski et al., 2014). The economic importance of the apple sector is also reflected in the projected continuing growth of world apple production at 4% in the period 2021–26 (Mordoerintelligence.com, 2021). More importantly, the breeding of new cultivars (see also Chapter 9) and improved storage assisted by sorting technology (see also Chapters 14 and 15) permits apple value chains to deliver apple fruit with superior appearance and flavor virtually year-round. The once fairly homogenous product has been altered by breeding and postharvest research establishing cultivar-specific growing, harvesting, and handling protocols, and in some cases, patents or licenses are granted for new apple cultivars. In the United States (Fig. 18.2), per capita consumption of apples has been flat, but what the data do not show are the differences in the cultivars being consumed. The once standard "Red Delicious" was replaced with several new cultivars. All those activities result in widely expanded consumer choices and access to a variety of fresh fruit. The lack of systematic data prevents the consideration of the sources of funding, private versus public, or the political influence exerted by the sheer number of growers and crop value, but those factors likely play an additional role in guiding the postharvest research.

The research interest in bananas, the most frequently consumed fruit in the United States (Fig. 18.2), shows a considerably lower number of research publications (Table 18.1). Banana fruit offers few market opportunities for differentiating the product and the category remains fairly homogenous as compared to apples. In addition, the vertical integration of banana value chains limits competition, and postharvest research in public institutions dominates among the published analyzed reports. Finally, the banana sector is subject to regulations dictating the type of fruit and even its origin, effectively limiting the focus of breeding and postharvest research. There was some decline in the number of published articles between the two periods, that is, 2009–14 and 2015–19, but overall the number of articles was quite high. Banana is the most traded fruit in the world [25% of production is traded internationally] with the temperate zone countries being the primary shipping destination. It is of consistent quality, convenient to eat, and has been competitively priced; surpassing in per capita consumption the main temperate zone fruit—the apple. It seems that every supermarket offers this fruit daily.

Surprisingly, the number of research publications on two fruits experienced a noticeable decrease (about 50%) in per capita consumption in the United States (Figs. 18.1 and 18.2).

Declines of per capita consumption of oranges and peaches indicate that they should be prioritized as fruits needing new research paradigms as described in Chapter 2. Interdisciplinary research teams representing all value chain links could use interactive systems thinking methodologies to learn the desirable and feasible postharvest changes required to provide consumers with affordable flavorful fruit. In contrast, the number of publications on postharvest of oranges and peaches held steady over time. The number of research articles for both fruits is very similar although oranges are consumed in higher per capita volume than peaches in the United States. Each fruit falls in a different category: oranges are managed as a citrus, while peaches as a stone fruit in distribution and retail, but have been a mainstay in the fruit and vegetable section in supermarkets. Both fruits are consumed globally and new cultivars have been developed in recent decades diversifying those fairly homogenous fruit categories and increasing their production. It appears that the postharvest research will continue worldwide, while the consumption trends in various regions and countries may suggest the opposite.

Overall, postharvest research yielded numerous articles on four fruits that experienced no growth or a decline in per capita consumption in the United States in recent decades (orange, grapefruit, peach, and apple). An outlier in the context of published articles and unremarkable per capita consumption is the pear. Pear consumption has been relatively small in the United States (Fig. 18.2), but the number of research papers related to postharvest of this fruit has increased by 25% between the two periods (Table 18.1). Such growth in research signals increased research intensity, possibly stimulated by an influx of funding across the world. That development is worth monitoring because it could indicate an increase in availability of competitively priced new cultivars (e.g., Florkowski & Łysiak, 2015), tastier fruit, improved appearance, and easier storage and postharvest handling. Appearance of some of the existing cultivars (lack of or slow color change as the fruit ripened) poorly signaled to consumers the best eating quality and possibly reduced purchases. However, like peach, a juicy pear may compromise eating convenience.

Considering the relative change in importance of postharvest research of specific fruit measured by an increase in the percentage of articles published in the period 2015−19 as compared to 2009−14 shows that the growth corresponds to an increase in per capita consumption of berries as a category and in terms of individual fruits. Per capita consumption of strawberries increased by 23% in the period 2009−14 as compared to 2008 and another 5% between 2015 and 2017, while blueberry per capita consumption (Fig. 18.4) doubled in the period 2009−14 and increased another 14% between 2015 and 2017, the last year for which the data were available. At the same time, the number of publications on their postharvest increased by 30.2% and the whopping 49.6% about strawberries and blueberries, respectively, between the two periods (Table 18.1). Per capita consumption of raspberries and blackberries also increased (Fig. 18.4). The berry category is growing and driven by the flavor, appearance, and versatility of the fruits. The reports about the health-promoting ingredients found in berry fruit will continue to stimulate demand (e.g., Carew, Florkowski, & He, 2005), while the expansion in production and improvement in postharvest handling contribute to competitive pricing of berry fruits. The convenience of eating berries and their appearance will appeal to an increasing number of consumers. This is the category of the future in every major retail outlet selling fresh produce.

If grapes fall into the berry category, then the interest in their postharvest research has been increasing at a respectful pace between the two periods (Table 18.1). Grapes gained publicity when resveratrol was identified in red wine, but grapes and several berry fruits are the source of this compound. Table grape consumption is likely to grow and postharvest research will be needed to develop handling protocols for various varieties under different handling conditions across climate zones. It was progress in postharvest research, including short-term storage and breeding new cultivars, that contributed to an increased per capita cherry consumption (Fig. 18.5). The number of publications on cherries increased by 82.6%, more than any other fruit or vegetables listed in Table 18.1. Cherry production expanded to the southern hemisphere expanding its availability to consumers and its flavor and convenience will keep attracting consumers.

The number of research publications on vegetable postharvest is dominated by tomatoes, and research interest has been increasing over time (21% increase; Table 18.1). Versatility of use of the tomato—botanically a fruit, not a vegetable—will continue in the foreseeable future. Its health-promoting ingredients will strengthen the consumption motives, and, likely, additional beneficial aspects of tomato eating will be discovered in the future. From the postharvest handling viewpoint, the increasing diversity of tomato varieties reflected in size, color at maturity, shape, and flavor will require additional research to generate advice to this expanding category.

The number of publications on lettuces has been decreasing over time, and this is best depicted by the decreasing tendency in the number of publications about iceberg lettuce (Table 18.1). The number of publications on Romaine lettuce is almost identical to that on iceberg lettuce in the period 2015–19 despite the growing per capita consumption of the former in the United States. Lettuce as a category includes other varieties and leafy greens and occupies a major place in the fresh produce section in supermarkets. The promotion of healthy nutrition includes fresh salads where lettuce is a major ingredient and green salads are an important side dish in food service and restaurant sectors. Spinach has been a focus of the published postharvest research with an increasing frequency (37% more publications in the period 2015–19). Its per capita consumption in the United States has fluctuated lately but spinach is increasingly eaten raw when mixed with other greens. A leafy vegetable gaining in popularity in the United States is kale and the number of publications listing kale increased over time although it remains small.

The interest in onions among the postharvest researchers remained steady between 2009–14 and 2015–19. Onions are an increasingly diversified category as the number of varieties increases and supply sources originate from both hemispheres. Onions are one of the most commonly eaten vegetables in the world and will remain a subject of postharvest research, especially as the trade in onions expands (Pânzaru & Medelete, 2013).

18.5 Results of mining published abstracts of postharvest research

18.5.1 When size matters: cloud graphs

The six figures (Figs. 18.11–18.16) show the relative change in frequency of the selected words representing any of the five groups (see the Appendix) in abstracts of publications

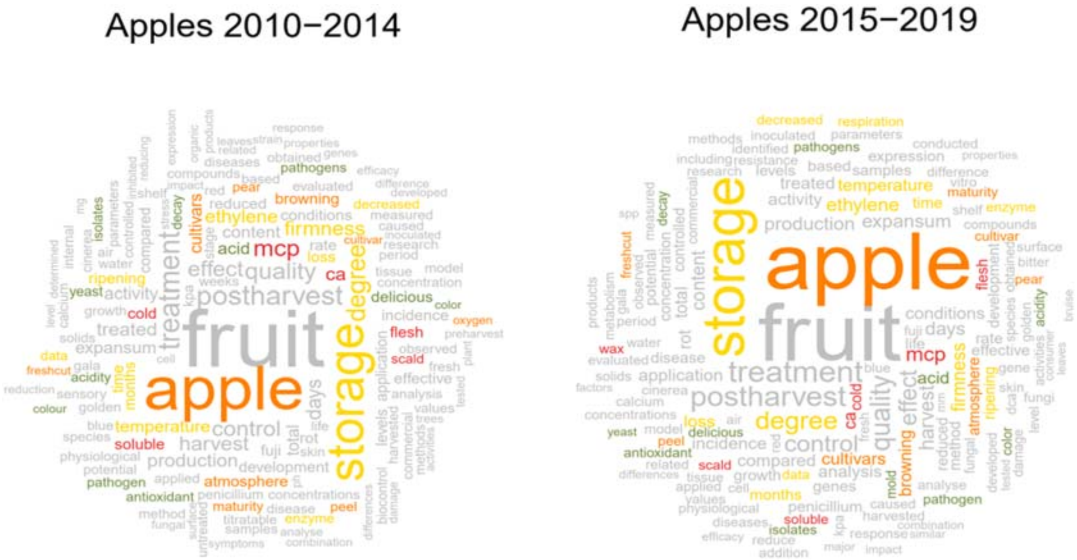


FIGURE 18.11 Relative frequency of words associated with postharvest research on apples in the sample of published abstracts. Source*: Authors.*

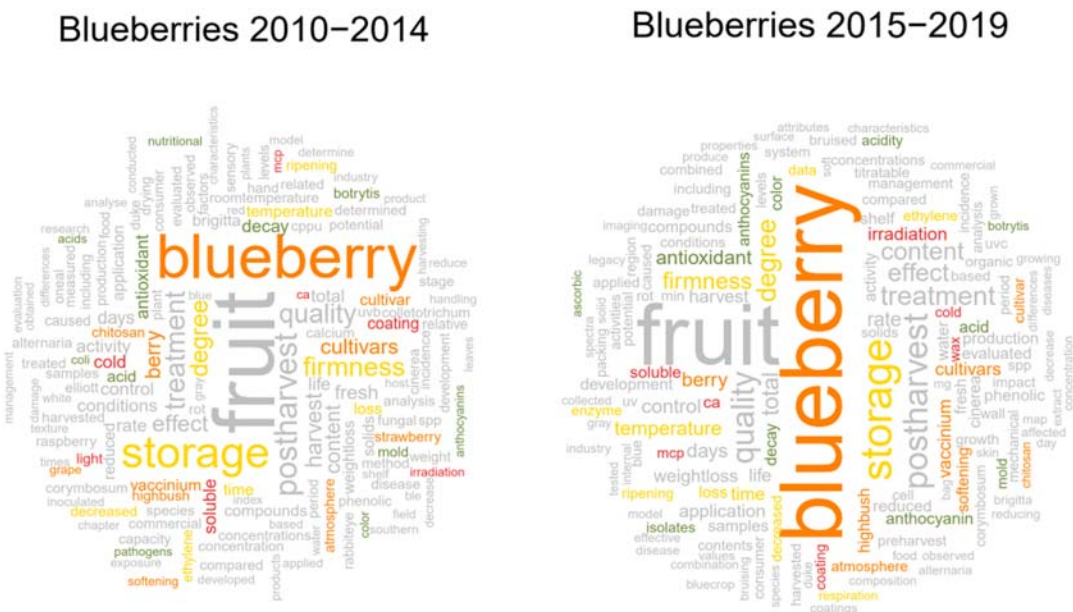


FIGURE 18.12 Relative frequency of words associated with postharvest research on blueberries in the sample of published abstracts. Source*: Authors.*

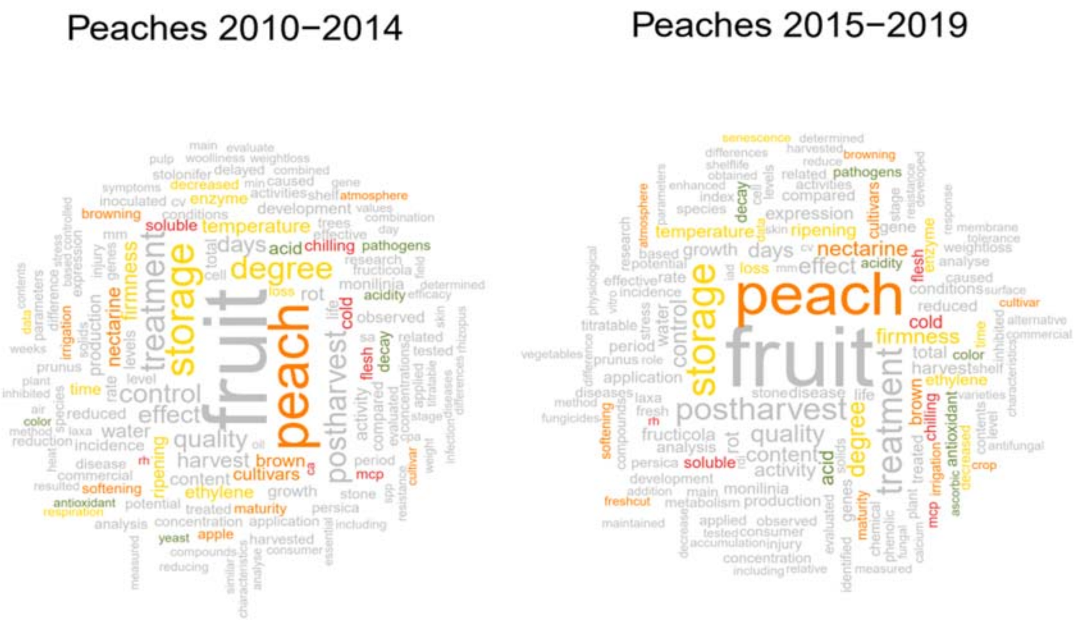


FIGURE 18.13 Relative frequency of words associated with postharvest research on peach in the sample of published abstracts. Source*: Authors.*

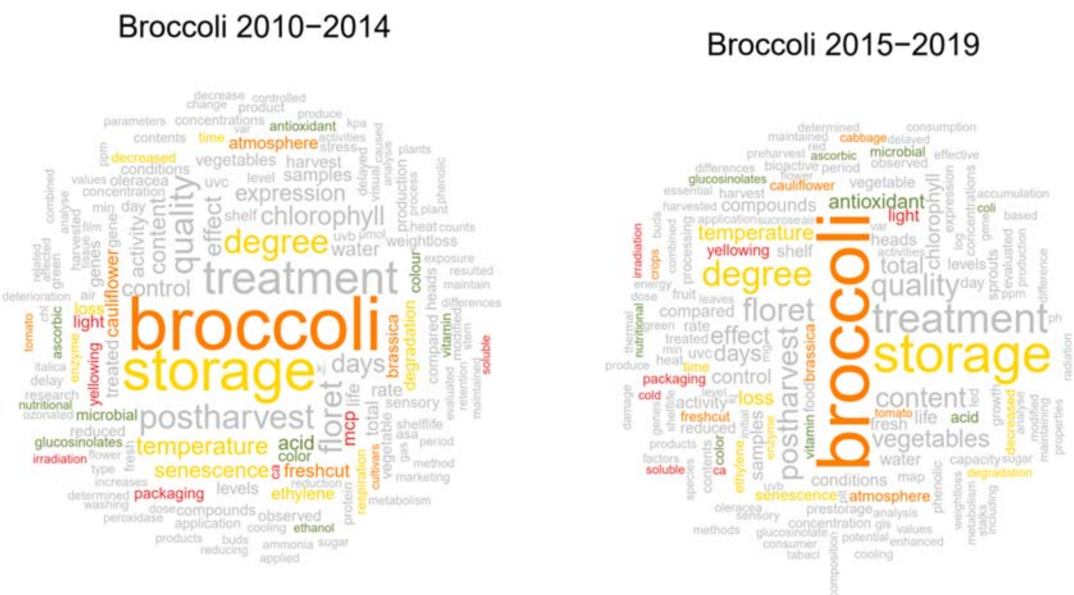


FIGURE 18.14 Relative frequency of words associated with postharvest research on broccoli in the sample of published abstracts. Source*: Authors.*

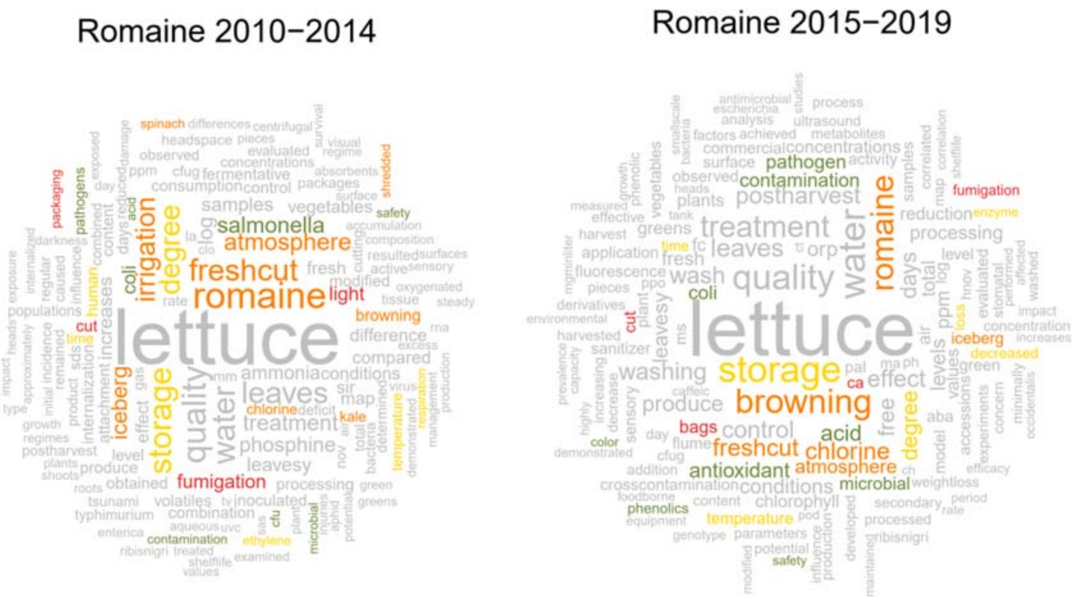


FIGURE 18.15 Relative frequency of words associated with postharvest research on Romaine lettuce in the sample of published abstracts. Source: *Authors.*

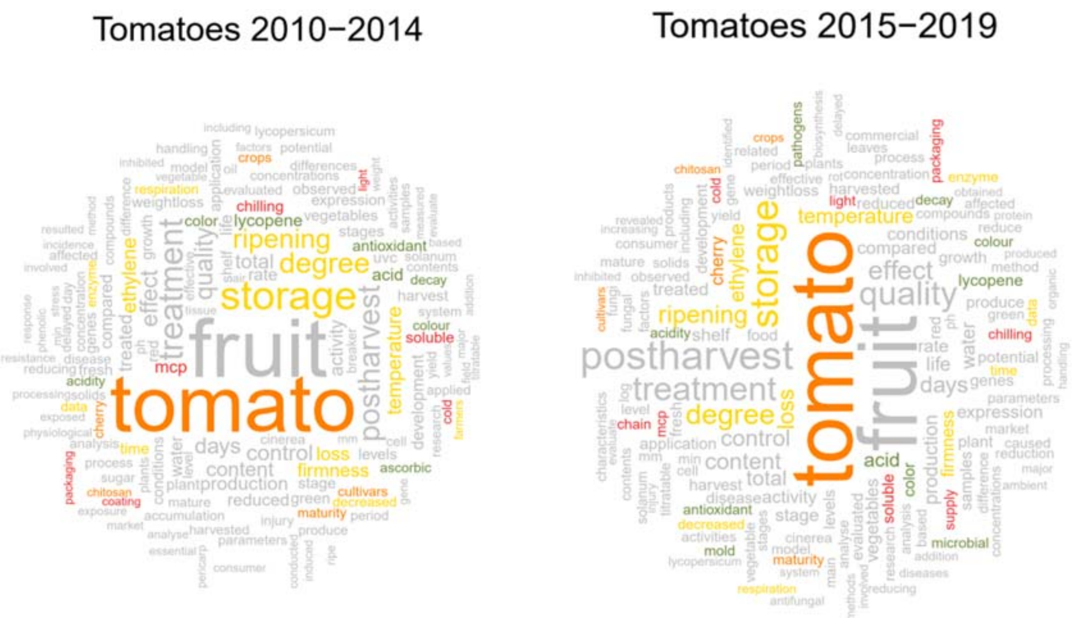


FIGURE 18.16 Relative frequency of words associated with postharvest research on tomato in the sample of published abstracts. Source: *Authors.*

from the periods 2009–14 and 2015–19. The relevant words are storage, quality, firmness, treatment, and 1-methylcyclopropene (MCP) in the case of apples. For example, storage and MCP treatment affect firmness, and firmness is associated with quality. There appears little difference in the focus of research between the two considered periods. Per capita consumption of apples remained fairly stable between 2009 and 2019 in the United States, yet research interest also remained steady with a largely similar focus.

Storage, firmness, and quality were among the most frequent words found in abstracts of published research on blueberries in either period (Fig. 18.12). The relative size of the words suggests fewer uses of the term "firmness" but more frequent use of the word "quality" in abstracts between 2015 and 2019 as compared to 2009–14. A slight shift in research is implied by "antioxidant" since the word is slightly larger in the panel representing research between 2009 and 2014 than between 2015 and 2019.

Storage, treatment, and quality stand out among the words used in research abstracts referring to peaches (Fig. 18.13) and published in the two analyzed periods. The word "firmness" was also used relatively frequently. Overall, the main research focus of the three fruits has changed little over time and emphasized storage, quality, and firmness. Storage is important because it provides flexibility in marketing fruit such as the delay of sale in periods of surging supplies during peak harvest. Firm fruit is associated with its freshness and may serve as a proxy for implying quality and flavor. Not surprisingly, it seems both commonly used words are related to fruit marketing potentially extending shelf life, making fruit available to consumers past immediate harvest. Fruit firmness is a quality attribute but its perception varies with fruit (e.g., firm apple vs soft peach) and may be valued differently by consumers.

The examination of figures depicting relative use frequency of words in abstracts of vegetable postharvest research shows a different emphasis than the case of fruit. In the case of broccoli (Fig. 18.14), the four words that appear to be used relatively often are storage, treatment, floret, and quality. Floret is a word specific to broccoli and an important visual attribute. Its condition and color signal freshness to consumers and imply the preferred flavor. The difference between the two periods is suggested by the relatively more frequent use of the word chlorophyll and senescence in the period 2009–14, while the word antioxidant and, to a lesser degree than earlier, chlorophyll have been used in abstracts published between 2015 and 2019. There appears to be a possible shift in emphasis away from the visual appearance to the ingredient contents in postharvest broccoli research over time. Such a shift would follow the typical initial importance of visual attributes as those driving sales, but sustained consumption is based on healthiness of product and that research could have been undertaken in response to decreasing consumption since 2015 (Fig. 18.6). The conclusion is tentative since the analyzed publications include international research (not limited to the United States).

Fig. 18.15 shows that the words quality, storage, freshcut, and water were relatively often used to report on Romaine lettuce postharvest research between 2009 and 2014. In the next period, 2015–19, a new word has appeared, namely, browning, while freshcut use has diminished. However, browning can be related to freshcut since it is likely associated with cut leaves. The words in both periods imply the importance of delivering quality with consumers in mind and are further evidenced by the use of the word "salmonella" in the first period and "coli" in the second period. Increased visibility of "antioxidant" suggests the increased research interest in Romaine lettuce health-promoting properties corresponding to consumer interest in healthy eating.

Fig. 18.16 shows the cloud plot regarding the frequency of words in the published abstracts from the postharvest research of tomatoes. The words "storage" and "treatment" seemed to be equally important in both periods as are the words "temperature" and "ethylene." "Ripening" was deemphasized in the period 2015–19, while the use of the words "quality" and "postharvest" became more frequent. Fresh tomatoes are traded internationally, especially in North America and in Europe, and the trade volume is subject to seasonal fluctuations.

Overall, several words dominating in the published abstracts of vegetable postharvest are identical to those in the postharvest fruit research and include "storage," "quality," and "treatment." However, several words, used less frequently pointed to the appearance, safety, and health-promoting attributes of vegetables. Those words are consistent with the choices motivating more often consumer purchase and likely will continue to increase in frequency. Expanding the searched database by including abstracts from other sciences, for example, food science, nutrition, or marketing could be worthwhile in the future.

18.5.2 When color matters: word use associated with the whole postharvest system (product, processes, and perceptions)

This section involves graphs showing the frequency of the most often used words in the postharvest publications of selected fruits and vegetables. The color of the bar corresponding to the use of a single word instantly signals the connection to a specific postharvest research area and the part of the book. As can be seen, there are a limited number of words directly associated with the Part IV—Perceptions, and possible benefits to consumer are indirect resulting from postharvest research in other areas.

Fruits. Apples continue to be the focus of much postharvest research between 2009–14 and 2015–19 as indicated by the word frequency scale (Fig. 18.17). The dominant issue is storage of apples driven by the fluctuating crop size, quality affected by pests and weather events, desire to maximize grower returns, desire to meet consumer preferences, and demand seasonality. Besides the obvious words, including storage, postharvest, or quality, the words indicating the focus of research frequently mentioned in the abstracts are MCP, firmness, and ethylene. However, the frequency of using those words has decreased between the 2015 and 2019 period as compared to the earlier considered period but have not been replaced by other terms suggesting a major change in the focus of research. Interestingly, the color-coded words suggest that research is focused on terms indicating the "product" and "process" falling under Parts II and III of this book. "Perceptions" (Part IV), implying concerns about consumers, are reflected only in the use of the word "acid," most likely influencing the taste.

Per capita blueberry consumption has been increasing rapidly in the United States (Fig. 18.4), and also worldwide. It is a result of expanding production of cultivated blueberry supported by access to capital and knowledge. Although the most often used words are the same in both periods (Fig. 18.18), the terms associated with healthiness of the fruit have been used with an increasing frequency. "Antioxidant" was among the top 10 words in abstracts published between 2015 and 2019, while the word "anthocyanin(s)" became a

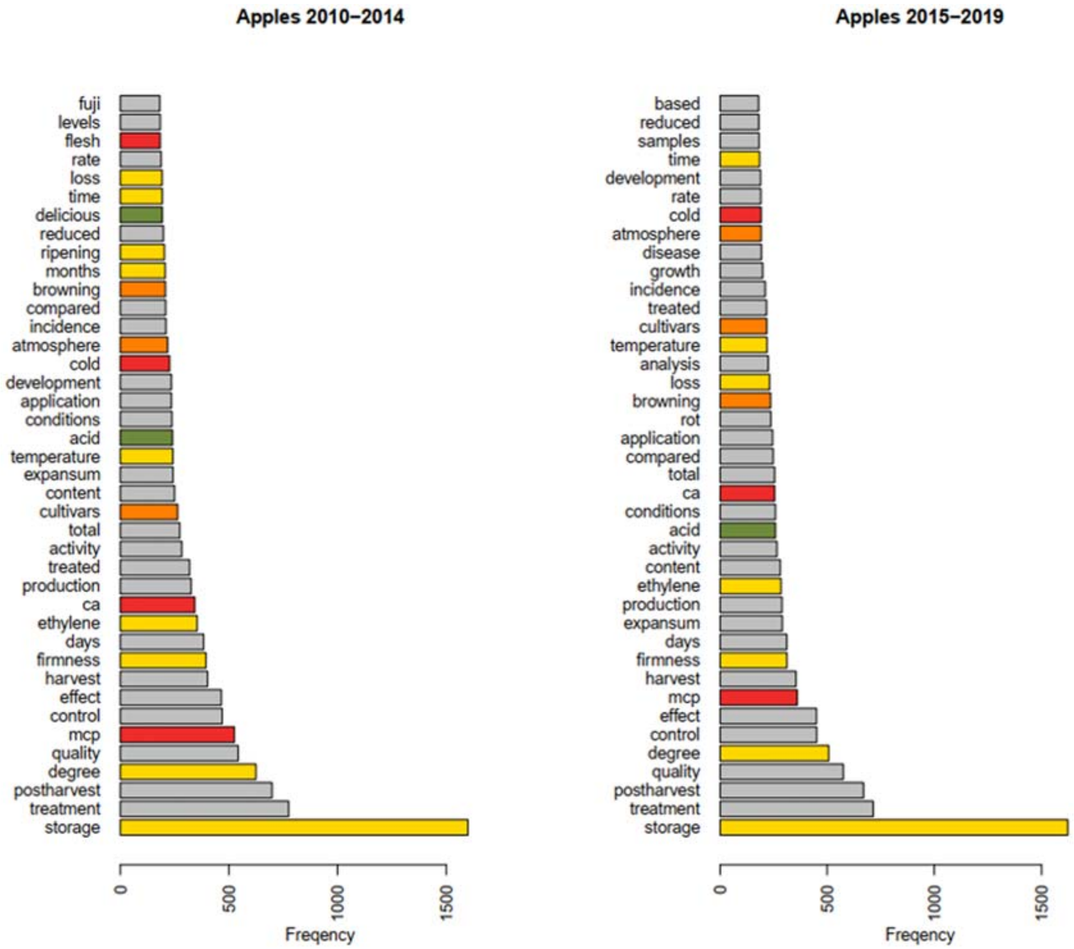


FIGURE 18.17 The frequency of words associated with postharvest apple research, by group [including four parts of the book: whole systems (yellow), product (orange), processes (red), and perceptions (green)]. Source: *Authors*.

new word, not listed in the previous period. Blueberry consumption reflects the preference of consumers for flavor and convenience in serving, but also health-promoting properties.

Per capita consumption of peach has been declining in the United States (Fig. 18.2), but not worldwide. The value of peach sales was estimated at $47.55 billion worldwide in 2018 (Mordoerintelligence.com, 2021). However, in terms of published postharvest research abstracts, the most often used words changed little between the two periods (Fig. 18.19). Besides the words associated with multiple research areas, words associated with the "whole system," "product," and "process" were used. However, use of the term "antioxidant" in the period 2015–19 is new and provides evidence of research relevant to consumer consumption motivation. The incentives for that type of research may reflect the rush toward examining

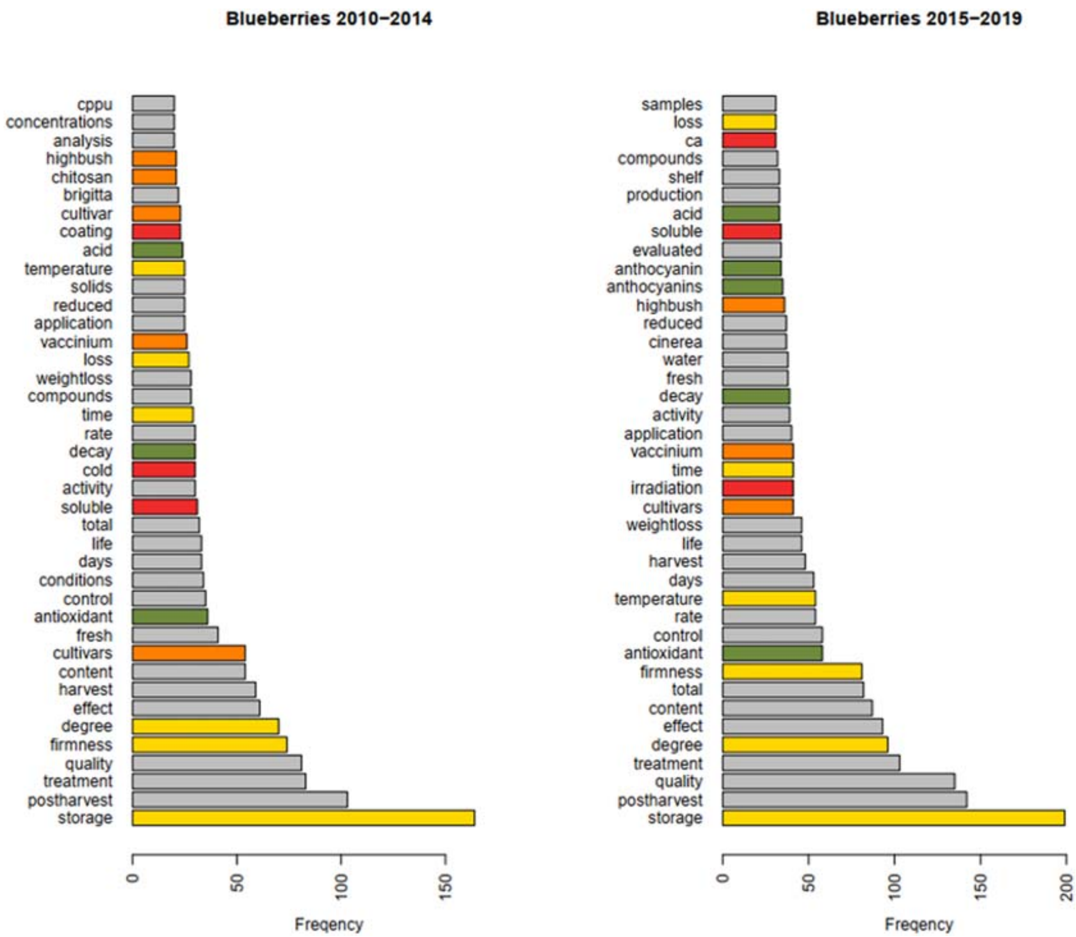


FIGURE 18.18 The frequency of words associated with postharvest blueberry research, by group (including four parts of the book: whole systems, product, processes, and perceptions). Source: *Authors.*

the health-promoting properties of fruits. Whether such research will stem the decline in the United States, consumption remains to be seen. The sheer number of publications (Table 18.1) suggests postharvest peach research is popular.

Vegetables. The frequency of words used in postharvest broccoli research is predominantly associated with any of the four groups in both periods (Fig. 18.20). However, in the period 2015–19, the term "antioxidant" is among the 15 most often used words. The growing body of research showing that eating vegetables benefits health and, in the case of broccoli, having potentially anticancerous properties likely stimulates postharvest research as well (e.g., Hwang & Lim, 2015). The distribution of various colors indicating word use frequency associated with any of the four parts of the book and the set of words classified as potentially linked to more than one group is shown in Fig. 18.20. The difference in color distribution is immediately visible between the multiple colors dominating the bottom of the column of words used

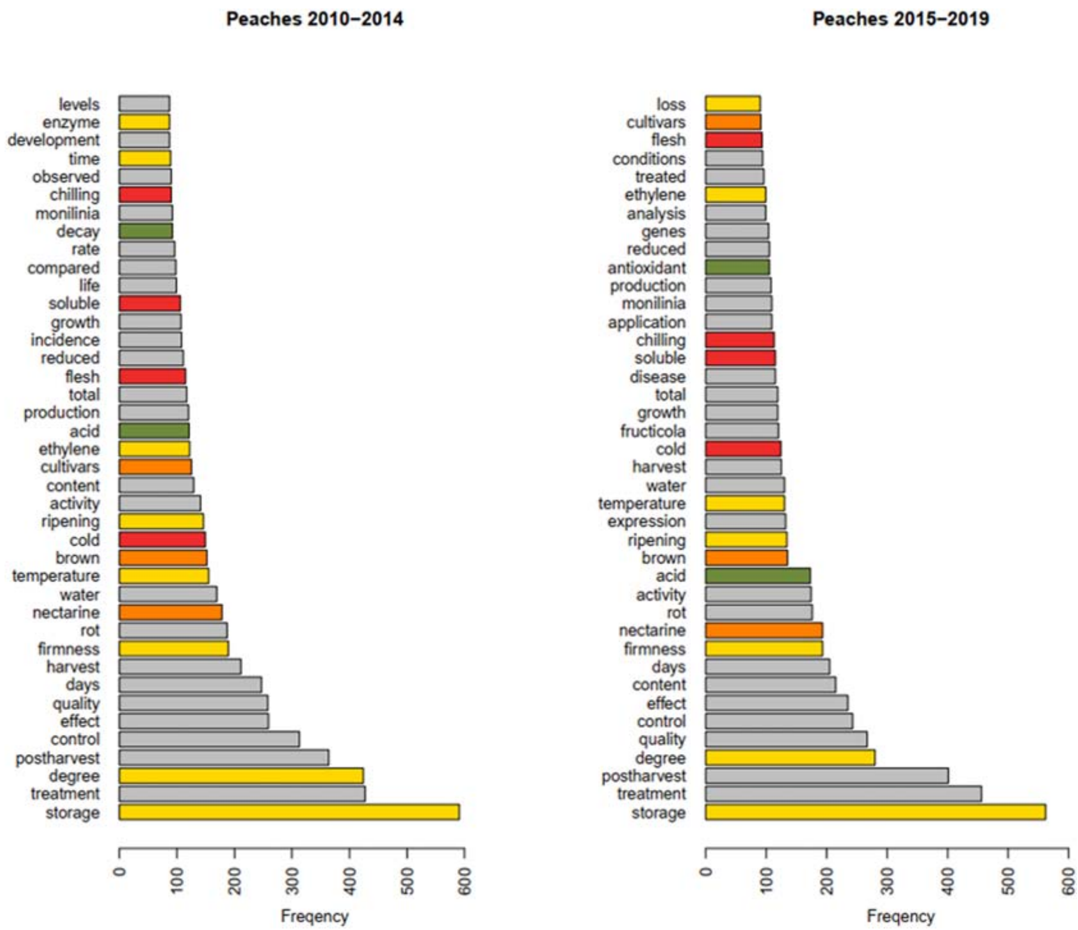


FIGURE 18.19 The frequency of words associated with postharvest peach research, by group (including four parts of the book: whole systems, product, processes, and perceptions). Source: *Authors.*

in abstracts published in the period 2009–14 and the mostly monochromatic column associated with the period 2015–19. In the first period the focus is on words assigned to the "whole system" and "process," but in the second period the words from both groups are few. Most interesting is the considerably higher frequency use of "green" words between 2015 and 2019 indicating a shifting research focus to issues accounting for perceptions. The specific words are related to safety and healthiness of Romaine lettuce (Fig. 18.21).

Tomato is among the most commonly eaten vegetables. The most frequently used set of words has not changed between the two considered periods (Fig. 18.22), but the overall number of published abstracts increased (Table 18.1). In this book, the focus is on fresh tomato consumption and the frequency of the word "acid" coincides with perceptions of taste. The word use increased with time (Fig. 18.22). Lycopene, a health-benefitting compound of tomato, has been used with roughly the same frequency in both periods and

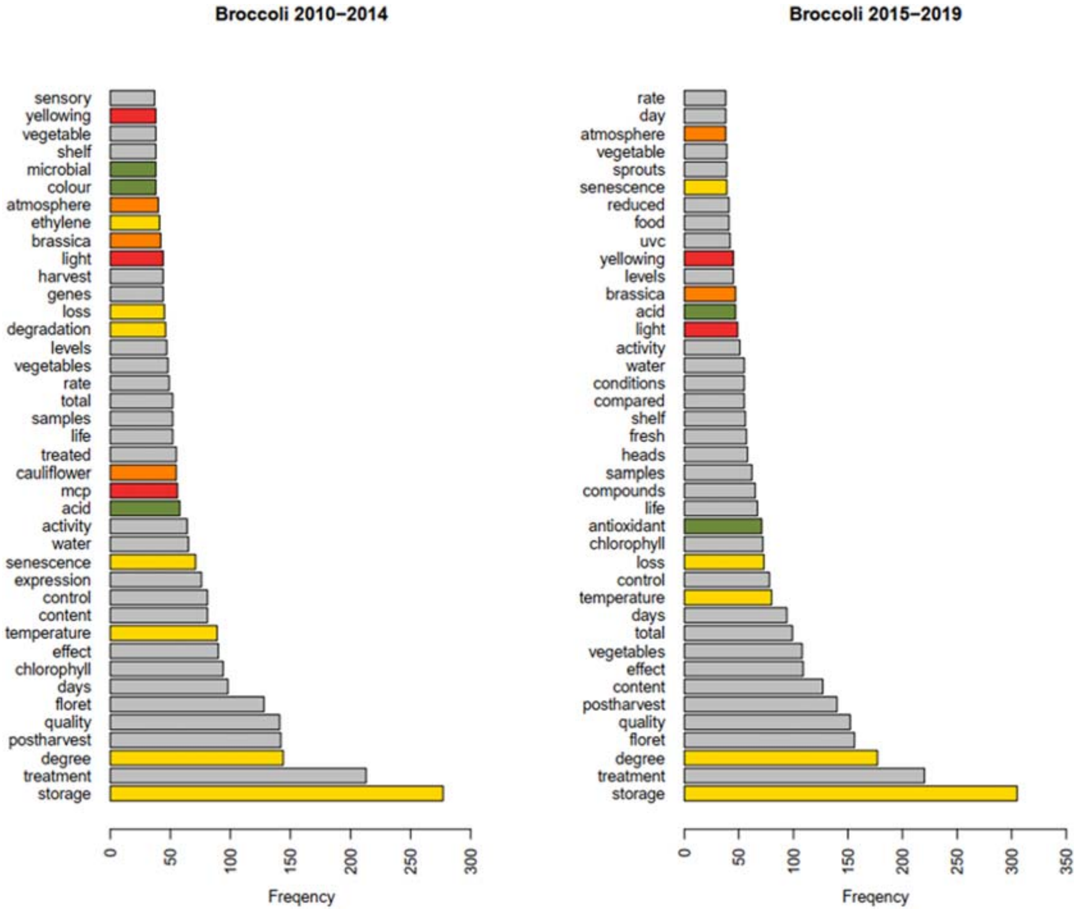


FIGURE 18.20 The frequency of words associated with postharvest broccoli research, by group (including four parts of the book: whole systems, product, processes, and perceptions).

suggests a continuing research interest. The versatility and popularity of tomato bode well for its sustained postharvest research in the future given the $190.1 billion tomato global market revenue in 2018 (Globalnewswire.com, 2021).

18.5.3 When word size, distance, and associations matter

This section describes figures showing color-coded circles, where the colors continue to correspond to the five groups of words (see Appendix), four of which are linked to four parts of the book. However, the diameter of the circle, the distance between the circles, and arrows carry a meaning. Specifically, an increasing diameter implies a greater frequency of a word in the published abstracts, the closer distance suggests the two words appeared more often in the abstracts, and the arrows imply the sequence in which the words appeared. The latter indication overcomes the limitation of the technique restricting

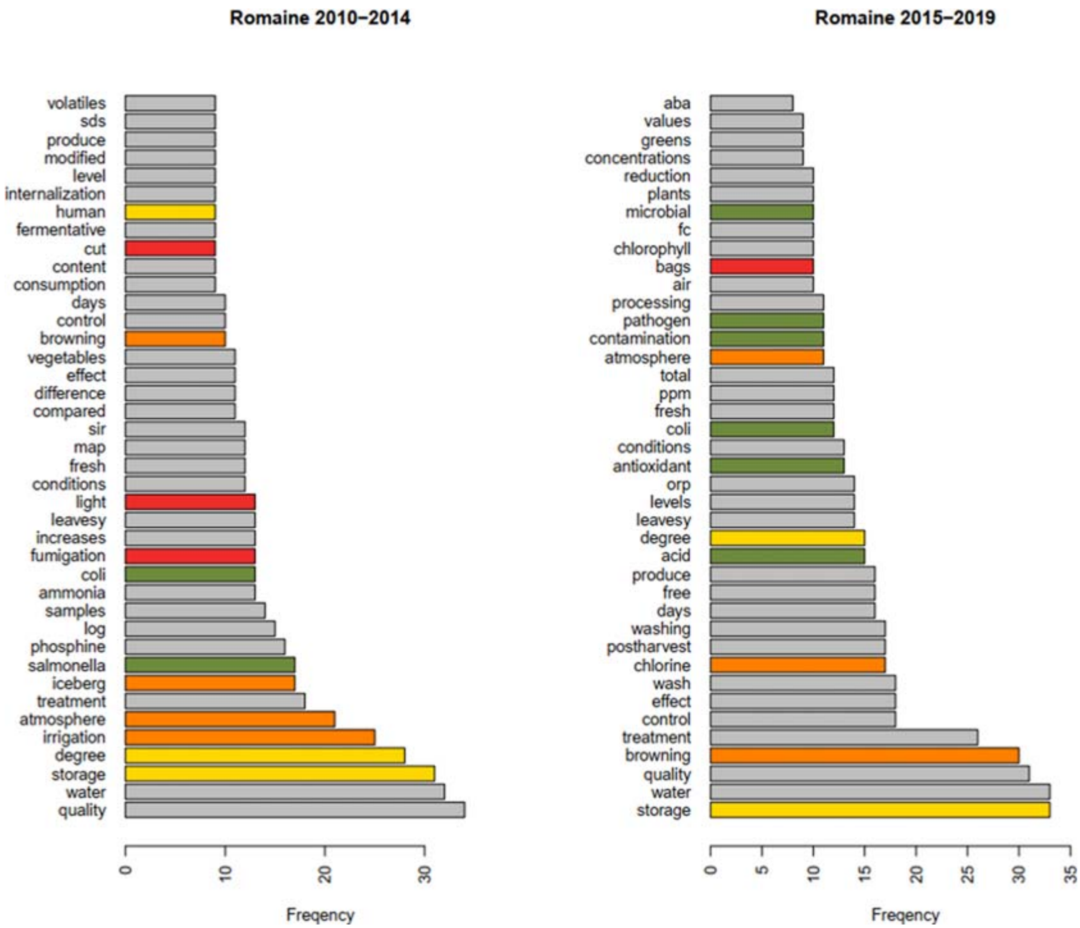


FIGURE 18.21 The frequency of words associated with postharvest Romaine lettuce research, by group (including four parts of the book: whole systems, product, processes, and perceptions). Source: *Authors.*

the analysis to the links between two words, rather than expressions such as "soluble solids." The size, frequency, and placement of green circles signal the extent to which the consumer was on the mind of postharvest researcher.

Fruits. A comparison of patterns associated with publications in the periods 2009–14 and 2025–19 shows similarity and the largest circles, relatively frequently used words, concentrated around "apple" (Fig. 18.23). One group forms a discernible cluster implying a research focus on cold storage (yellow, red, and black circles corresponding to the "whole system," "product," and generic word groups). Another cluster includes words "MCP," "firmness," and "losses" that are associated with the attempts to research delay in apple fruit quality. The third cluster involves "freshcut," "cultivar," and the names of apple cultivars suggesting research on postharvest handling of specific cultivars and their specific uses. On both panels (Fig. 18.23), the words associated with perceptions are few, represented by relatively small circles and scattered on the

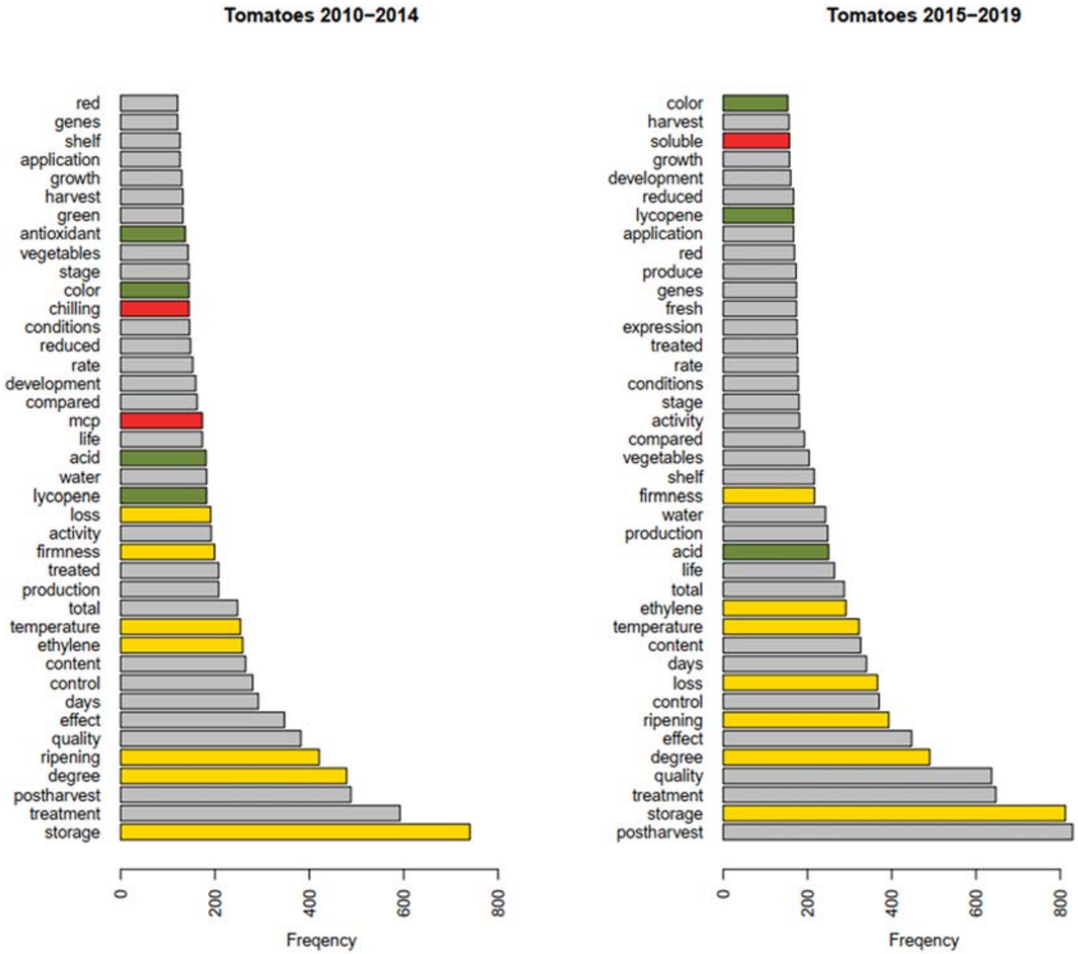


FIGURE 18.22 The frequency of words associated with postharvest tomato research, by group (including four parts of the book: whole systems, product, processes, and perceptions). Source: *Authors.*

edges of the graph. It appears that consumers could benefit indirectly from postharvest research on prolonged storage and quality protection, making fruits of various cultivars available between harvests. That research benefits growers by offering flexibility in marketing.

The overall pattern of the word frequency, closeness, and associations in the blueberry postharvest research has been similar to that of apples (Fig. 18.24). The three clusters of words concentrate around the words “cold” and “storage,” “firmness” and “ripening,” “cultivar,” and words implying varieties. The pattern is similar in both periods, 2009–14 and 2015–19. The words associated with perceptions are scattered on the edges of the graph. Blueberries cannot be stored as long as apples as their quality, especially firmness, deteriorates after a few weeks (see also Chapter 5). But the relatively high value of the fruit and steady demand throughout the year motivate research on storage and its effects on quality.

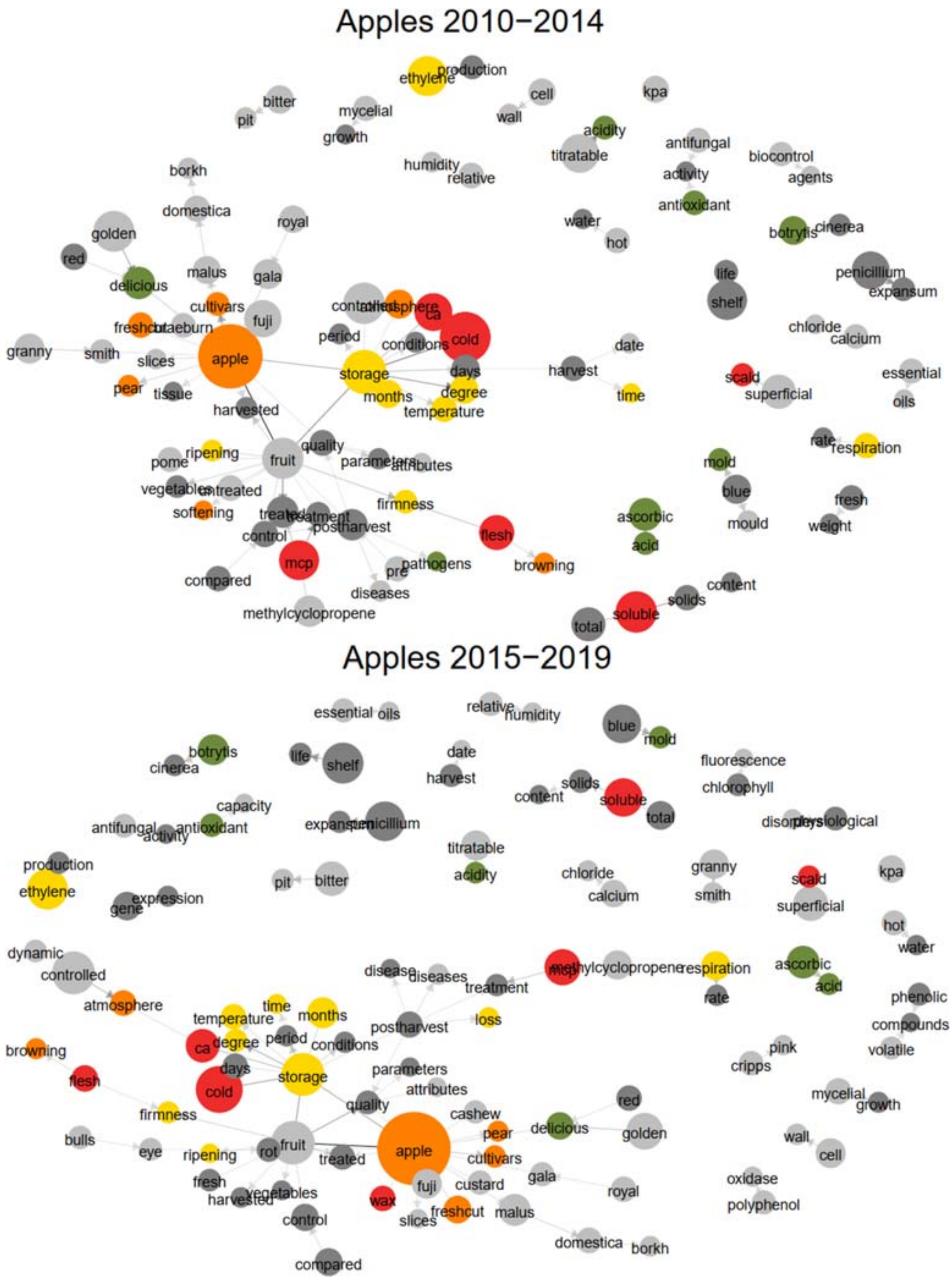


FIGURE 18.23 Use frequency and associations of words from given groups in abstracts on apple postharvest research in the periods 2010–14 and 2015–19. Source: *Authors.*

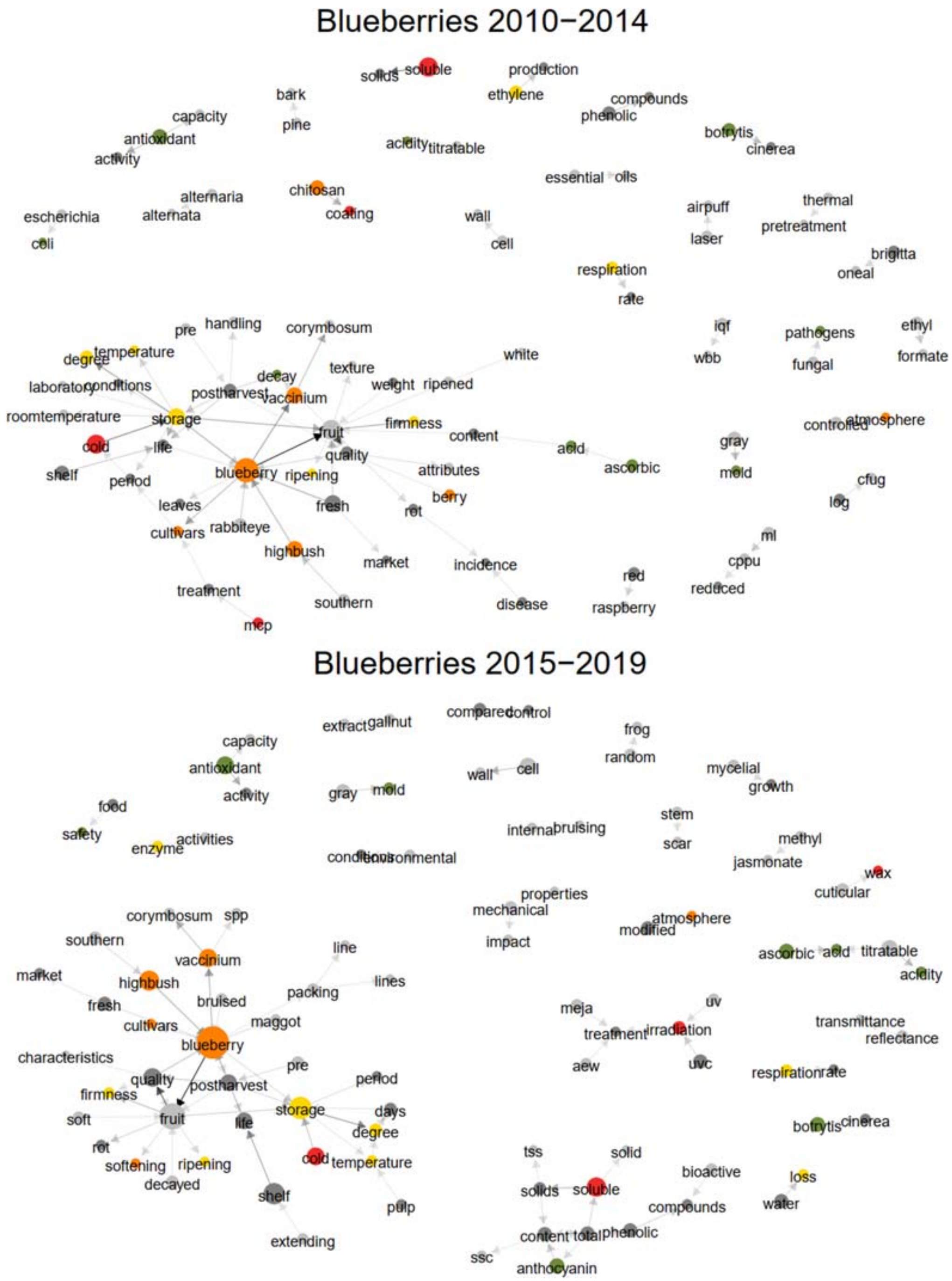


FIGURE 18.24 Use frequency and associations of words from given groups in abstracts on blueberry postharvest research in the periods 2010–14 and 2015–19. Source: *Authors.*

Fig. 18.25 shows that three clusters of words have dominated in the abstracts of analyzed publications. In a familiar pattern, one cluster concentrates on the words "cold" and "storage," while another on words "firmness," "loss," "browning," and "flesh." The latter is a common problem in peach fruit and linked to postharvest handling (e.g., Lurie, 2021). The third cluster is associated with managing trees, likely cultivar-specific. Words associated with perceptions are few and scattered on the edges of Fig. 18.25. Postharvest research on peaches focused on providing flexibility in sales (cold storage) and quality protection (firmness, flesh browning), directly benefiting growers and indirectly benefiting consumers.

Overall, the three fruits considered in this section attracted postharvest research on similar issues and the number of published articles is quite large (in the case of apples and peaches) or rapidly increasing (in the case of blueberries). However, whereas apple consumption has been stable, peach consumption has been decreasing, while blueberry consumption has been swiftly growing. Apples and peaches have been consumed for a long period of time, but blueberries gained popularity in recent decades. The analysis in this chapter ignores the changing cultivar composition, which has been substantial in the case of apples, and in the case of blueberries involves the highbush and rabbiteye cultivars rather than the low bush wild blueberries. A future analysis may track variety-specific postharvest research, which could have contributed to the observed consumption changes. In addition, consumption changes differ across countries and likely differ from those reported here for the United States.

Vegetables. The postharvest research on broccoli (Fig. 18.26) differed somewhat from the research on fruit. The three areas of relative concentration included words "storage," "temperature," and "days," suggesting that storage was important in the period 2009−14. As noted earlier, the consumption of broccoli increased as the consumption of cabbage decreased, but fresh cabbage has been easier to store than broccoli. With increasing consumption, growers responded but postharvest requirements changed and required the development of new protocols. Another concentration of words is associated with "quality" but also "nutrition," "freshcut," "microbial," and "sensory," suggesting more emphasis on attributes relevant to consumers. The third area is less pronounced and includes words "minimally," "processed," and "floret."

In the period 2014−19, the focus on broccoli storage continued, but another cluster of words included "phenols," "glucosinolate," "soluble," and "solids." The third area involved words "quality," "visual," and "sensory," among others. As can be noticed, the size of the circles in Fig. 18.26 is smaller than on the graphs presenting similar patterns for apple and peach postharvest research. However, there seems to be stronger focus on issues concerning consumers.

Published abstracts on postharvest research involving Romaine lettuce were limited in number in both periods (Fig. 18.27). There appear to be clusters of words, but the circles are quite indistinguishable. It is likely that postharvest research was quite limited and conducted by a small number of researchers (see the next section). The observed surge in consumption likely has been driven by the industry and plausibly by the growth of the freshcut sector. Romaine lettuce is more suitable for freshcut and also more convenient for home use than iceberg lettuce. At retail, Romaine prices are higher than iceberg lettuce but seem to generate smaller losses.

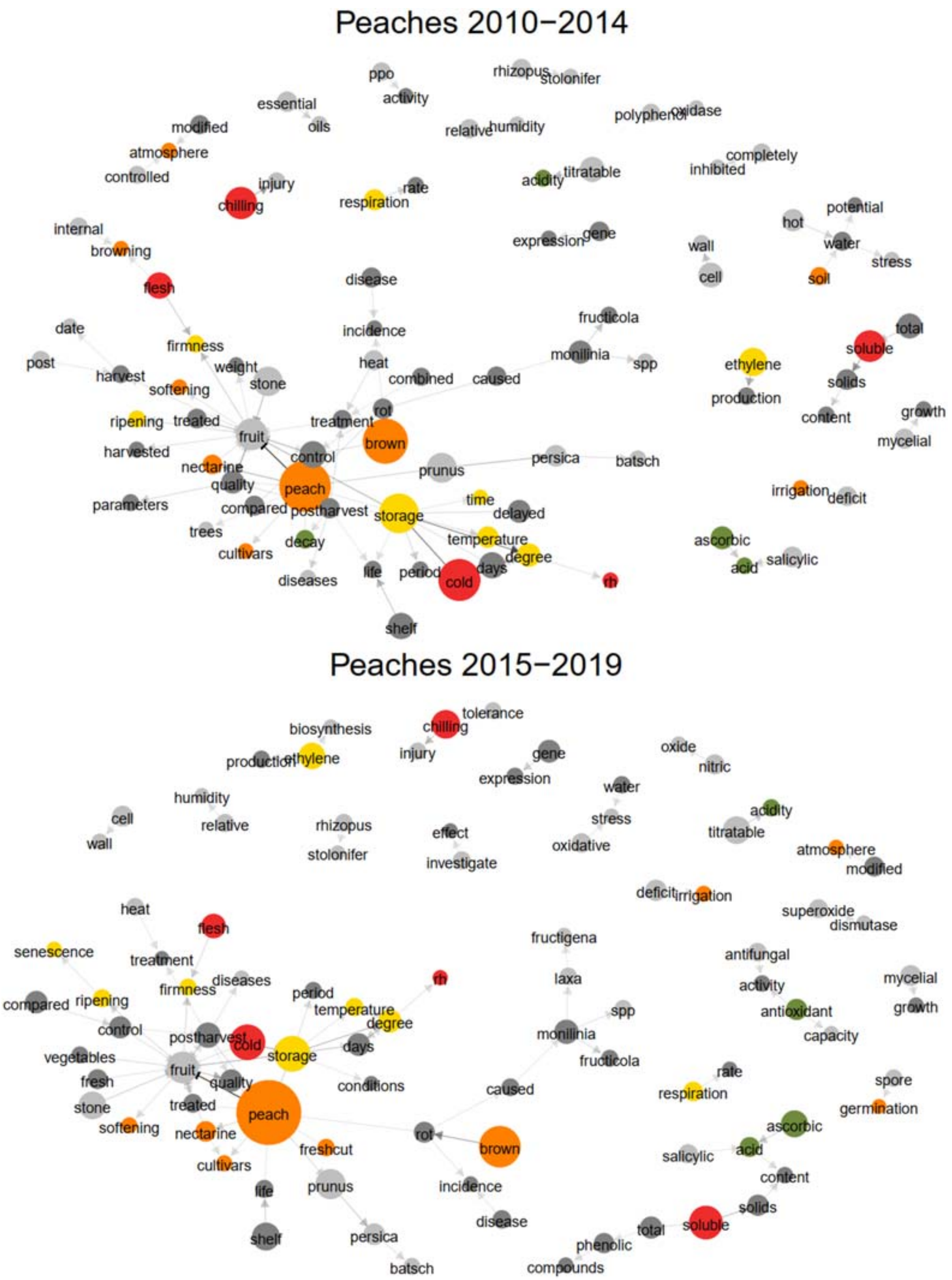


FIGURE 18.25 Use frequency and associations of words from given groups in abstracts on peach postharvest research in the periods 2010–14 and 2015–19. Source: *Authors.*

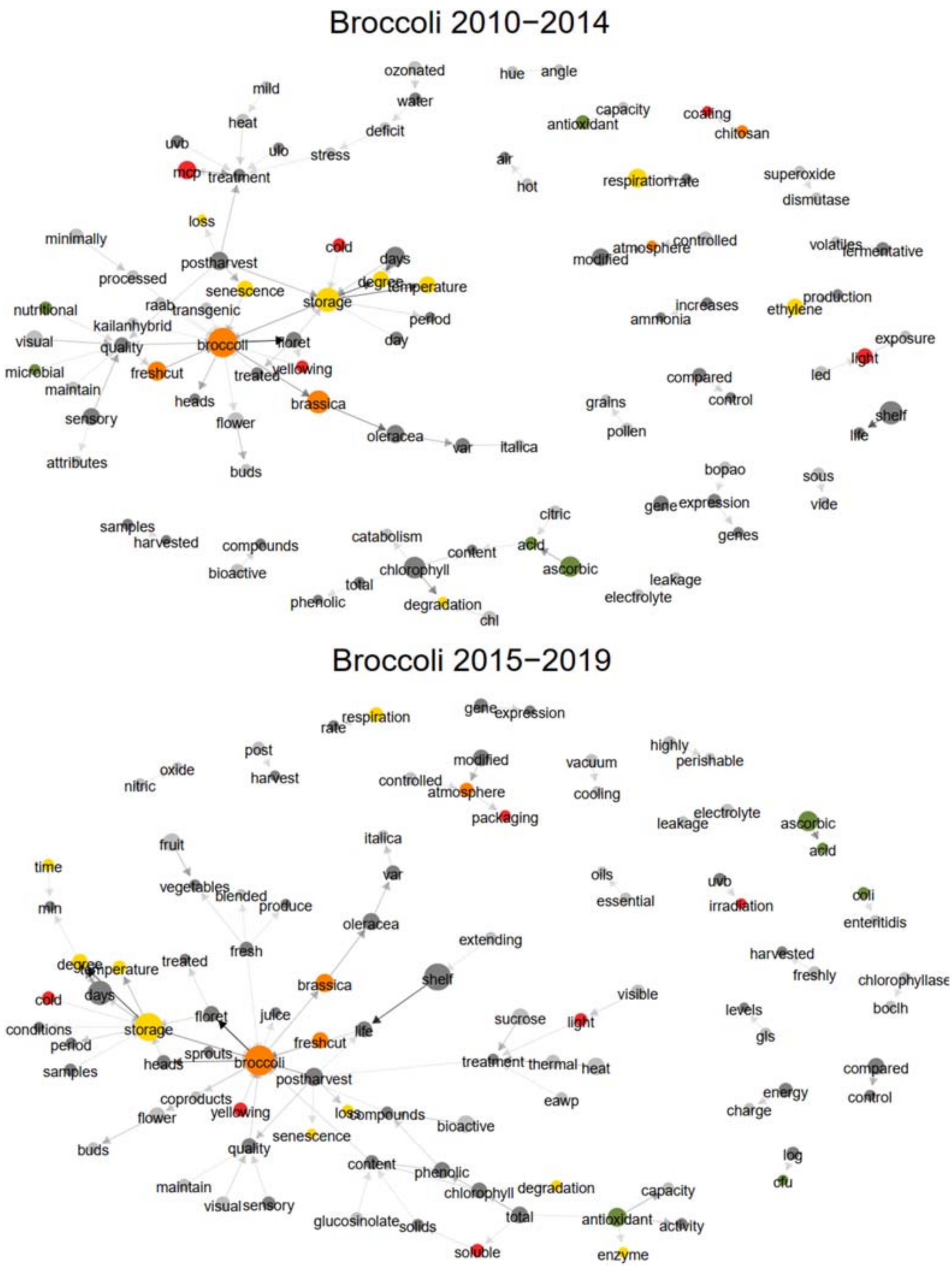


FIGURE 18.26 Use frequency and associations of words from given groups in abstracts on broccoli research in the periods 2010−14 and 2015−19. Source: *Authors.*

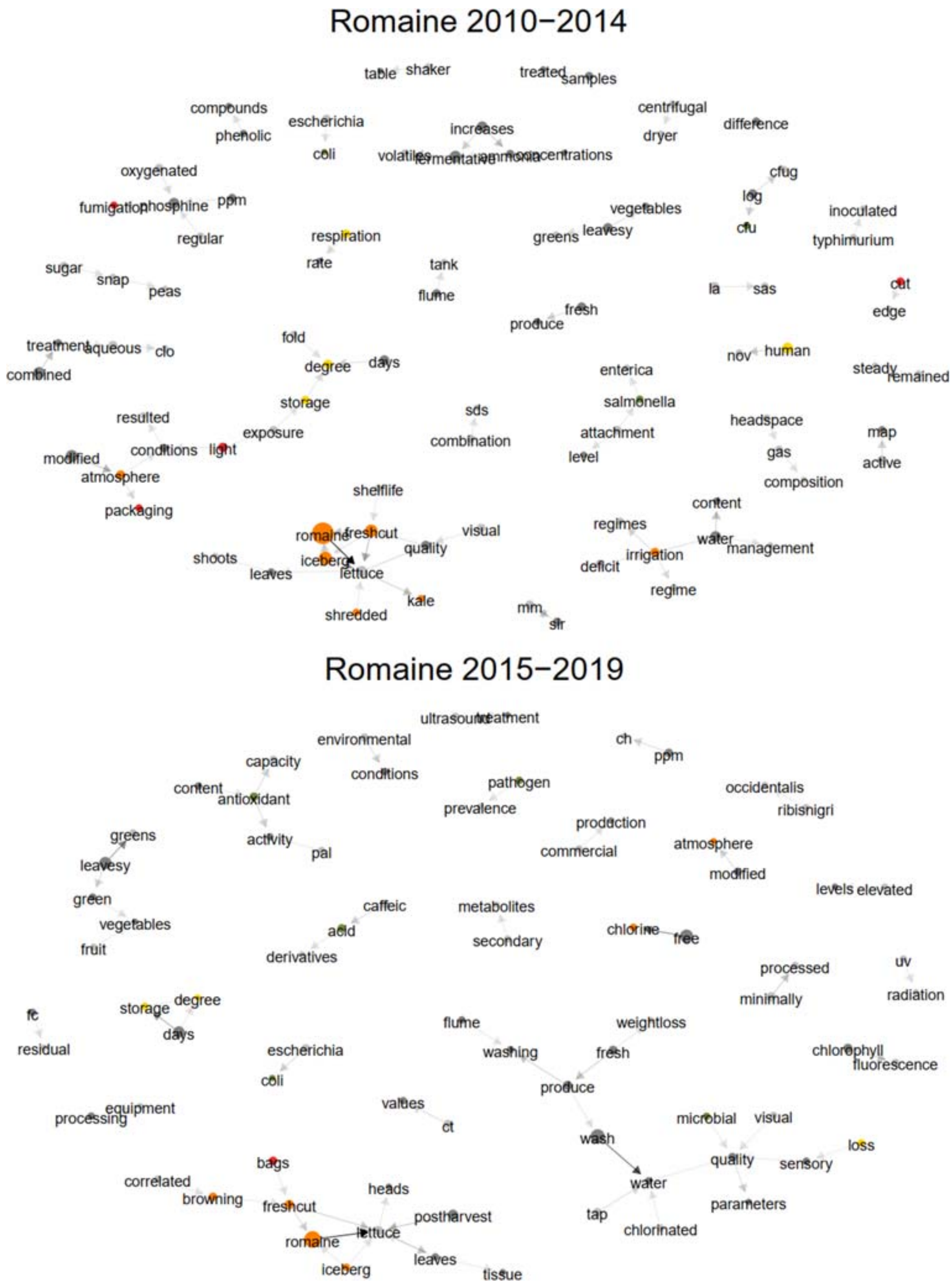


FIGURE 18.27 Use frequency and associations of words from given groups in abstracts on Romaine lettuce postharvest research in the periods 2010–14 and 2015–19. Source: *Authors.*

"Tomatoes," next to onions the most often eaten vegetable, has been a subject of postharvest research globally. Fig. 18.28 shows a cluster of words linked to "storage," "cold," and "temperature." In an already familiar pattern, concern about storage was important in both periods, 2009–14 and 2015–19. The word "storage" is associated closely with "cold" and "temperature." In the period 2009–14, a separate cluster includes "fruit," "quality," "postharvest," "losses," "ripening," and "firmness." Those words, except for "quality," also form a cluster in the period 2015–19. A similar cluster including words "cherry," "mature," and "lycopene" characterize yet another cluster (Fig. 18.28).

Overall, storage was a major focus of postharvest research on the two vegetables very popular with consumers. Other words suggest interest in freshcut and attributes relevant to consumers, more so than in the case of the three fruits discussed earlier in the section. All three vegetables cannot be stored for long and their overall quality is easily compromised by mishandling and temperature abuse (see also Chapter 16).

18.5.4 When "who" and "how many" matter

The text mining of abstracts allows taking the examination a step further and identifying authors publishing fruit and vegetable postharvest-related research. The graphic presentation of the examinations of abstracts published in the two periods identified clusters of coauthors whose research pertained to three fruits (apple, blueberries, and peach) and three vegetables (broccoli, Romaine lettuce, and tomato). Space limitations and the unnecessary complexity of full graphs led to the choice of clusters of coauthors who published at least twice in a given period to illustrate the technique. The identified clusters show who researched a particular fruit or vegetable in what period. As can be seen, the largest clusters of authors conducted research in a number of countries supporting the universal need for postharvest research. The perspective of who was engaged in research-specific produce varies from tracking per capita consumption using the example of the US consumer. Presumably, the satisfaction of the consumer eating the fresh produce inspired more studies than reflected in the frequency of words linked to the group of words reflecting consumer preferences and perceptions. Future research can further examine if there is a confirmed association between the location of postharvest research, commercial production, and per capita consumption, assuming data become available.

Fruit. Fig. 18.29 shows two prominent clusters of researchers identified as authors of abstracts on apple fruit. Between 2009 and 2014, the largest cluster included 15 authors (e.g., Herremans et al., 2014; Mellidou et al., 2014). Interestingly, some of the names are familiar contributors to this book edition, namely, B. Nicolai and M. Hertog (Panel A) (see Chapter 15). Those authors continued their research on apple postharvest in the period 2015–19 (Panel B) (e.g., Bekele et al., 2016) although the number of all authors dropped to eight. Their research coincides with the development of automated rapid apple sorting machines detecting misshapen fruit and internal bruising, but also identifying coloration, size, and Brix (soluble solids) content.

Fig. 18.30 shows the cluster of six authors publishing on the postharvest of blueberries between 2009 and 2014. The identified group involved researchers from universities in Chile and Spain. Some of the researchers continued to publish in the next period

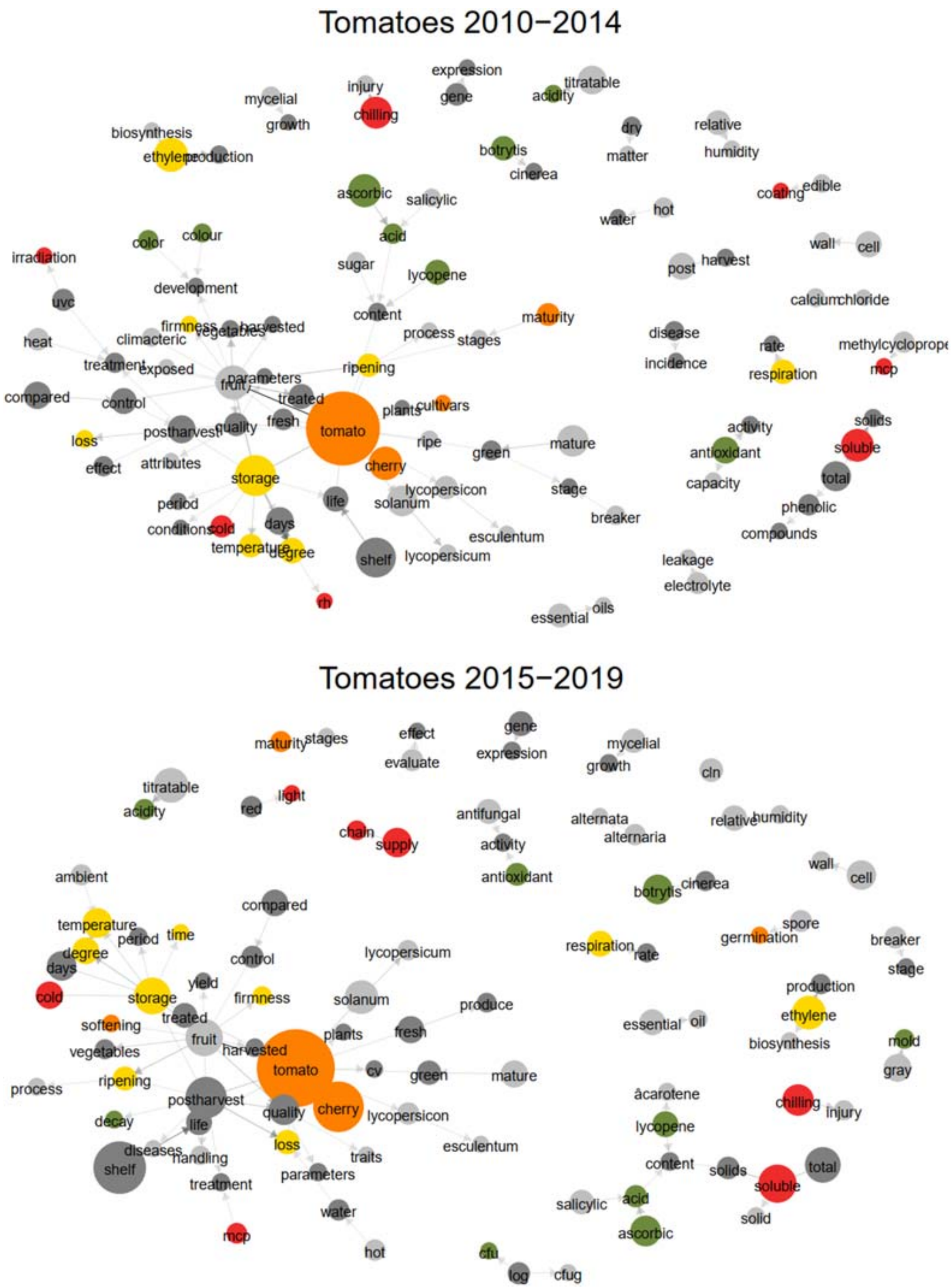


FIGURE 18.28 Use frequency and associations of words from given groups in abstracts on tomato postharvest research in the periods 2010–14 and 2015–19. Source: *Authors.*

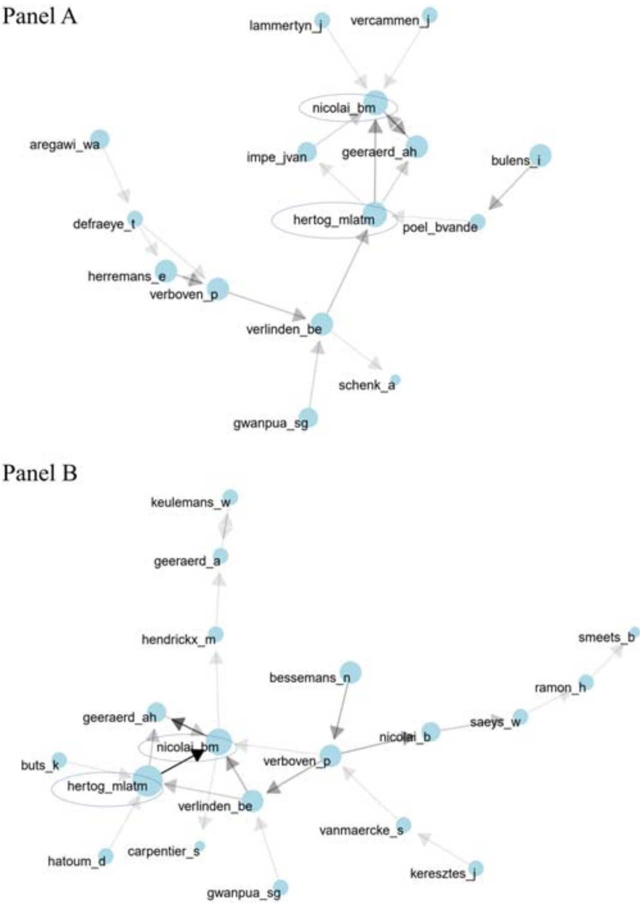


FIGURE 18.29 Clusters of researchers publishing on postharvest handling of apples in the periods 2010–14 (Panel A) and 2015–19 (Panel B). Source: *Authors*.

(2015–19) and their focus was on berry firmness, water loss, and related quality deterioration (Moggia et al., 2016). Chile has a competitive blueberry sector and takes advantage of the demand in the northern hemisphere. Another six researchers conducted research in this area in the Republic of Korea and published in the period 2015–19 (Chung et al., 2019). Their work involved anthocyanins and antioxidant content of blueberries has been driving the demand (Carew & Florkowski, 2007). The Republic of Korea has been importing cultivated blueberries from North America and not surprisingly the researchers listed on Panel B have published a number of articles on blueberries.

The declining per capita peach consumption in the United States may not accurately indicate the global demand for this fruit. Fig. 18.31, Panel A, shows a large team of researchers involved in peach postharvest research in the period 2009–14 as identified in the applied database (e.g., Abrisqueta et al., 2013). The team members were located in Spain, an important fresh peach producer shipping fruit to other European countries. Some of the research focused on brown rot (not present in European peach orchards until very recently) that affects the eating quality of peach (e.g., Casals et al., 2010). Panel B

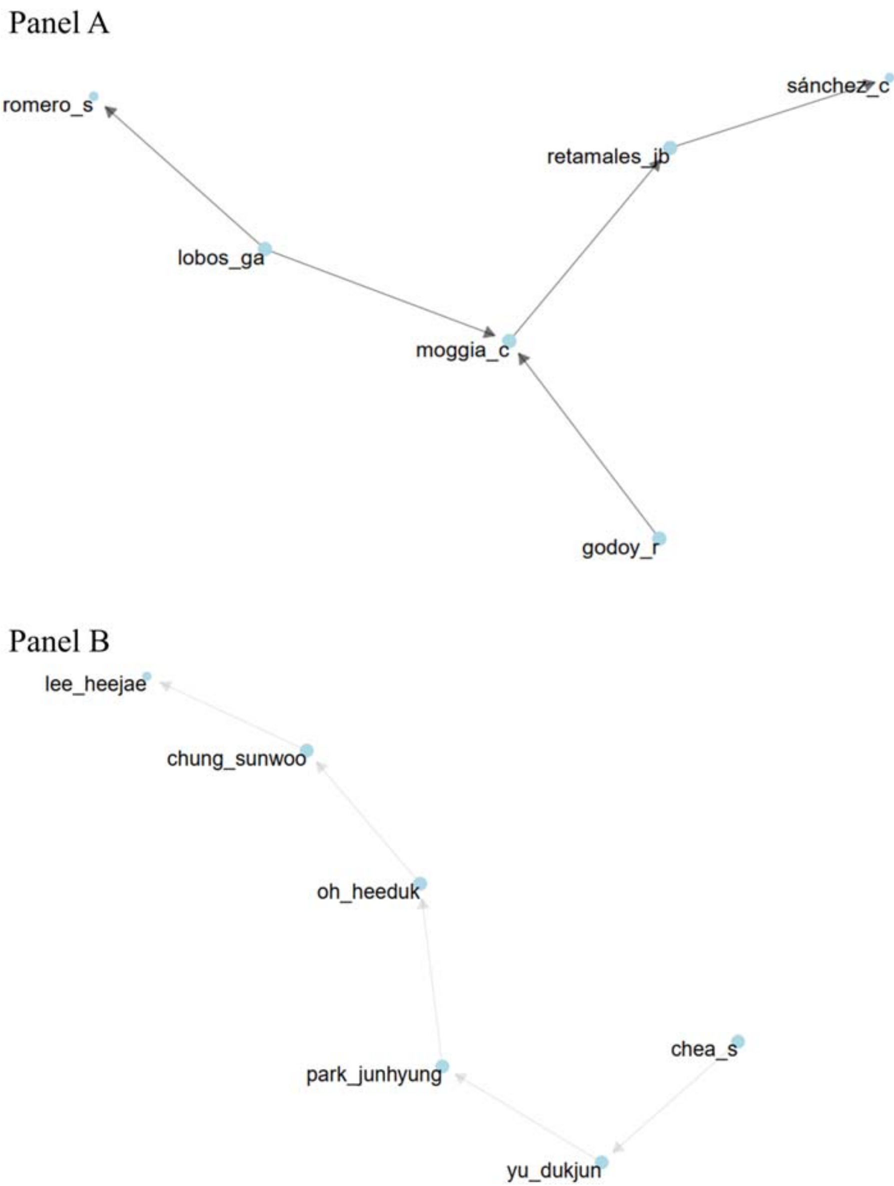


FIGURE 18.30 Clusters of researchers publishing on postharvest handling of blueberries in the periods 2009–14 (Panel A) and 2015–19 (Panel B). Source: *Authors.*

shows another group of postharvest researchers, also located in Spain, investigating, among other things, production practices and the content of health-promoting compounds in peaches. It appears that the research has matched the consumer interest in eating fresh fruit to support health.

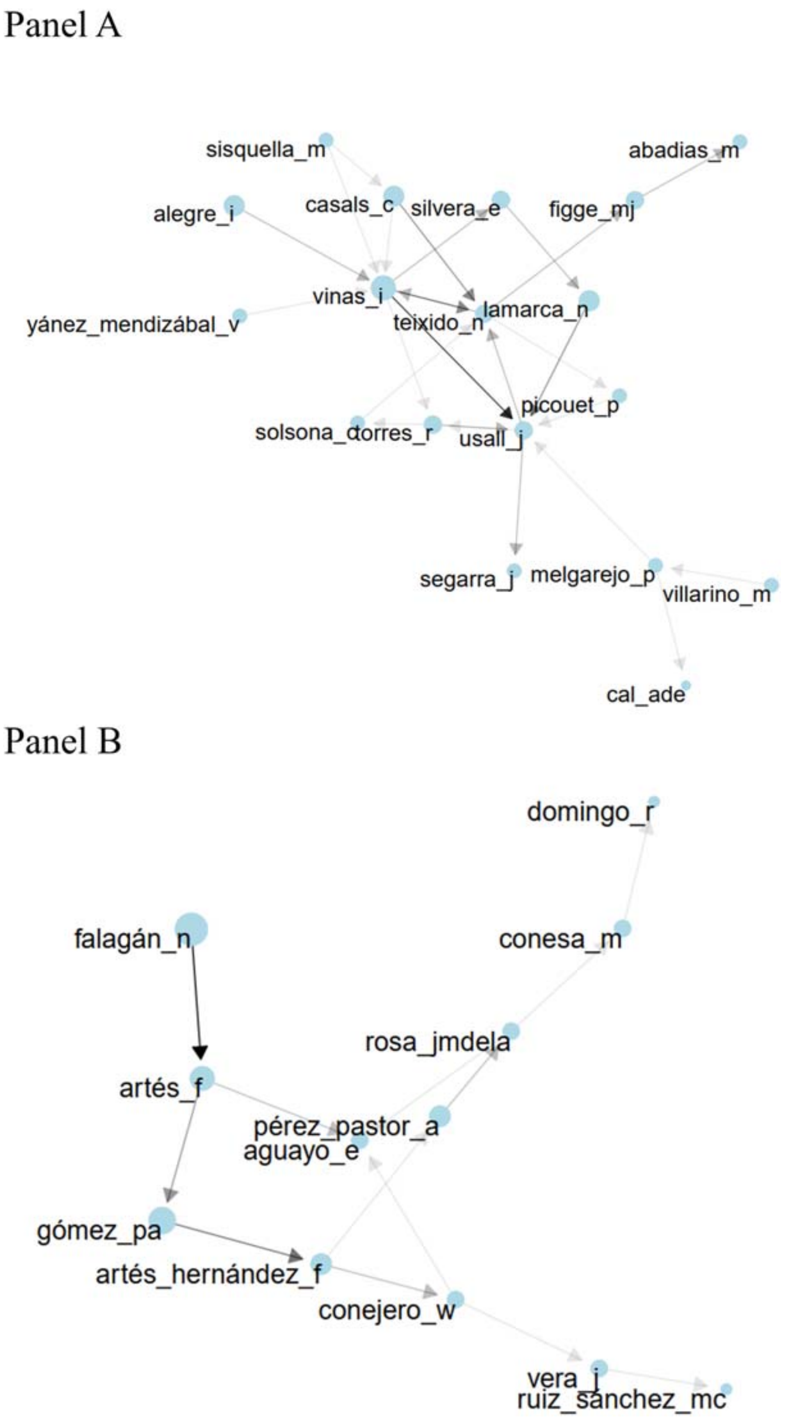


FIGURE 18.31 Clusters of researchers publishing on postharvest handling of peaches in the periods 2010–14 (Panel A) and 2015–19 (Panel B). Source: *Authors.*

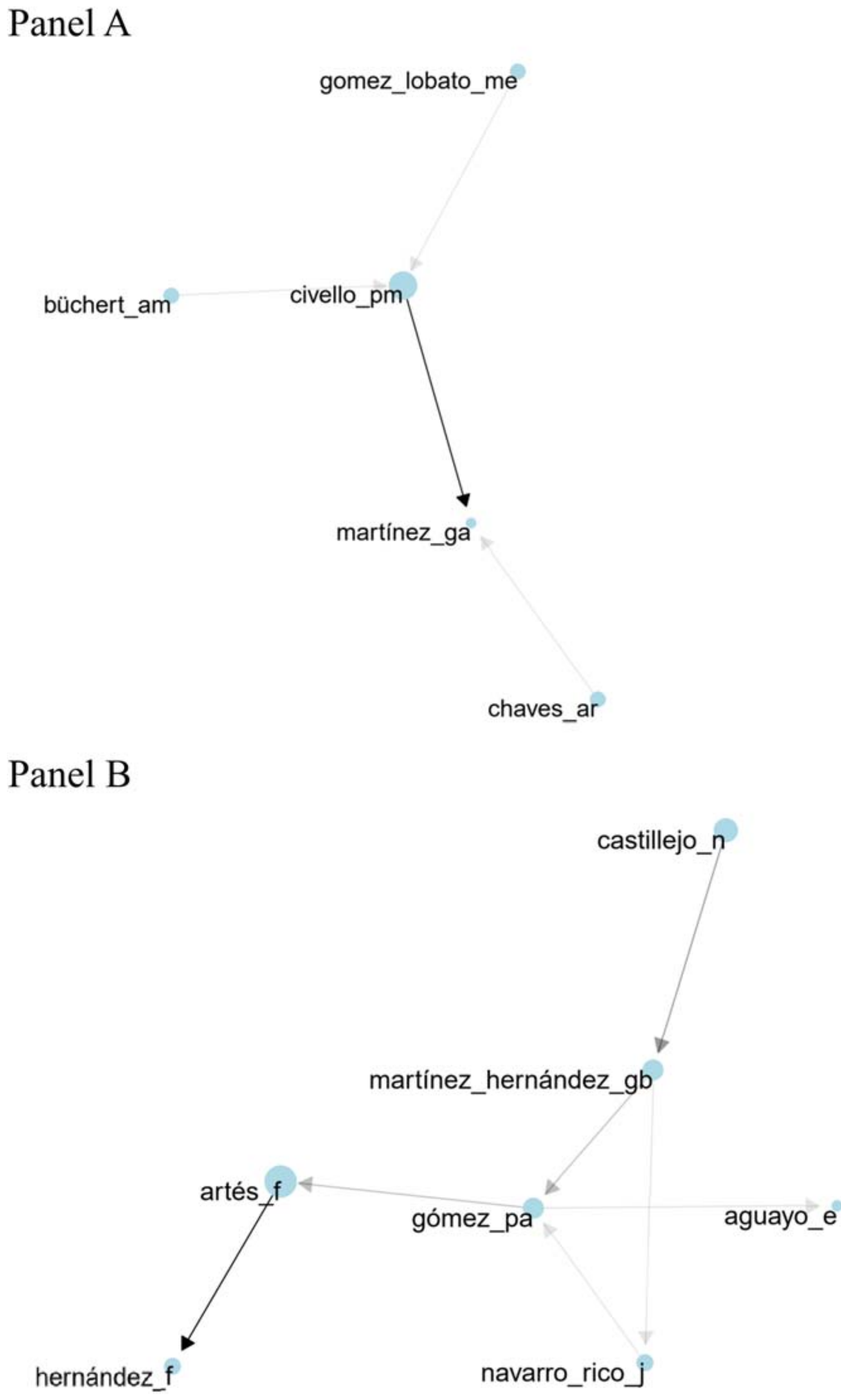


FIGURE 18.32 Clusters of researchers publishing on postharvest handling of broccoli in the periods 2010–14 (Panel A) and 2015–19 (Panel B). Source*: Authors.*

Panel A, Fig. 18.32, shows a cluster of researchers working on postharvest of broccoli in Argentina. The research addressed, among other things, senescence and methods to slow chlorophyll degradation (e.g., Büchert, Civello, & Martínez, 2011). Visual appearance is an important quality attribute for the consumer, especially if broccoli is to be consumed fresh. Some of the researchers continued their postharvest broccoli studies

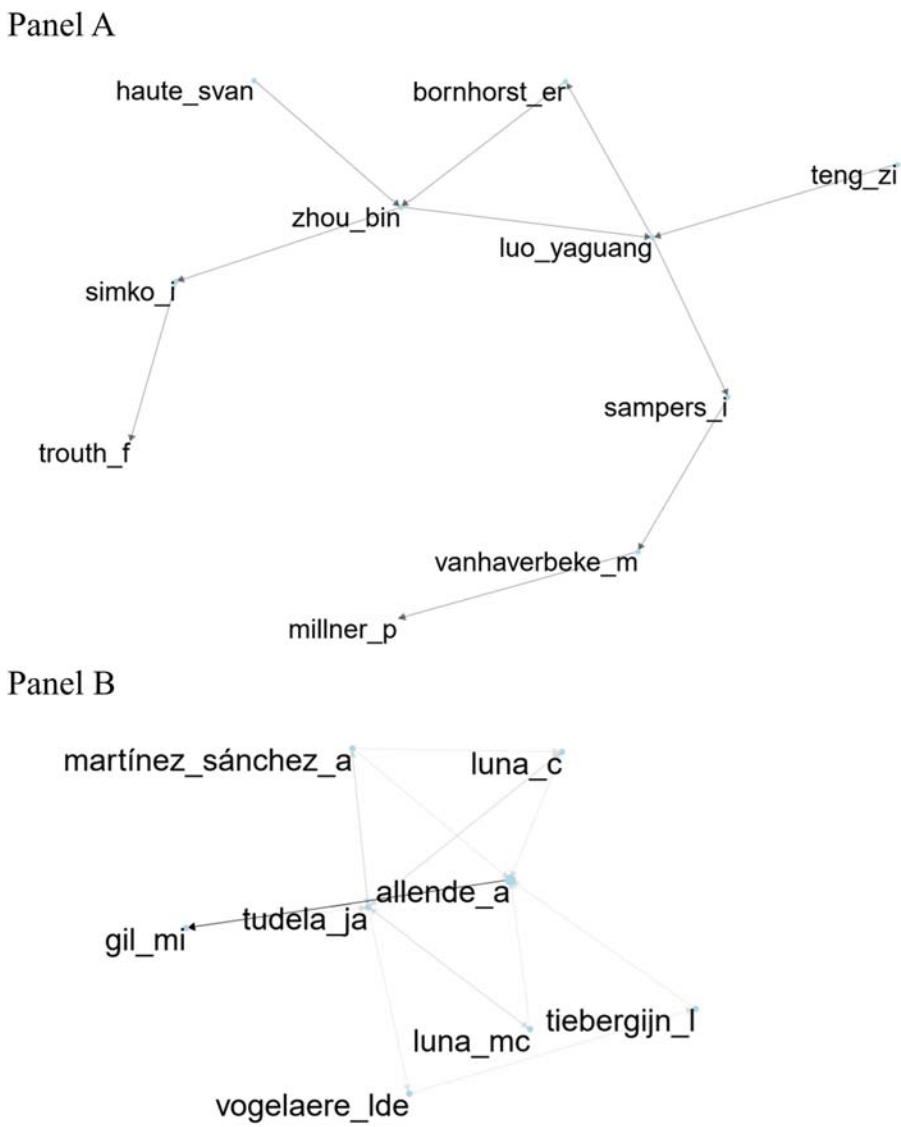


FIGURE 18.33 Clusters of researchers publishing on postharvest handling of Romaine lettuce in the periods 2010–14 (Panel A) and 2015–19 (Panel B). Source: *Authors.*

in the second period. However, the group of researchers in that period (Panel B) was larger (seven vs five persons) and was associated with universities in Spain. The researched topics included those related to flavonols (e.g., Rybarczyk-Plonska et al., 2016), freshcut broccoli, and the use of product development for revalorizing broccoli. Popularity of freshcut broccoli with consumers and food service is undeniable, while reducing the waste has broad benefits.

Postharvest research on Romaine lettuce did not necessarily involve fewer researchers than was the case for other produce but certainly involved fewer publications (Fig. 18.33). In the period 2009–14, the most frequent topic of the cluster shown on Panel A involved safety (e.g., Luna, Tudela, Martínez-Sánchez, Allende, & Gil, 2013) and methods to eliminate microbial contamination. Researchers were affiliated with the US Department of Agriculture and a university in China, among others. Leafy vegetables, including lettuces, have been linked to outbreaks of disease that negatively affects sales, even if the sales recover over time. The costs of disruption can threaten the economic existence of growers or packers. Researchers on Panel B, publishing between 2015 and 2019, were located in Spain and investigated respiration rates, browning (e.g., Luna, Tudela, Tomás-Barberán, & Gil, 2016), and microbial load. Use of freshcut lettuce was also researched.

Fig. 18.34 shows a cluster of postharvest researchers publishing on tomato in the periods 2009–14 (Panel A) and 2015–19 (Panel B), respectively. In the first period, a team from Mexico researched and published on, among other things, antioxidant capacity of tomatoes (e.g., Dávila-Aviña et al., 2014). The topic is related to the health-promoting compounds in fresh fruits and vegetables. Some of those researchers continued to publish on phenolic compounds in food in the later period. The cluster of researchers in the period 2015–19 is much larger and the topics included linking quality of tomatoes to genotypes (e.g., Rawal et al., 2016), postharvest losses, and microbial contamination (e.g., Khadka, Marasini, Rawal, Gautam, & Acedo, 2017). Researchers were associated with public research institutions in India, Nepal, Thailand, Taiwan, and other countries. It appears that the popularity of tomato with consumers is echoed in the diversity of postharvest research and institutional engagement.

18.6 Conclusion

Our illustrations of per capita fruit and vegetable consumption reveal shifts in the consumption of types of fresh products with time. Consumption of fresh produce in the United States remains below the recommended daily amount. We have explored patterns in word use in postharvest research publications over similar time periods. Our search involved publications listed in the CAB database using words that are classified in four groups corresponding to four sections of this book. The search for word patterns applies and the graphic presentation of the summary results.

The total volume of published research articles has increased with time. The number of publications on specific fruits or vegetables has grown or declined in a pattern different from the observed shifts in per capita consumption. Several text mining tools consistently identify keywords in postharvest research publications focused on three fruits (apple, blueberry, and peach) and three vegetables (broccoli, Romaine lettuce, and tomato). The

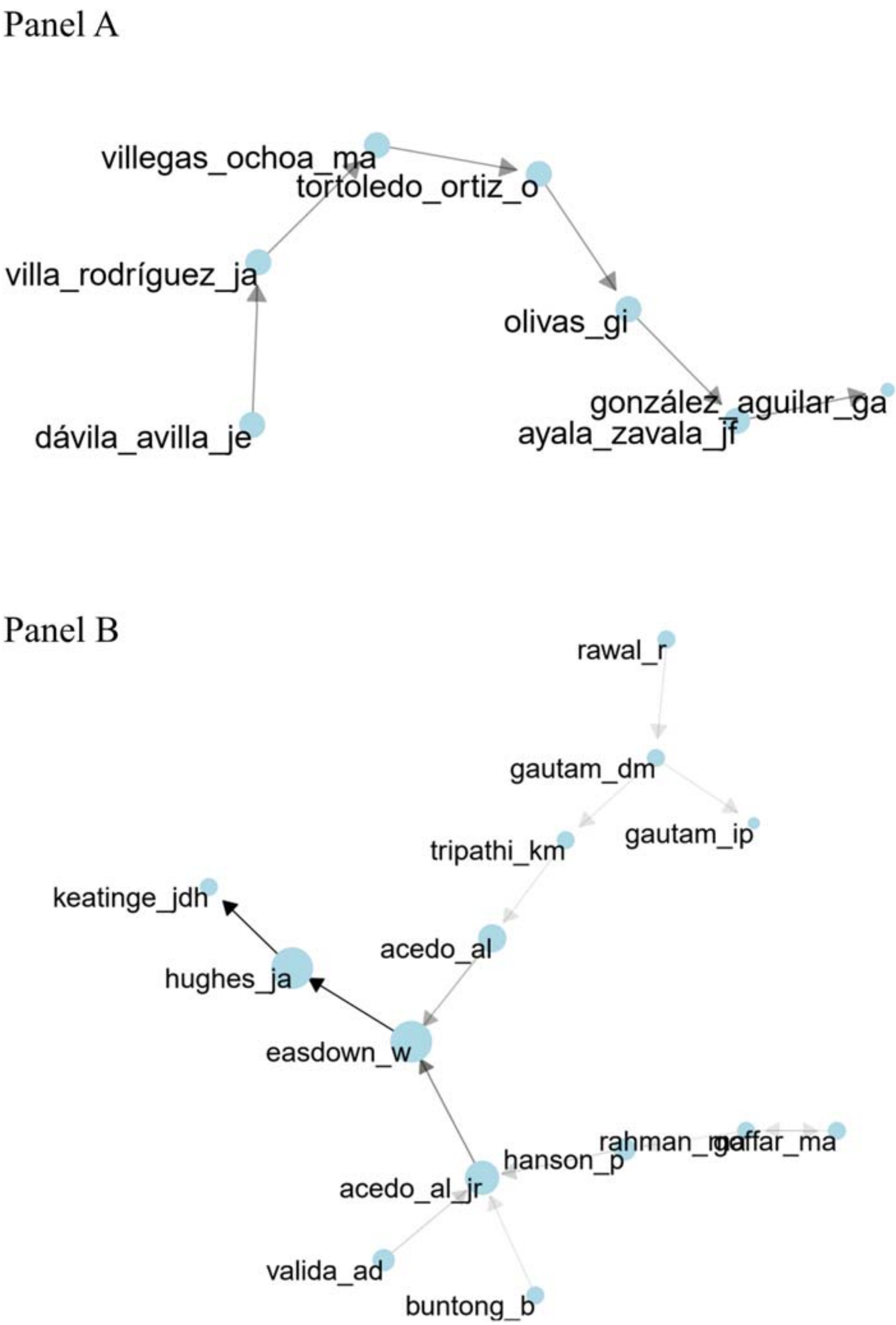


FIGURE 18.34 Clusters of researchers publishing on postharvest handling of tomato in the periods 2010–14 (Panel A) and 2015–19 (Panel B).

general criteria for selecting the three fruits and three vegetables involved one of the following: a large per capita consumption, rapid increase in consumption over time, or a steady decline in consumption. The text mining results for both fruit and vegetable publications identified the words “storage” and “quality” among the most frequently used. As time progressed, the words associated with the microbiological safety and health-protecting compounds have been used more often. The increased use of such words differed across the six selected fruits and vegetables. The tendency is clearly discernible suggesting that postharvest researchers recognize the nutritional and health benefits as motives driving fresh fruit and vegetable consumption. Likewise, safety issues raise concerns and limit consumption of fresh produce. It is expected that postharvest research will continue its focus on characteristics important to consumers such as the health and weight management benefits, while continuing more traditional lines of research such as storage, quality, and appearance.

The text mining techniques proved useful in revealing those words used most frequently. This reflected the focus of the presented research. The alternative techniques we used provided flexible ways to represent word frequencies. We believe that use of color, shape, and placement on the graph with these techniques more clearly presents the findings than two-dimensional “black and white” figures. Text mining helped us discern otherwise difficult to recognize patterns in postharvest research. Assuming that word frequency does indeed represent research focus, the approach has helped to identify some potential gaps in ongoing research.

Our characterization of word frequency patterns may become more robust with working with information from additional databases. Likewise, we recognize that the trends we have characterized may differ with the study of different specific fruits and vegetables—working, say, with products with the largest production volume produced across given countries or with the largest area harvested. For example, mango or watermelon could be eaten in larger volume than apples. Our chosen periods, 2009−14 and 2015−19, covered the time between the second and third edition of this book and the period starting a year after the publication of the third edition. Exploring further periods will be supported by the future development in tools for data analysis.

A more extensive review of clusters of researchers working on postharvest across the globe could provide another interesting dimension useful in tracking the link between the location of research and the consumption change. The low frequency or lack of words like interdisciplinary, teams, business, losses, waste, and systems thinking highlights the need of new research approaches that use systems thinking and enlist active participation by representatives from all business links in the value chains studied (see the conclusions of Chapter 2), not limited to biological and physical disciplines.

Postharvest research output continues to grow, reflecting the efforts of postharvest researchers scattered in numerous institutions around the globe. This growth in volume, together with responsiveness to gaps in knowledge, will support the continuing ability of value chains to deliver quality fresh produce in quantities that match trends in consumer demand. We believe that further development of the approach we have described can help to optimize targeting of future postharvest research. A vibrant global postharvest research portfolio will support further growth in fresh produce consumption, health, and well-being.

18.7 Appendix

The search of the database was limited to the selected terms and expressions relevant to postharvest. The words create five groups. The groups correspond to the four parts of the book. Those parts are whole system (yellow), product (orange), processes (red), and perceptions (green). A separate group of words was created to include terms and expression applying to more than a single group (black). Specifically, black implies the group 0 that includes words potentially relevant to any of the four other groups. Associating a group of words with a color provides a visual cue showing research applicable to specific fruit or vegetables on graphs summarizing the results of mining the text of abstracts of research articles from the database.

Group 0—Black	**Group 0—Black**	**Group 1—Yellow**	**Group 2—Orange**	**Group 3—Red**	**Group 4—Green**
Group 0—Black	Group 0—Black	Group 1—Yellow	Group 2—Orange	Group 3—Red	Group 4—Green
Actinidia	Activity	Control	Apple	Appearance	Acid
Agar	Air	Data	Artichoke	Bags	Acidity
Ala	Ammonia	Days	Atmosphere	Bulb	Acids
Analysis	Apc	Decay green	Banana	Bulb storage	Anthocyanin
Application	Applied	Decay juice	Berry	Ca	Anthocyanins
Arils	Baby	Decay total	Berry fruit	Chilling	Anthracnose
Bag	Based	Decreased	Blueberry	Coating	Antilisterial
Blue	Brigitta	Degradation	Brassica	Cold	Antioxidant
Cardunculus	Caused	Degree	Broccoli	Crown	Ascorbic
Chinese	Chlorophyll	Human	Brown	Curing	Bacterial
Cinerea	Cinerea water	Enzyme	Browning	Cut	Botrytis
Cod	Collectors	Enzyme RP	Cabbage	Dehydration	Coli
Colletotrichum	Combined	Ethylene	Chlorine	Flesh	Color
Compared	Compounds	Farmer	Carrot	Fumigation	Color
Concentrations	Concentration	Farmers	Cauliflower	Irradiation	Contamination
Concentrations	Conditions	Firmness	Cherry	Light	Control coli
Consumer	Consumers	Loss	Chitosan	MCP	Decay
Consumption	Content	Losses	Citrus	Moisture	Deliciosa
Contents	Control coli	Months	Corn	Packaging	Delicious
Corn	Cover	Respiration	Crop	Retailers	Flavor

(*Continued*)

(Continued)

Group 0—Black	Group 0—Black	Group 1—Yellow	Group 2—Orange	Group 3—Red	Group 4—Green
Cp	Crown	Ripening	Crops	Scald	Glucosinolates
Cultivars agar	Cultivars life	Senescence	Cultivars	Soluble solids	Lycopene
Cultivars total	Cysteine	Storage	Dextrose	Transport	Microbial
Dark	Delayed	Temperature	Fertilizer	Wax	Nutritional
Development	Difference	Time	Freshcut	Weight	Pathogen
Digitatum	Disease		Germination	Yellowing	Radish
Dry	Effect		Grape		Safety
Effect Days	Electrolyzed		Grapefruit		Salmonella
Energy	Evaluated		Highbush		Sodium
Expansum	Expression		Iceberg		Sweet
Factors crops			Irrigation		Vitamin
Feed	Fermentative		Kale		
Floret	Flume		Kiwifruit		
Food	Fresh		Lettuce		
Fructicola	Fruit		Mandarin		
Galega	Gene		Manure		
Genes	Globe		Maturity		
Green	Growth		Nectarine		
Growth fresh	Harvest		Onion		
Harvest life	Harvested		Orange		
Hayward	Head		Oxygen		
Heads	Hypocotyl		Ozone		
Improve	Imz		Peach		
Incidence	Increase		Pear		
Indigenous	Industrial		Peel		
Kinnow	Leaves		Potato		
Leaves	Leavesy		Romaine		
Leavesy total	Level crops		Shredded		
Levels	Levels yeast		Softening		
Life	Life disease		Soil		

(*Continued*)

(Continued)

Group 0—Black	Group 0—Black	Group 1—Yellow	Group 2—Orange	Group 3—Red	Group 4—Green
Life soluble	Log		Strawberry		
Lowest	modified atmosphere (MA)		Spinach		
Map	Market		Tangerine		
MG	Microbial log		Tomato		
Microgreens	Min		Vaccinium		
Modified	*Monilinia*				
Monocytogenes	Musa				
Musae	Navel				
Navel juice					
Observed	Oleracea				
Orp	Parameters				
Penicillium	Peptides				
Period	Ph				
Phenolic	Phosphine				
Physiological	Pieces				
Plants	Postharvest				
Potential	PPMparts per million (PPM)				
Preservation	Processing				
Produce	Product				
Production	Products				
Pulp	Quality				
Raphanus	Rate				
Rate cultivars	Rate research				
Rate weight	Red				
Reduced	Reduction				
Research	Rind				
Roots	Rot				
Ruby	Sample log				
Samples	Sativus				

(*Continued*)

(Continued)

Group 0—Black	Group 0—Black	Group 1—Yellow	Group 2—Orange	Group 3—Red	Group 4—Green
Scale	Seed				
Sensory	Shelf				
Single pass	Sir				
Solids	Species				
Spheres	Splitting				
Sprouts	Stage				
Star	Storage fruit				
System	Table				
Tha	Tissue				
Total	Treated				
Treated rate	Treatment				
Tuber	Type				
Ulo	medium wave ultraviolate light (UVB)				
short wave ultraviolate light (UVC)	Values				
Var	Varieties				
Vase	Vegetables				
Violetto	Wash				
Washing	Water				
Water effect	Water mold				
Weeks	Weeks globe				
Weight peel	Wholesalers				
Wine	Yellowing				
Yield					

References

Abrisqueta, I., Abrisqueta, J. M., Tapia, L. M., Munguía, J. P., Conejero, W., Vera, J., & Ruiz-Sánchez, M. C. (2013). Basal crop coefficients for early-season peach trees. *Agricultural Water Management*, *121*, 158–163.

Basu, A., Nguyen, A., Betts, N. M., & Lyons, T. J. (2014). Strawberry as a functional food: An evidence-based review. *Critical Reviews in Food Science and Nutrition*, *54*, 90–806.

Bekele, E. A., Ampofo-Asiama, J., Alis, R. R., Hertog, M. L. A. T. M., Nicolaï, B. M., & Geeraerd, A. H. (2016). Dynamics of metabolic adaptation during initiation of controlled atmosphere storage of 'Jonagold' apple: Effects of storage gas concentrations and conditioning. *Postharvest Biology and Technology*, *117*, 9–20.

Büchert, A. M., Civello, P. M., & Martínez, G. A. (2011). Chlorophyllase vs pheophytinase as candidates for chlorophyll dephytilation during senescence of broccoli. *Journal of Plant Physiology*, *168*, 337–343.

Carew, R., & Florkowski, W. J. (2007). Contribution of health attributes, research investment, and innovation to developments in the blueberry industry. *International Journal of Fruit Science*, *6*(2), 23–46.

Carew, R., Florkowski, W. J., & He, S. (2005). Contribution of health attributes, research investment and innovation to developments in the blueberry industry: A Canada-U.S. comparison. *International Journal of Fruit Science*, *5*(4), 95–117.

Casals, C., Teixidó, N., Wiñas, I., Silvera, E., Lamarca, N., & Usall, J. (2010). Combination of hot water, *Bacillus subtilis* CPA-8 and sodium bicarbonate treatments to control postharvest brown rot on peaches and nectarines. *European Journal Plant Pathology*, *128*, 51–63.

Chung, S. W., Yu, D. J., Oh, H. D., Ahn, J. H., Huh, J. H., & Lee, H. J. (2019). Transcriptional regulation of abscisic acid biosynthesis and signal transduction, and anthocyanin biosynthesis in 'Bluecrop' highbush blueberry fruit during ripening. *PLoS One*, *14*(7), e0220015. Available from https://doi.org/10.1371/journal.pone.0220015.

Dávila-Aviña, J. E., Villa-Rodríguez, J. A., Villegas-Ochoa, M. A., Tortoledo-Otriz, O., Olivas, G. I., Ayala-Zavala, J. F., & González-Aguilar, G. A. (2014). Effect of edible coatings on bioactive compounds and antioxidant capacity of tomatoes at different maturity stages. *Journal of Food Science and Technology*, *51*(10), 2706–2712.

Evans, E. A., Bollen, F. H., & Siddiq, M. (2020). Banana production, global trade, consumption trends, postharvest handling, and processing. In M. Siddiq, J. Ahmed, & M. G. Lobo (Eds.), *Handbook of banana production, postharvest science, processing technology and nutrition*. Wiley & Sons, Ltd, ch 1.

Florkowski, W., & Łysiak, G. (2015). Opportunities for horticultural production in Podlaskie Voivodeship: Pears for fresh fruit market. *Optimum—Studia Ekonomiczne*, *78*(6), 159–167. Available from https://doi.org/10.15290/ose.2015.06.78.12.

Florkowski, W. J., Klepacka, A. M., Nambiar, P. M., Meng, T., Fu, S., Sheremenko, G., & Sarpong, D. B. (2014). Consumer expenditures on fresh fruit and vegetables. In W. J. Florkowski, R. L. Shewfelt, B. Brueckner, & S. E. Prussia (Eds.), *Postharvest handling: A systems approach* (pp. 147–166). Elsevier.

Franck, M., de Toro-Martin, J., Garneau, V., Guay, V., Kearney, M., Pilon, G., ... Vohl, M.-C. (2020). Effects of daily raspberry consumption on immune-metabolic health in subjects at risk of metabolic syndrome: A randomized controlled trial. *Nutrients*, *12*, 3858.

Globalnewswire.com (2021). *Global tomato industry report 2020: Trends & opportunities by country, consumption, production, price developments, imports and exports (2007–2025)*. https://www.globenewswire.com/news-release/2020/02/14/1985135/0/en/Global-Tomato-Industry-Report-2020-Trends-Opportunities-by-Country-Consumption-Production-Price-Developments-Imports-and-Exports-2007-2025.html Accessed 28.04.21.

Herremans, E., Melado-Herreros, A., Defraeye, T., Verlinden, B., Hertog, M., Verboven, P., ... Nicolaï, B. M. (2014). Comparison of X-ray CT and MRI of watercore disorder of different apple cultivars. *Postharvest Biology and Technology*, *87*, 42–50.

Huh, Y. C., Choi, H. S., & Kim, S. (2014). orphological characterization of Korean and Turkish watermelon germplasm. *Korean Journal of Agricultural Science*, *41*(4), 309–314. Available from https://doi.org/10.7744/CNUJAS.2014.41.4.309.

Hwang, J.-H., & Lim, S. B. (2015). Antioxidant and anticancer activities of broccoli by-products from different cultivars and maturity stages at harvest. *Preventive Nutrition and Food Science*, *20*, 8–14.

Khadka, R. B., Marasini, M., Rawal, R., Gautam, D. M., & Acedo, A. L., Jr. (2017). Effects of variety and postharvest handling practices on microbial population at different stages of the value chain of fresh tomato (*Solanum lycopersicum*) in Western Terai of Nepa. *BioMed Research International*, *2017*(7148076), 6.

Kiani, J., & Imam, S. (2007). Medicinal importance of grapefruit juice and its interaction with various drugs. *Nutrition Journal*, *6*, 33. Available from https://doi.org/10.1186/1475-2891-6-33.

Kurzer, A. B., Bechtel, R., & Ginard, J.-X. (2019). Adult and child focus group views of oranges and mandarins. *HortTechnology*, *24*(4), 408–416.

Luna, M. C., Tudela, J. A., Martínez-Sánchez, A. M., Allende, A., & Gil, M. I. (2013). Optimizing water management to control respiration rate and reduce browning and microbial load of fresh-cut romaine lettuce. *Postharvest Biology and Technology*, *80*, 9–17.

Luna, M. C., Tudela, J. A., Tomás-Barberán, F. A., & Gil, M. I. (2016). Modified atmosphere (MA) prevents browning of fresh-cut romaine lettuce through multi-target effects related to phenolic metabolism. *Postharvest Biology and Technology*, *119*, 84−93.

Lurie, S. (2021). Genomic and transcriptomic studies on chilling injury in peach and nectarine. *Postharvest Biology and Technology*, *174*, 111444.

Mellidou, I., Buts, K., Hatoum, D., Ho, Q. T., Johnston, J. W., Watkins, C. B., ... Nicolai, B. M. (2014). Transcriptomic events associated with internal browning of apple during postharvest storage. *BMC Plant Biology*, *14*(328), 1471−2229.

Moggia, C., Graell, J., Lara, I., Schmeda-Hirschmann, G., Thomas-Valdés, S., & Lobos, G. A. (2016). Fruit characteristics and cuticle triterpenes as related to postharvest quality of highbush blueberries. *Scientia Horticulturae*, *211*, 449−457.

Mordoerintelligence.com (2021). *Fresh apple market − Growth, trends, Covid-19 impact, and forecasts (2021−2026)*. https://www.mordorintelligence.com/industry-reports/fresh-apples-market#:∼:text = Market%20Overview, period%. Accessed 02.04.21.

Pânzaru, R. L., & Medelete, D. M. (2013). International trade with onions. *Economic Engineering in Agriculture and Rural Development*, *12*, 301−306.

Rawal, R., Gautam, D. M., Khadka, R. B., Gautam I. P., Mishra, K., Acedo A. L., Jr., ... Keatinge, J. D. H. (2016). Fruit quality characters of tomato (*Solanum lycopersicum*) genotypes differed by maturity stages. In: *Fifth international conference on agriculture, environment and biological sciences ICAEBS-16*, April 28−29, Pattaya, Thailand. https://doi.org/10.17758/IAAST.A0416069.

Rocha, D. M. U. P., Silva Caldas, A. P., Pereira da Silva, B., Hermsdorff, H. H. M., & de Cássia Gonçalves Alfenas, R. (2018). Effects of blueberry and cranberry consumption on type 2 diabetes glycemic control: A systematic review. *Critical Reviews in Food Science and Nutrition*, *59*, 1816−1828.

Rybarczyk-Plonska, A., Wold, A.-B., Bengtsson, G. B., Borge, G. I. A., Hansen, M. K., & Hagen, S. F. (2016). Flavonols in broccoli (*Brassica oleracea* L. var. italica) flower buds as affected by postharvest temperature and radiation treatments. *Postharvest Biology and Technology*, *116*, 105−114.

Walsh, K. A., Bennett, S. D., Mahovic, M., & Gould, L. H. (2014). Outbreaks associated with cantaloupe, watermelon, and honeydew in the United States, 1973−2011. *Foodborne Pathogens and Disease*, *vol. 11*, 945−952.

CHAPTER

19

Compositional determinants of fruit and vegetable quality and nutritional value

Ariel R. Vicente[1], *George A. Manganaris*[2], *Magalí Darre*[1], *Cristian M. Ortiz*[1], *Gabriel O. Sozzi*[3] and *Carlos H. Crisosto*[4]

[1]Research Laboratory in Agroindustrial Products (LIPA), National University of La Plata, La Plata, Argentina [2]Department of Agricultural Sciences, Biotechnology and Food Science, Cyprus University of Technology, Lemesos, Cyprus [3]National Council of Scientific and Technical Research (CONICET), Buenos Aires, Argentina [4]Department of Plant Sciences, University of California, Davis, CA, United States

19.1 Introduction

Chronic diseases such as heart disease, stroke, cancer, and diabetes are a leading cause of mortality (Narayan et al., 2020). Excessive weight and outright obesity are also a growing concern. These problems have been linked to lifestyle choices. A growing body of research indicates that eating fruits and vegetables reduces the risk of major diseases and delays the onset of age-related disorders, due to the contribution of nutrients and bioactive compounds and by displacing highly processed foods (Roman, Jackson, Gadhia, Roman, & Reis, 2019; Vainik, García-García, & Dagher, 2019).

The dietary constituents obtained from fruits vegetables include water, fiber, proteins (legumes), sometimes fats (olive, avocado, and nuts), minerals and digestible carbohydrates. Starch-based staples, such as potato, cassava, corn, banana, and plantain, provide a major energy source in several regions, being particularly important dietary sources in developing countries (Rinaldo, 2020). Fruits and vegetables are the main dietary source of vitamin C and a significant source of provitamin A and vitamin B_6 (Sarker, Hossain, & Oba, 2020). Compared to other food sources, they are high in potassium and low in sodium. Ascorbic acid (AsA) in horticultural commodities may enhance the bioavailability of dietary iron (Nowak, Gośliński, Wojtowicz, & Przygoński, 2018). Fruits and vegetables are low in calories (excluding staple crops) and are cholesterol-free. They also include a variety of nonnutritive bioactive phytochemicals (phytosterols, carotenoids such

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00019-1

as lycopene, AsA, tocopherols, glucosinolates, thiosulfinates, and phenolics) that may help to prevent disease incidence (Alasalvar, Salvadó, & Ros, 2020). This has led to the current recommendation that healthful diets include a variety of fresh horticultural commodities (www.dietaryguidelines.gov). Despite efforts made in the last decade, in the United States, only 1 in 10 adults eat enough fruits or vegetables (https://www.cdc.gov/). This chapter provides an overview of the composition and nutritional properties of fruits and vegetables (see also Chapter 19: Nutritional quality of fruits and vegetables).

19.2 Nutrient components

19.2.1 Water

Water is the most abundant single component of fresh fruits and vegetables. The amount varies among individual commodities due to structural differences. In leafy vegetables, water may comprise up to 97% of the mass. Water is essential for good health and though individual needs depend on environmental conditions, diet, and physical activity, an intake of 2–3 L/day is recommended.

19.2.2 Proteins and nitrogen compounds

Proteins represent <1% of the fresh mass of most fruit and vegetable tissues. Vegetables account for ~6% of protein intake in the United States, while fruits contribute with 1% (Hiza & Bente, 2007). Fruits may be also rich in simple nitrogenous substances such as free amino acids, chlorophylls, polyamines, or alkaloids. In apple, estimates range from 10% to 70%. Senescent tissues and overripe fruits may contain greater proportions of nonprotein nitrogen. Asparagine is abundant in potato and apple nonprotein nitrogen fractions. Pears and oranges are rich in proline; black and red currants, in alanine; and dates, in hydroxyproline (Maqsood, Adiamo, Ahmad, & Mudgil, 2020). The nitrogen steroidal glycoalkaloids (GLS) α-solanine and α-chaconine can induce neurological disorders. Solanin concentrations exceeding 20 mg/100 g fresh weight (FW) are unsafe for human consumption (Jamakhani, Lele, & Rekadwad, 2018). Solanin is present at highest concentration immediately under the skin of potatoes. Its concentration is 5–15 mg/100 g but may increase if tubers are light-exposed or under conditions that promote sprouting. As a rule, fluorescent light above 800-lx exposure at 20°C, for a few days, will initiate the greening process. Consequently, tubers must be stored in cool conditions and 90% relative humidity and complete darkness to prevent deterioration. Adequate and unrestricted air movement is also necessary to maintain constant temperature and humidity throughout the storage pile and to prevent excessive shrinkage from moisture loss and decay.

19.2.3 Lipids and fatty acids

Plant lipids are a large group of compounds with many functions. They could be stored as energy reserves or have structural functions such as in cellular membranes and cuticular waxes. They are present as triglycerides (esters of glycerol and three fatty acids). Yet, they include diverse chemical forms. For instance, phospholipids, in which one fatty acid is replaced by phosphoric acid, are important membrane constituents. The lipid concentration in fruit vegetables varies with the commodity. For most commodities, besides avocado and olive, lipids account for less than 1% (e.g., 0.2% in grape, 0.1% in banana, and 0.06% in apple). Lipids comprise 35%–70% of dry mass in avocado, olive, and nuts (Maestri, Cittadini, Bodoira, & Martínez, 2020).

The physical and chemical properties of lipids are determined by their constituent fatty acids. Most fatty acids in foods are aliphatic, contain 4–26 carbons, and are monocarboxylic. They may be saturated or unsaturated to varying degrees. Oleic (18:1) and linoleic (18:2) acids are the most abundant. Lipids derived from vegetable sources tend to be richer in unsaturated fatty acids than animal fats (Table 19.1). Olive oil and other fats high in unsaturated fatty acids lower low density lipoprotein (LDL) cholesterol (so-called bad cholesterol) while protecting high density lipoprotein (HDL) cholesterol ("good" cholesterol) when consumed in moderation in place of saturated fats (Tomé-Carneiro, Crespo, López de Las Hazas, Visioli, & Dávalos, 2020). Each fatty acid double bond has either *cis* or *trans* conformation. In the *cis* geometry, the carbons next to the unsaturated site bond atoms are oriented toward the same side. In plants, unsaturated fatty acids are in the *cis* form. *Trans*-fatty acids may be present in animal fats or produced during processing (e.g., hydrogenation of vegetable oils). Excessive *trans*-fat intake has a high correlation with atherosclerosis and coronary heart disease (El-Aal, Abdel-Fattah, & Ahmed, 2019). Fatty acids are required for human body functions: to produce lipids and hormone-like substances that regulate blood pressure, blood clotting, immune, and inflammatory responses.

TABLE 19.1 Fatty acid, vitamin E, and cholesterol composition of some common dietary fats. (Kays, 1997)

	Saturated (%)	Monounsaturated (%)	Polyunsaturated (%)	Cholesterol (mg/100 g)
Animal fats				
Lard	40.8	43.8	9.6	93
Butter	54.0	19.8	2.6	230
Vegetable fats				
Coconut oil	85.2	6.6	1.7	0
Palm oil	45.3	41.6	8.3	0
Cottonseed oil	25.5	21.3	48.1	0
Wheat germ oil	18.8	15.9	60.7	0
Soya oil	14.5	23.2	56.5	0
Olive oil	14.0	69.7	11.2	0
Corn oil	12.7	24.7	57.8	0
Sunflower oil	11.9	20.2	63.0	0
Safflower oil	10.2	12.6	72.1	0
Canola oil	5.3	64.3	24.8	0

From Kays, S. J. (1997). Postharvest physiology of perishables plant products. *Athens, GA: Exon Press.*

Plant-derived foods do not have significant amounts of cholesterol but contain cholesterol-like steroids or phytosterols (Asl, Niazmand, & Jahani, 2020). They are absorbed only in trace amounts but inhibit absorption of intestinal cholesterol. Fat-rich fruits and nuts, cauliflower, broccoli, and carrots are good sources of phytosterols (Shahzad et al., 2017). Natural dietary intake varies from 167 to 437 mg/day, being higher in vegetarian diets (1 g/day) (Ostlund, 2002).

19.2.4 Organic acids

Organic acids (OAs), defined by the presence of carboxylic acid groups, are divided into aliphatic (straight chain) and aromatic (Chahardoli, Jalilian, Memariani, Farzaei, & Shokoohinia, 2020). Citrate, malate, and tartrate, the most abundant acids in fruits and vegetables, are aliphatic. Malate is the major acid in pome- and stone-fruit species; citrate is abundant in citrus species, soft fruits, melon, and tomato, while tartrate is predominant in grapes. Aromatic OAs occur in several fruits but at low concentrations. Benzoic acid is found in cranberry; quinic acid, in banana and kiwifruit; and chlorogenic acid, in potato and eggplant. Based on the number of carboxylic groups, acids are divided in mono-, di-, or tricarboxylic acids. Citrate is tricarboxylic, while malate and tartrate are both dicarboxylic. Lactic and acetic acids are monocarboxylic and are present in significant amounts in picked or acidified vegetables.

Fruits are more acidic than most vegetables. Acidic foods are also most commonly spoiled by fungi, while neutral or low acid products stands as appropriate hosts for bacterial infection (see also Chapter 20). Except for lemons, acidity decreases with the progress of ripening. Opposite to apples and pears, in peaches, citrate decreases faster than malate. OA distribution within a fruit may not be uniform. For instance, the inner pulp of eggplants is less acidic than the region closer to the peel.

OAs play several different roles in fruits. They have a major effect on taste (see also Chapter 15: Cooling fresh produce). Some nutrients, such as vitamin C, are OAs. The most common fruit OAs can be a source of energy, since they can be incorporated into the tricarboxylic acid cycle, yielding ATP. Besides, OA C chains are precursors for synthesis of several important molecules, including some amino acids. Fruit OAs may stabilize some vitamins and prevent oxidation of phenolic compounds during processing.

19.2.5 Digestible carbohydrates

Carbohydrates are the second most abundant constituents in fruits and vegetables. They may account for 50%−80% of dry weight. Nonstarchy root vegetables (parsnip, beetroot, and carrot) are rich in simple sugars (8%−18%). But, most vegetables contain smaller amounts of digestible carbohydrate. Carbohydrate stores energy reserves and makes cell structural framework. Simple carbohydrates are important components of sensory quality. Carbohydrates and proteins yield 4 kCal/g while fats yield nine. In some fruits, monosaccharides are the major sugars. Glucose and fructose are the most common simple sugars in fruits. The disaccharide sucrose is the primary sugar transported in plants. These three sugars are responsible for the sweet taste of fruits and vegetables. In many fruits, (apple, pear, strawberry, figs, melon, and grape), glucose and fructose are predominant. In parsnip, beetroot, carrot, onion, sweet corn, pea, and sweet potato, banana, pineapple, peach, and melon, sucrose is the more abundant sugar (Byeon & Lee, 2020). Mono- and disaccharide sugars (xylose, arabinose, mannose, galactose, and maltose) may also be present but in small amounts.

19.2.6 Dietary fiber

19.2.6.1 Definition and composition

Dietary fiber includes nondigestible carbohydrates (cellulose, hemicelluloses, pectins, resistant starch, and nondigestible oligosaccharides and lignin) (Saldívar & Soto, 2020). Fiber-rich products include most fruits and vegetables, seeds, and whole cereals (Canteri, Renard, Le Bourvellec, & Bureau, 2020).

19.2.6.1.1 Cellulose

Cellulose is a cell wall polymer consisting of β-1,4-linked glucose. Individual glucan chains associate through hydrogen bonds to form stable microfibrils (Carpita & McCann, 2015). The cell wall of fruits and vegetables is 1%–2% of FW and cellulose can be one-third of that. Except for avocado, in which the whole cell wall is degraded, there is little change in cellulose concentration during ripening.

19.2.6.1.2 Hemicelluloses

Hemicelluloses are alkali-soluble polymers. Primary cell walls contain 25%–35% hemicelluloses (Carpita & McCann, 2015). The most common compound within this group in dicotyledonous species is xyloglucan, characterized by a backbone of β-1,4-linked glucose with α-1,6-linked xylosyl lateral chains. The pentose residues can be further decorated with galactose, arabinose, and/or fucose. Xylans are abundant hemicellulose in monocot species, with a backbone of β-1,4-linked xylose decorated with side chains of arabinose and/or glucuronic acid. Other less abundant hemicelluloses include glucomannans, galactomannans, and galactoglucomannans

19.2.6.1.3 Pectins

Pectins are also a diverse group, with a high proportion of galacturonic acid as a common feature. Fruit tissues are particularly rich in pectins, which can be up to 40% of the cell wall polysaccharides. Extensive work has demonstrated a central role of pectin degradation in fruit softening. The most abundant cell wall polyuronide is homogalacturonan, a homopolymer of α-1,4-linked galacturonic acid with variable degree of methyl esterification at C6. The degree of polymerization and proportion of methyl esters affect pectin solubility. The degree of pectins methyl esterification decreases during ripening as well as its size for example in berries, grape, and apricot (Ayour et al., 2020; Leszczuk, Kalaitzis, Blazakis, & Zdunek, 2020; Vicente, Saladié, Rose, & Labavitch, 2007). The extent of pectin depolymerization is variable: avocado fruit undergoes a dramatic decrease in polyuronide size, while only small changes occur in peppers and some berries (Vicente et al., 2007). Rhamnogalacturonan I (RGI) and II (RGII) are also pectic polysaccharides present in plant cell walls. RGI has a backbone of alternating α-1,2-rhamnosyl and α-1,4-galacturonosyl residues with side chains rich in arabinose and galactose. Losses of side chain residues are common during fruit ripening and affect pectin solubility and hydration potential (Uluisik & Seymour, 2020). RGII is the most complex cell wall polysaccharide and forms diamers via borate diester bonds.

Good sources of pectin include apple, or sugar beet, and may be used as stabilizers in jams and jellies, as fat replacers and probiotic vehicles (Khedmat, Izadi, Mofid, & Mojtahedi, 2020).

19.2.6.1.4 Lignin

Lignin, cellulose, and chitin are the most abundant biopolymers in nature. Lignin is an aromatic heteropolymer formed by the association of three hydroxycinnamyl alcohol derivatives (*p*-coumaryl, coniferyl, and sinapyl alcohols) (Vanholme, De Meester, Ralph, & Boerjan, 2019). It is a resistant polymer present in secondary cell walls and is associated with fiber sclereids, xylem vessels, seed coats, and pith of some fruits. Most fruits and vegetables have low lignin concentrations, but in some commodities, it can impair quality. Loquat fruit exhibits chilling injury (CI) symptoms after extended cold storage, evident as increased firmness and lignin content, decreased juice yield, and loss of fruit flavor (Huang, Zhu, Zhu, Wu, & Chen, 2019). Lignin deposition in asparagus spears during storage increases toughness (Lwin, Srilaong, Boonyaritthongchai, Wongs-Aree, & Pongprasert, 2020).

19.2.6.1.5 Resistant starch

Starches are polysaccharides of glucosyl residues linked by α-D-(1−4) and/or α-D-(1−6) linkages. Resistant starch and its degradation products are not digested in the small intestine. The microbiota ferments it in the large intestine (Öztür & Mutlu, 2019). Legumes are rich in resistant starch. Up to 35% of this polysaccharide could escape digestion (Marlett & Longacre, 1997). Unripe bananas, mango, and potato are also rich in resistant starch (Quintero-Castaño, Castellanos-Galeano, Álvarez-Barreto, Bello-Pérez, & Alvarez-Ramirez, 2020).

19.2.6.1.6 Nondigestible oligosaccharides

Oligosaccharides are low molecular weight carbohydrates, intermediate between simple sugars and polysaccharides. Oligosaccharides could be hydrolyzed in the digestive tract or resist digestion. Common oligosaccharides include raffinose, stachyose, and verbascose. Legumes, nuts, and blueberry are rich in NDOs (Coleman & Ferreira, 2020; Dahl & Alvarez, 2019).

19.2.6.2 Benefits of fiber intake

Dietary fiber modulates the intestinal function (see also Chapter 19: Nutritional quality of fruits and vegetables). Fiber-rich meals promote satiety earlier, have fewer calories. They also improve glycemic control and bodyweight management (Marlett, McBurney, & Slavin, 2002; Martin, Zhang, Tonelli, & Petroni, 2013). High fiber intake reduced cholesterol and blood pressure as well as the risk of coronary disease and colorectal cancer (Martin, Butelli, Petroni, & Tonelli, 2011). On the other side is rich mineral phytochemicals (Palafox-Carlos, Ayala-Zavala, & González-Aguilar, 2011). A growing body of evidence shows that fiber has a major impact in gut microbiome (Chijiiwa et al., 2020; Myhrstad, Tunsjø, Charnock, & Telle-Hansen, 2020). National dietary guidelines recommend a dietary fiber intake of 38 and 25 g/day for men and women. The average fiber intake of United States adults is less than half of this (Soliman, 2019). Good examples of fiber rich fresh fruits are mango, orange, papaya, sweet lime, and watermelon among tropical and subtropical species, apple among temperate species (Ramulu & Rao, 2003), and leafy species and gourds among vegetables (Khanum, Swamy, Krishna, Santhanam, & Viswanathan, 2000; Li, Andrews, & Pehrsson, 2002).

19.2.6.3 Sources of fiber

Whole grains, fruits, and vegetables are good sources of fiber. Fruits and vegetables provide 37% of the fiber in the diet, followed by grains (36%) and legumes (13%) (Hiza & Bente, 2007). Fruits and vegetables average 1%–3% fiber on a FW basis (Table 19.2). Fiber properties differ depending on the food source. Pectin is low in grains but makes up ~20%–35% of total fiber in fruits, vegetables, legumes, and nuts. Hemicelluloses account for about half of the total fiber in grains, but 25%–35% of total fiber in other foods. Cellulose is one-third or less of total fiber in most foods (Guillon & Champ, 2000). During storage, fruit fiber solubility increases. In contrast, it becomes more insoluble in some vegetables (artichoke, celery, and asparagus). Processing or home preparation, other than peeling, do not cause major fiber loss.

19.2.7 Vitamins

They are essential compounds required in trace amounts that cannot be produced in enough quantities. The term derives from "vital amine," because thiamine, the first one described contained an amino group (Godswill, Somtochukwu, Ikechukwu, & Kate, 2020). They are vitamin A (retinol), B1 (thiamine), B2 (riboflavin), B3 (niacin), B5 (pantothenic acid), B6 (pyridoxine), B9 (folate/folic acid), biotin, choline, and B12 (cyanocobalamine), and vitamins C, D, E, and K (Price & Preedy, 2020).

19.2.7.1 Provitamin A

The term provitamin A refers to precursors of vitamin A, playing a crucial role in vision, bone development, and reproduction. They are carotenoids formed by eight isoprene units (2-methyl-1,3-butadiene) which contain an unsubstituted β-ring with an 11-carbon polyene chain. Around 60 carotenoids meet this structural need, the most common being α- and β-carotene and cryptoxanthin Table 19.3. Adult daily vitamin A need is 5000 international units (1 IU = 0.3 μg retinol or 0.6 μg β-carotene). Vitamin A deficiency is frequent in populations having single, starch-based crop diets (Mayer, Pfeiffer, & Beyer, 2008). It can cause in severe cases blindness or even death. The problem affects about one-third of children under the age of five worldwide, especially in Africa and Asia (Watkins & Pogson, 2020). Commodities rich in provitamin A include carrot, pumpkin, peach, and mango.

19.2.7.2 Vitamin B complex

Thiamine pyrophosphate is an enzyme cofactor, present in all living systems. It is particularly important in carbohydrate metabolism. A daily intake of 1–2 mg is recommended for a normal adult. Thiamine is more heat stable than ascorbic. Yet, at cooking temperatures and low acid conditions large losses (25%–40%) may occur.

TABLE 19.2 Fiber content of selected fruits, vegetables, and nuts. (U.S. Department of Agriculture, 2008)

Product	Dietary fiber (%)
Almond	12.2
Apple	2.4
Asparagus	2.1
Avocado	6.8
Banana	2.6
Broccoli	2.6
Carrot	2.8
Kiwifruit	3.4
Lettuce	2.1
Onion	1.7
Orange	2.4
Pea	2.6
Peach	1.5
Peanut	8.5
Pear	3.1
Pepper	2.1
Pineapple	1.4
Plum	1.4
Potato	2.2
Prune	7.1
Raisin	3.7
Spinach	2.2
Strawberry	2.0
Tomato	1.2
Walnut	6.7

From US Department of Agriculture (2008).'Composition of foods, raw, processed, prepared' USDA national nutrient database for standard reference, release 20. *Beltsville, MD: USDA-ARS, Beltsville Human Nutrition Research Center, Nutrient Data Laboratory. http://www.ars.usda.gov/nutrientdata. Accessed 04/2008.*

Riboflavin is the central component of flavoproteins. The average human requires 1–2 mg/day. Green vegetables such as bean, beet, pepper, and spinach are good sources of riboflavin.

TABLE 19.3 Carotene concentration (mean values) of selected fruits.

Product	Carotene (μg/100 g)
Mango	1800
Cantaloupe	1000
Pawpaw	810
Guava	435
Apricot	405
Plum	295
Watermelon	230

From (Rodriguez-Amaya, 2001).

Niacin, or nicotinic acid, is a precursor to nicotinamide adenine dinucleotide (NAD) and icotinamide adenine dinucleotide phosphate (NADP). A daily intake of 10−15-mg niacin is recommended. Almonds, avocado and cape gooseberries are good sources. It is stable but is not stored in the body more than 0−14 days. Deficiency symptoms include skin inflammation, depression and psychiatric affections (Price & Preedy, 2020).

Vitamin B5 or pantothenic acid deficiency leads to fatigue, headaches, sleep disturbances, tingling of hands, and impaired immune responses. Meats, potatoes, oat cereals, tomato products, and whole grains were among the better sources of pantothenic acid (Walsh, Wyse, & Hansen, 1981). Also, pantothenic acid is discreetly present in bananas and citrus fruits (de Assis et al., 2020).

Vitamin B6 (pyridoxal phosphate) is a common cofactor in transamination, decarboxylation, and deamination reactions. Formation of the ethylene precursor 1-Aminocyclopropane 1-Carboxylic Acid (ACC) by ACC synthase in plants requires pyridoxal phosphate. Common symptoms of vitamin B6 deficiency include dermatitis around the eyes, elbows, and mouth. It can also lead to dizziness, vomiting, weight loss, and severe nervous disturbances. Sources of vitamin B6 include bean, cabbage, cauliflower, spinach, sweet potato, grape, avocado, and banana.

Biotin deficiency leads to depression, sleeplessness, and muscle pains. It occurs in peas, beans, nuts, broccoli, mushrooms, potatoes, strawberries and sweet potatoes.

Folic acid is essential for reproduction and normal growth. Folate deficiency causes neural tube defects and anemia (García-Salinas, Ramos-Parra, & de la Garza, 2016). It is present in strawberry, tomato, avocado, spinach, cabbage and other green vegetables (Muley & Singhal, 2020). Vitamin B12 does not occur in fruits and vegetables.

19.2.7.3 Vitamin C

AsA and its first oxidation product dehydroascorbic acid are both considered vitamin C. AsA is a water-soluble, carbohydrate-derived compound with antioxidant and acidic properties due to a 2,3-enediol moiety (Fig. 19.1). Humans and a few other species cannot synthesize it (Kang et al., 2020), because the gene coding for the last enzyme in the pathway (L-gulono-1,4-lactone oxidase) is not functional. AsA is involved in collagen biosynthesis. Even though nutritional deficiencies are rare in modern Western cultures, it is generally recognized that

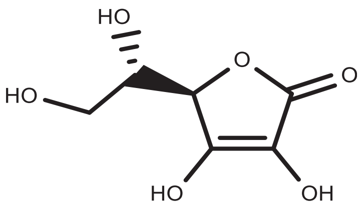


FIGURE 19.1 Structure of ascorbic acid, a primary antioxidant present in fruits and vegetables.

TABLE 19.4 Vitamin C concentration (mean values) of selected fruits. (Salunkhe, Bolin, and Reddy, 1991).

Product	Vitamin C (mg/100 g)
Guava, raw	184
Kiwi, raw	118
Litchi, raw	72
Pawpaw, raw	62
Strawberry, raw	57
Citrus fruits	31-53
Cantaloupe	42

From Salunkhe, D. K., Bolin, H. R. & Reddy, N. R. (Eds.) (1991). Storage, processing, and nutritional quality of fruits and vegetables. Volume I. Fresh fruits and vegetables. *Boston, MA: CRC Press.*

dietary AsA has important health benefits (Hancock & Viola, 2005). In meat-poor diets, dietary AsA can improve iron uptake. The recommended dietary allowance of vitamin C is 75 and 90 mg/day for men and young women (Levine, Wang, Padayatty, & Morrow, 2001). Plants synthesize AsA via a pathway that uses L-galactose as a precursor. A galacturonic acid pathway is also present in plants (Yuan et al., 2020). Fruits, vegetables, and juices are the main dietary sources (90%) of vitamin C (Hiza & Bente, 2007). Vitamin C concentration varies depending on the commodity from one to 150 mg/100 g (Lee & Kader, 2000). In berry fruits, AsA ranged from 14 to 103 mg/100 g (Pantelidis, Vasilakakis, Manganaris, & Diamantidis, 2007). Rosehip, jujube, guava, kiwifruit, peppers, citrus fruit, spinach, broccoli, and cabbage are rich in AsA (Table 19.4). For any given product, AsA concentrations vary due to environmental factors. Sunlight exposure is a main factor determining AsA concentration (Kang et al., 2020). In general, more sunlight received during growth increases AsA. Retention of AsA is also affected by storage and processing conditions. Potatoes lose up to 80% of the original AsA over 9 months storage. Most other fruits and vegetables also lose AsA during storage. AsA stability is reduced at high temperatures and bruising increases AsA degradation. AsA is susceptible to oxidation (Sanmartin, Pateraki, Chatzopoulou, & Kanellis, 2007). During cooking, high losses of vitamin C occur. Starchy vegetables lose 40%–80% of the vitamin C during cooking due to leaching and oxidation. Freezing does not reduce vitamin C content, but losses are found after long-term frozen storage (Leong & Oey, 2012).

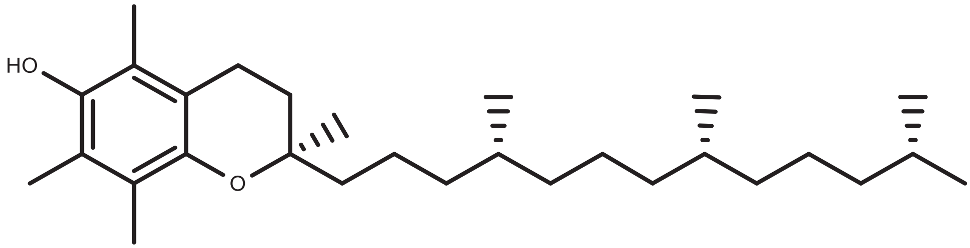


FIGURE 19.2 Structure of tocopherol.

19.2.7.4 Vitamin D

Vitamin D promotes calcium and phosphate absorption, and thus it aids bone and tooth mineralization. It also exerts a role in cell signaling and in the inhibition of autoimmune responses related to carcinogenic and cardiovascular disease (Price & Preedy, 2020). It occurs in trace amounts in fruits and vegetables. Vitamin D insufficiency affects almost 50% of the population worldwide. The major source of vitamin D for children and adults is exposure to natural sunlight. Approximately 20% of total vitamin D is obtained through the diet (Borel, Caillaud, & Cano, 2015).

19.2.7.5 Vitamin E

Vitamin E is a general term used to describe a group of eight lipophilic compounds known as tocochromanols (Mellidou et al., 2018). These compounds exist in eight forms (four tocopherols and four tocotrienols). All isomers have aromatic rings with a hydroxyl group that donates hydrogen atoms to reduce reactive oxygen species (ROS). The terms α, β, γ, and δ refer to the number and position of methyl groups on the chromanol ring. All forms have vitamin E activity, but α-tocopherol is the most active (Fig. 19.2). The biological role of vitamin E relies on its antioxidant properties (Price & Preedy, 2020). It is abundant in oily seeds, olives, nuts, peanuts, avocados, and almonds. In olives, tocochromanol levels and composition were dependent on cultivar and, to a lesser extent, on fruit developmental stage (Georgiadou et al., 2019). Broccoli and leafy vegetables have less tocopherol than fats and oils but are still a good source. Vitamin E is strong antioxidant involved in cell membrane protection during storage. Vitamin E remains relatively stable in fruits and vegetables during storage, but not many studies have characterized tocopherol metabolism during postharvest life.

19.2.7.6 Vitamin K

Vitamin K is essential for bone metabolism, the antiinflamatory response, and blood coagulation. With a recommended daily intake of 120 μg, vitamin K deficiency is uncommon (Johnson, 2020). It is abundant in lettuce, spinach, cauliflower, and cabbage. Also, it can be produced by gut microbiota.

19.2.8 Minerals

Mineral nutrition is of interest to plant postharvest biologists because of the many processes it is involved in, its effect on internal and external quality traits of fruits and vegetables that affect consumer behavior, and the benefits of an adequate and balanced intake for human health. The level of minerals in fruit and vegetables at harvest can be affected by soil nutrient availability, fertilization practices, and prevailing growing conditions. The mineral contents in fruit and vegetable tissues can also show variations due to losses of water and respirable substrates. Postharvest deliberate supplementations would also alter the level of the minerals applied.

Although there is no universally accepted definition or classification, the dietary "minerals" support the biosynthetic apparatus with required elemental components other than carbon (C), hydrogen (H), and oxygen (O). Seventeen nutrient elements are essential in plants. The three elements most abundant in plant tissues, C, H, and O, are not minerals. The remaining 14 mineral elements are required by plants for successful completion of their life cycle, as components of essential plant components or metabolites. Minerals are classified as macrominerals or microminerals, based on the relative concentrations of each nutrient considered adequate for normal tissue function. Plant macrominerals include nitrogen (N), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and sulfur (S). Their concentrations in plant tissues range from 1000 to 15,000 μg/g dry weight. Macrominerals can also be classified into those that maintain their identity as ions within plant tissues (K^+, Ca^{2+}, and Mg^{2+}) and those that are assimilated into organic compounds (N, P, and S). Plant essential microminerals include chlorine (Cl), boron (B), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), molybdenum (Mo) and nickel (Ni), and their concentrations are 100- to 10,000-fold less than those of macrominerals. Other microminerals such as sodium (Na), silicon (Si), and cobalt (Co) may be beneficial over a certain concentration range. Fluorine and iodine are essential for animal and human health but not for plant growth.

Minerals in food items are defined as the total ash content. The classification of many elements as essential minerals for human nutrition is not definitive and there is still debate over the natural biological roles of vanadium, chromium, aluminum, and silicon in human health.

Macrominerals required for good human health include Ca, Mg, P, K, Na, Cl, and S, all essential in amounts >50 mg/day. Essential microminerals (Fe, I, Fl, Zn, Se, Cu, Mn, Cr, Mo, Co, Ni, and B) are required in trace concentrations (<50 mg/day). In general, vegetables are considered as richer sources of minerals than fruits (Table 19.5).

Minerals have both direct and indirect effects on human health. The direct effects of minerals are the consequences of their consumption by humans; while indirect effects include impact on fruit and vegetable quality and subsequent consumer acceptance. From a direct nutrition standpoint, potassium is the most abundant in both fruits and vegetables, but nitrogen and calcium also have major impacts on food quality. Nutrition research has focused on single-mineral effects on human health, generally with incongruent results (Aaron & Sanders, 2013). Epidemiological surveys suggest that total diet has more influence on health than specific components. It is increasingly clear that it is not only an excess or deficiency of a single mineral that affects health, but also effects of multiple nutrients in combination that affect dietary health.

TABLE 19.5 Fruit and vegetable sources of potassium, ranked by potassium/standard amount, also showing calories in the standard amount[a].

Fruits and vegetables, standard amount	Potassium (mg)	Calories
Sweet potato, baked, 1 potato (146 g)	694	131
Tomato paste, 1/4 cup	664	54
Beet greens, cooked, 1/2 cup	655	19
Potato, baked, flesh, 1 potato (156 g)	610	145
White beans, canned, 1/2 cup	595	153
Tomato puree, 1/2 cup	549	48
Prune juice, 3/4 cup	530	136
Carrot juice, 3/4 cup	517	71
Lima beans, cooked, 1/2 cup	484	104
Winter squash, cooked, 1/2 cup	448	40
Banana, 1 medium	422	105
Spinach, cooked, 1/2 cup	419	21
Tomato juice, 3/4 cup	417	31
Tomato sauce, 1/2 cup	405	39
Peaches, dried, uncooked, 1/4 cup	398	96
Prunes, stewed, 1/2 cup	398	133
Apricots, dried, uncooked, 1/4 cup	378	78
Cantaloupe, 1/4 medium	368	47
Honeydew melon, 1/8 medium	365	58
Plantains, cooked, 1/2 cup slices	358	90
Kidney beans, cooked, 1/2 cup	358	112
Orange juice, 3/4 cup	355	85
Split peas, cooked, 1/2 cup	355	116

[a]*U.S. Department of Health and Human Services and U.S. Department of Agriculture (2005). The dietary reference intake (DRI) for potassium for adults and adolescents is 4700 mg/day.*

Fruits and vegetables are not recognized as primary sources of mineral nutrients but hold a place in dietary advice because of mineral content, especially electrolytes (Slavin & Lloyd, 2012). The Dietary Approaches to Stop Hypertension (DASH) emphasizes fruits, vegetables, and low-fat dairy products as sources of minerals. In the DASH dietary pattern, vegetables contribute 14.3%, 15.5%, 16.2%, and 10.4% of required calcium, magnesium, potassium, and zinc, respectively (Lin et al., 2003). Vegetable contribution of potassium, phosphorus, magnesium, calcium, copper, iron, and zinc to the United States

TABLE 19.6 Minerals (%) contributed from fruits and vegetables to the US food supply in selected years. (Hiza and Bente, 2007).

	Fruits			Vegetables		
	Year/s			Year/s		
Mineral	**1909–19**	**1960–69**	**2004**	**1909–19**	**1960–69**	**2004**
Potassium	8.0	8.7	11.2	36.7	27.1	26.6
Calcium	2.6	2.2	2.6	8.7	6.0	7.0
Phosphorus	1.5	1.5	1.8	10.4	7.7	7.7
Magnesium	4.5	5.6	6.1	18.2	15.9	13.9
Copper	5.2	6.1	6.1	30.2	22.8	17.2
Iron	3.3	3.1	2.5	18.4	13.5	10.1
Zinc	1.2	1.3	1.2	9.1	7.4	6.4
Sodium	0.8	1.3	2.0	10.4	23.4	28.9
Selenium	0.5	0.6	0.4	1.2	2.4	2.3

From Hiza, H. A. B. & Bente, L. (2007). Nutrient content of the U.S. food supply, 1909–2004: A summary report. Home economics research report number 57. *Washington, DC: U.S. Department of Agriculture, Center for Nutrition Policy and Promotion.*

food supply decreased significantly during the last century, while the fruit contribution of potassium, phosphorus, magnesium, and copper increased (Table 19.6). Strategies for improving mineral intake from fruits and vegetables have been implemented. These comprise increasing the consumption of fruits and vegetables and increasing concentrations of essential nutrients through fortification. Alternative approaches include improving nutrient bioavailability and retention.

19.2.8.1 Potassium (K)

Adequate intake of potassium for adult males and females is 4700 mg/ day (Davison, 2017). A potassium-rich diet helps lower blood pressure, blunting the effects of NaCl. Inadequate potassium intake has long been associated with increased mortality (Wang et al., 2014) and higher blood pressure (Mccarron & Reusser, 2001). Potassium regulates heartbeat, assists in muscle contraction, and is needed to send nerve impulses and to release energy from fat, carbohydrates, and protein. Different nutrients and phytochemicals in fruits and vegetables, including potassium, may independently or jointly reduce cardiovascular disease risk (Ignarro, Balestrieri, & Napoli, 2007). Hypertension is rapidly increasing in sub-Saharan Africa, an area where such health problems did not exist a couple of decades ago. It is now the fastest growing health problem there and increased consumption of fresh fruit as a source to alleviate the problem.

Potassium is a systemic electrolyte that coregulates ATP with sodium. Potassium affects acid–base metabolism favorably, which may reduce the risk of developing kidney stones (Zerwekh, Odvina, Wuermser, & Pak, 2007), and possibly decreases bone loss with age. Potassium is the most abundant individual mineral element in fruits and vegetables, at concentrations ranging between 60 and 600 mg/100 g FW. The commodities accumulation higher levels of potassium are those presenting lower water contents such as potato, pumpkin plantain, and banana. It is active in many cellular and whole plant functions. It balances the charges of anions, activates ~60 plant enzymes, maintains cytoplasmic pH homeostasis and is involved in key metabolic processes, including protein synthesis. Other roles are linked to potassium high mobility. Potassium movement is the driving force for osmotic changes, since it serves as an osmotic for cellular growth and stomata function, translocation of assimilation products and light-driven and seismonastic movements of organs. Also, it provides a charge-balancing counter-flux that supports the movement of other ions. Growth requires directed movement of potassium (Amtmann, Armengaud, & Volkov, 2004). In fruits and vegetables, potassium occurs mainly in combination with OAs. Examples of potassium-rich fruits and vegetables include bananas and plantains, leafy green vegetables, many dried fruits, oranges and orange juice, cantaloupes, honeydew melons, tomatoes, and root vegetables (Tables 19.5 and 19.7). Notably, potatoes provide >10% of the potassium intake in the United States and United Kingdom populations (Lanham-New, Lambert, & Frassetto, 2012).

19.2.8.2 Calcium (Ca)

Adequate intake of calcium is 1 g/day for adults aged 19−50 years and 1.2 g for adults over 50 years (Davison, 2017). Additional amounts are recommended to meet the needs of pregnancy, infancy, childhood, adolescence, and lactation, since calcium is essential for bone and tooth formation. Calcium is very important during later adulthood from a public health perspective, because inadequate calcium intake may increase the risk of osteoporosis, a condition in which bone mass decreases (Cohen & Roe, 2000). Nearly half of American women over 50 have low mineral bone density or osteoporosis (Debar et al., 2004). In the United States, annual osteoporosis-related fractures are projected to increase from 1.9 to 3.2 million (68%), from 2018 to 2040, with annual direct medical costs associated with fractures estimated at $48.8 billion in 2018 (Lewiecki et al., 2019), so osteoporosis prevention is a major public health target.

Calcium fluxes are important mediators of hormonal effects on target organs through the phosphoinositol system and are closely linked with cyclic adenosine monophosphate (AMP) systems. In plants, calcium plays a dual role, both as a structural component of cell walls and membranes and as a ubiquitous second messenger involved in a wide range of physiological processes and responses. Calcium is primarily associated with pectins: it has a major influence on the rheological properties of the cell wall and, consequently, in the texture and storage life of fruits and vegetables. Ca^{2+} can interact with anionic pectic polysaccharides, coordinating with the oxygen functions of two adjacent pectin chains to form the so-called eggbox structure and cross-linking the chains. Also, intracellular Ca^{2+} occupies a pivotal role in cell signal transduction. Plant signals associated with Ca^{2+} signatures include wounding, temperature stress, fungal elicitors, oxidative stress, anaerobiosis, abscisic acid, osmotic stress, red or blue light or ultraviolet-B (UV-B) signaling, and mineral nutrition (Bailey et al., 2010). Transient increases in intracellular Ca^{2+} are often associated with initiation of responses. Thus Ca^{2+} is a prominent intracellular second messenger for a variety of processes and must be maintained in the cytoplasm at concentrations many orders of magnitude lower than in the cell wall (Thor, 2019).

TABLE 19.7 Mineral composition of some fruits in mg/100 g fresh weight.

	Mineral									
Fruit	**K**	**Ca**	**Mg**	**P**	**Mn**	**Cu**	**Fe**	**Zn**	**Na**	**Se**
Apple, with skin	107	6	5	11	0.035	0.027	0.12	0.04	1	0.0
Apricot	259	13	10	23	0.077	0.078	0.39	0.2	1	0.1
Avocado (California)	507	13	29	54	0.149	0.170	0.61	0.68	8	0.4
Avocado (Florida)	351	10	24	40	0.095	0.311	0.17	0.4	2	–
Banana	358	5	27	22	0.270	0.078	0.26	0.15	1	1.0
Blackberries, raw	162	29	20	22	0.646	0.165	0.62	0.53	1	0.4
Blueberries, raw	77	6	6	12	0.336	0.057	0.28	0.16	1	0.1
Cherries, sweet, raw	222	13	11	21	0.070	0.060	0.36	0.07	0	0.0
Figs, raw	232	35	17	14	0.128	0.070	0.37	0.15	1	0.2
Grapefruit, raw, pink, and red pi re3u	147	11	9	12	0.020	0.032	0.08	0.07	1	–
(California and Arizona)										
Grapefruit, raw, pink and red (Florida)	127	15	8	9	0.010	0.044	0.12	0.07	0	1.4
Grapes, red, or green (European type, e.g., "Thompson Seedless"), raw	191	10	7	20	0.071	0.127	0.36	0.07	2	0.1
Kiwifruit, fresh, raw	312	34	17	34	0.098	0.130	0.31	0.14	3	0.2
Lemons, raw, without peel	138	26	8	16	0.030	0.037	0.60	0.06	2	0.4
Mangos, raw	156	10	9	11	0.027	0.110	0.13	0.04	2	0.6
Melons, Cantaloupe, raw	267	9	12	15	0.041	0.041	0.21	0.18	16	0.4
Oranges, raw, California, 'Valencia'	179	40	10	17	0.023	0.037	0.09	0.06	0	–
Papayas, raw	257	24	10	5	0.011	0.016	0.10	0.07	3	0.6
Peaches, raw	190	6	9	20	0.061	0.068	0.25	0.17	0	0.1
Pears, raw	119	9	7	11	0.049	0.082	0.17	0.10	1	0.1
Pineapples, raw, all varieties	109	13	12	8	0.927	0.110	0.29	0.12	1	0.1
Plums, raw	157	6	7	16	0.052	0.057	0.17	0.10	0	0.0
Pomegranates, raw	259	3	3	8	--	0.070	0.30	0.12	3	0.6
Raspberries, raw	151	25	22	29	0.670	0.090	0.69	0.42	1	0.2
Strawberries, raw	153	16	13	24	0.386	0.048	0.41	0.14	1	0.4
Watermelon, raw	112	7	10	11	0.038	0.042	0.24	0.10	1	0.4

From US Department of Agriculture (2008).'Composition of foods, raw, processed, prepared' USDA national nutrient database for standard reference, release 20. *Beltsville, MD: USDA-ARS, Beltsville Human Nutrition Research Center, Nutrient Data Laboratory. http://www.ars.usda.gov/nutrientdata. Accessed 04/2008.*

TABLE 19.8 Fruits and vegetables particularly rich in specific antioxidant groups.

Ascorbic acid	Vitamin E	Carotenoids	Phenolics
Strawberry	Almond	Pineapple	Blueberry
Pepper	Corn	Plum	Plum
Kiwifruit	Broccoli	Peach	Raspberry
Orange	Spinach	Pepper	Strawberry
Pepper	Peanut	Mango	Apple
Broccoli	Avocado	Melon	Blackberry
Guava		Tomato	
Rosehip		Carrot	
Persimmon			

Horticultural crops are a secondary source of calcium to dairy products, but fruits and vegetables account for ~10% of the calcium in the United States food supply (Table 19.7). Dark green, leafy cabbage family vegetables and turnip greens are good calcium sources and most green leafy vegetables are potential sources of absorbable calcium (Titchenal & Dobbs, 2007). Projects designed to test the efficacy of a health plan-based lifestyle intervention for increasing bone mineral density propose not only increased consumption of high-calcium dairy products but also of fruits and vegetables (Debar et al., 2004) (Table 19.8).

Bioavailability of calcium can be reduced in the presence of antinutrient components, mainly oxalates and phytates. Soluble oxalate is found mostly in vegetables such as spinach and green amaranth and in seeds, while fruit and green tea contain moderate amounts of oxalate (Lo, Wang, Wu, & Yang, 2018). Almost no calcium is absorbed from spinach, while low-oxalate vegetables such as broccoli and kale show high calcium bioavailability. Domestic processing such as blanching or boiling can leach soluble oxalate into the cooking water and it is a recommended way to reduce soluble oxalate (Gharibzahedi & MahdiJafari, 2017). Phytates are present in beans, nuts, cereals, and, to a lesser extent, in fruits, leafy vegetables and tubers (Lo et al., 2018). They can form nonabsorbable complexes with calcium impairing its absorption: a phytate/calcium molar ratio >0.24 impairs bioavailability of calcium (Lo et al., 2018).

19.2.8.3 Magnesium (Mg)

The recommended dietary allowance for magnesium is 420 mg/day for adult males and 320 for adult females over 31 years old (Davison, 2017). Magnesium is important in protein synthesis and acts as a controlling factor in skeletal and smooth muscle contraction, release of energy from muscle storage, cardiac excitability, body temperature regulation, immune system health and nerve impulse transmission. It is critical for proper heart function and bone formation as described previously. Magnesium activates over 100 enzymes.

In plants, Ca^{2+} and Mg^{2+} are the most abundant divalent cations and appear to have antagonistic cellular interactions. A homeostatic balance between Ca^{2+} and Mg^{2+} is necessary in plants for optimal growth and development (Tang & Luan, 2017). The porphyrin-like ring structure of chlorophyll contains a central magnesium atom coordinated to the four pyrrole rings. Magnesium is also involved in energy metabolism, as a constituent of the Mg-ATP or Mg-ADP complex. The Calvin cycle pathway that produces a three-carbon compound as the first stable product in the multistep conversion of CO_2 into carbohydrates is regulated partially via stromal Mg^{2+} concentration.

The vegetable contribution to total magnesium in the United States food supply was 14% (Table 19.6). Mixed users, who are more likely to consume grains, fruit, and dairy products, have greater magnesium densities than high-fat users, who consumed more meat (Sigman-Grant, Warland, & Hsieh, 2003). Generally, magnesium is significantly more abundant in vegetables than in fruits, while nuts are good sources of this nutrient. Overall, dry fruits, legumes, pumpkin seeds, nuts (Brazil nuts), artichokes, and spinach are high in magnesium (Gharibzahedi & Jafari, 2017). As for calcium, oxalic acid can form poorly soluble magnesium oxalate and phytate can produce complexes with magnesium, making this macromineral nonabsorbable.

19.2.8.4 Phosphorus (P)

The recommended dietary allowance for phosphorus is 700 mg/day for adults over 19 years old (Davison, 2017). Inorganic phosphate is essential for skeletal mineralization and for multiple cellular functions, including glycolysis, gluconeogenesis, DNA synthesis, RNA synthesis, cellular protein phosphorylation, phospholipid synthesis, and intracellular regulatory roles (Dimeglio, White, & Econs, 2000). Phosphorus is a primary bone-forming mineral. Because most Westerners eat high-phosphate diets, isolated dietary phosphate deficiency is exceedingly rare, except for occasional metabolic disorders such as hyperphosphatemia.

Phosphorus exists in plants as both inorganic phosphate anions and organophosphate compounds. Unlike sulfate and nitrate, phosphate is not reduced during assimilation, but remains in its oxidized state, forming phosphate esters with a variety of organic compounds. Inorganic phosphorus is a primary structural component of nucleic acids and phospholipids, plays a central role in energy conversion in the form of high-energy phosphoester and diphosphate bonds, is important as a substrate and a regulatory factor in oxidative metabolism and photosynthesis, participates in signal transduction and regulates the activities of an assortment of proteins through covalent phosphorylation/dephosphorylation reactions.

Fruit and vegetable contribution to total phosphorus in 2004 was 9.5% (Table 19.6). According to the National Health and Nutrition Examination Survey (2001–14), grains are the largest dietary phosphorus source, followed by meats and milk products, while the contributions of vegetables and fruits (excluding nuts) to phosphorus intake are 6.7% and 2%, respectively. Legumes, nuts, and seeds are also significant sources (4.8%) (McClure, Chang, Selvin, Rebholz, & Appel, 2017). Pumpkin seeds and Brazil nuts are rich in phosphorus (Gharibzahedi & Jafari, 2017).

19.2.8.5 Nitrogen (N)

Nitrogen is a chemical element essential to life. It is considered a "mineral" for plants, as it is often included in fertilizers. It is one of the four major structural elements in the human body by weight (together with oxygen, hydrogen, and carbon), but it is not included in lists of major nutrient minerals. The largest requirement for nitrogen in eukaryotic organisms is for amino acid biosynthesis, building blocks of proteins and precursors of many other compounds. Proteins represent a large percentage of the human body and carry out many different cell functions. Therefore, protein synthesis is central to cell growth, differentiation, and reproduction. Nitrogen is also an essential component of nucleic acids, cofactors, and other metabolites. Several plant hormones (indole-3-acetic acid, zeatine, spermidine) contain nitrogen or are derived from nitrogenous precursors. Alkaloids and other secondary compounds contain nitrogen and various phenolics derived from the amino acid phenylalanine. Nitrogen is also a major constituent of chlorophyll. The characteristic preharvest yellow color of nitrogen-starved vegetables—a physiological disorder called chlorosis—reflects their inability to synthesize adequate amounts of green chlorophyll under nitrogen-limiting conditions.

19.2.8.6 Sulfur (S)

Sulfur is an essential nutrient for growth, used primarily to synthesize cysteine and methionine. Most dietary sulfur is provided by these sulfur-containing amino acids, with a daily sulfur amino acid requirement of 13 mg/kg body weight for healthy adults (Van de Poll, Dejong, & Soeters, 2006). Methionine is the only essential sulfur amino acid and can provide sulfur for cysteine and taurine synthesis. These amino acids are pivotal for structural and catalytic functions of proteins and are used to form numerous essential and secondary metabolites. Oxidized thiol groups of two cysteine residues form disulfide bonds: covalent linkages that establish tertiary and sometimes quaternary protein structures. The dithiol↔disulfide interchange can be a regulatory mechanism that mediates redox reactions.

Sulfur nutrition is important for species in the order Brassicales (e.g., white cabbage, broccoli, cauliflower, kale, Brussels sprouts, capers) to synthesize anticarcinogenic glucosinolate compounds (reviewed in Sozzi, 2001). In caper (*Capparis spinosa* L.), 160 flavor components were identified, including elemental sulfur (S_8) and >40 sulfur-containing compounds, among them thiocyanates and isothiocyanates. *Allium* vegetables (garlic, onions, leeks, chives) are also rich in sulfur compounds (Gharibzahedi & Jafari, 2017). Although essential for human and plant life, sulfur is a minor component compared to nitrogen. Generally, it is not a growth-limiting nutrient, since sulfate, the oxidized anion, is abundant in the environment.

19.2.8.7 Manganese (Mn)

Recommended dietary intakes of manganese differ considerably among countries, ranging from 1.4 mg/day in the United Kingdom to 5.5 mg/day in Australia and New Zealand (Freeland-Graves, Mousa, & Kim, 2016). In humans, manganese is involved in a variety of processes and functions including bone and connective tissue growth (bone stores the most Mn in the human body: ~40%–50% total body Mn), reproduction, brain function, blood sugar regulation, protein and energy metabolism, and cellular protection (Chen, Bornhorst, & Aschner, 2018). It serves as a cofactor for several critical enzymes: the mitochondrial manganese superoxide dismutase 2 (involved in antioxidant protection), arginase (the rate-limiting enzyme in urea synthesis), acetyl-Co A carboxylase (first and rate-limiting enzyme in de novo fatty acid synthesis), phosphoenolpyruvate carboxykinase and pyruvate carboxylase (metabolic enzymes in the gluconeogenesis pathway), and the astrocyte-specific glutamine synthetase (crucial for brain ammonia metabolism). In plants, manganese atoms undergo successive oxidations to yield a strongly oxidizing complex that can oxidize water during photosynthesis. Like magnesium, manganese is required in enzyme reactions involving carbon assimilation. Chloroplasts are most sensitive to manganese deficiency. Among horticultural crops, nuts (hazelnuts, pecans, and almonds), pumpkin seeds, green leafy vegetables (spinach), fruits, and fruit juices are good sources of manganese (Gharibzahedi & Jafari, 2017).

19.2.8.8 Copper (Cu)

The recommended dietary allowance for copper is 900 μg/day for adults over 19 years old (Davison, 2017). Copper is a cofactor for over 30 proteins, including superoxide dismutases 1 and 3 (with a key role in antioxidant defense), ceruloplasmin (the major copper-carrying ferroxidase in the blood, it plays a role in iron metabolism) and hephaestin (a ferroxidase involved in intestinal iron absorption), lysyl oxidase (that catalyzes formation of aldehydes from lysine residues in collagen and elastin precursors), mitochondrial cytochrome *c* oxidase (the last enzyme in the respiratory electron transport chain of cells located in the membrane), tyrosinase (the rate-limiting enzyme of melanin production, plays an important role in enzymatic browning) and dopamine-β-hydroxylase (an essential neurotransmitter-synthesizing enzyme that primarily contributes to catecholamine and trace amine biosynthesis), peptidylglycine alpha-amidating monooxygenase (involved in the alpha-amidation of neuropeptides), and amine, monoamine, and diamine oxidases (Collins, 2017). Also, many copper-binding proteins have been identified (Collins, 2017). Copper, a redox-active metal, is critical for the oxidative defense system; oxidative stress is a characteristic of copper deficiency (Uriu-Adams & Keen, 2005). Copper is required for brain development and supports the functions of the central nervous system. It is involved in neuropeptide synthesis and immune function and is necessary to form hemoglobin and connective and bone tissue (Collins, 2017). Deficits in this nutrient during pregnancy can cause gross structural malformations in the fetus and persistent neurological and immunological abnormalities in the offspring (Uriu-Adams & Keen, 2005).

In plants, copper is required for chlorophyll synthesis and several copper-containing enzymes that reduce molecular oxygen. As with other trace minerals, the availability of copper to plants decreases as the pH rises above seven. At high pH, copper is strongly adsorbed to clays, iron and aluminum oxides, and organic matter. Of the micronutrients required by plants, copper often has the lowest total concentration in soil. Grains (21%), legumes, nuts, and soy (20%) are the leading sources of dietary copper, followed by vegetables (17%) (Table 19.7; Hiza & Bente, 2007). Among horticultural crops, nuts (cashew nuts in particular), raw kale, dried fruit (prunes), and avocados are good sources of copper (Gharibzahedi & Jafari, 2017).

19.2.8.9 Iron (Fe)

The recommended dietary allowance for iron is 8 mg/day for adult males over 19 years old and adult females over 50 years old, and 18 mg/day for adult females between 19 and

50 years (Davison, 2017). The metabolic fates of copper and iron are intimately related. Their essential role resides in their capacity to participate in one-electron exchange reactions. Systemic copper deficiency generates cellular iron deficiency, which in humans results in reduced intellectual capacity, stunted growth, altered bone mineralization, and compromised immune responses. Iron is required in heme-containing proteins involved in binding and/or transporting oxygen: hemoglobin, myoglobin, neuroglobin, and cytoglobin. Some hemoproteins are enzymes: cytochrome P450s, cytochrome *c* oxidase, catalase, and peroxidases. Other hemeproteins enable electron transfer, as they form part of the electron transport chain (cytochrome a, cytochrome *b*, and cytochrome *c*) and microsomal electron transport. Iron is also required for deoxyribonucleotide synthesis (ribonucleotide reductase) and for other nonheme iron enzymes (phenylalaninehydroxylase, tyrosine hydroxylase) and iron−sulfur enzymes (aconitase) (Abbaspour, Hurrell, & Kelishadi, 2014). Almost 70% of the body's iron is found in the hemoglobin present in circulating erythrocytes, another 5% helps form myoglobin, 5% is distributed across body cells as an enzyme cofactor, a minor percentage circulates in the plasma bound to transferrin, and ~20% of the iron in the body is stored as ferritin or held as hemosiderin.

In plants, iron is required for chlorophyll synthesis and photosynthesis. In vegetable green leaves, there is good correlation between iron and chlorophyll concentrations. Inadequate iron nutrition results in abnormal chlorophyll development: deficiency begins as interveinal chlorosis on younger leaves, resulting in prominently green veins. The resultant reduced photosynthetic capability also reduces the weight and area of affected leaves. The plant plastid stroma may contain deposits of phytoferritin, an iron storage form similar to the ferritin of animal cells. Phytoferritin occurs almost exclusively in plastids, especially those of storage organs (Briat & Lobreaux, 1997).

Plant sources supply only nonheme iron, tightly bound to organic compounds. It has low bioavailability (<10%, Saini, Nile, & Keum, 2016) and is strongly influenced by the presence of other food constituents. Adult users of lower fat foods consume more nutrient-dense diets and more iron (Sigman-Grant et al., 2003). The predominant source of iron in the American food supply is grain products, followed by meat, poultry, and fish. Between 1909 and 1919, vegetables furnished 18% of the iron in the food supply, but in 2004, that share dropped to 10% (Table 19.6), partially due to reduced consumption of white potatoes after 1920. Although potatoes are not a good source of iron, their contribution increases when eaten in large quantities (Hiza & Bente, 2007), particularly if the skin is consumed: baked potato skin has 20-fold more iron than the flesh. Spices and herbs are very good sources of iron (Saini et al., 2016). Nuts (cashew, hazelnut, pistachio, almonds, walnuts, and pecans), pumpkin seeds, green vegetables (parsley, spinach, Swiss chard, broccoli, kale, and collards), and legumes (green peas and beans) are also good sources of iron (Gharibzahedi & Jafari, 2017).

19.2.8.10 Zinc (Zn)

The recommended dietary allowance for zinc is 11 mg/day for men and 8 mg/day for women (Davison, 2017). Zinc is a pervasive and versatile microelement that plays a catalytic or structural role in over 300 enzymes involved in digestion (carboxypeptidase, liver alcohol dehydrogenase, carbonic anhydrase), metabolism, reproduction, and wound healing (Prasad, 2017). Over 2000 transcription factors require zinc to conserve their structures and to bind to DNA. Zn^{2+} is a cation with various coordination possibilities and several potential geometries. Thus it easily adapts to different ligands. The primary role of structural Zn^{2+} in proteins is to stabilize tertiary structures. Zinc has also a critical role in the immune response and is an important antioxidant and antiinflammatory agent (Prasad, 2017).

Zinc activates many plant cell enzymes, but only a few (alcohol dehydrogenase, superoxide dismutase, carbonic anhydrase, and RNA polymerase) contain the micronutrient. Zinc affects carbohydrate metabolism because Zn-dependent enzymes participate in biochemical reactions of sugars (Sozzi, Greve, Prody, & Labavitch, 2002). Zinc also plays a role in maintaining cell membrane integrity, protecting from $O_2^{-\bullet}$damage and synthesizing RNA and tryptophan, a precursor of indole-3-acetic acid. Several mechanisms involve zinc in plant defense against pathogens and herbivores (Cabot et al., 2019). Fruits and vegetables account for only 1.2% and 6.4%, respectively, of the zinc in the American food supply (Hiza & Bente, 2007). As with magnesium, zinc intakes may be insufficient in both adults and children (Sigman-Grant et al., 2003). Fruits are poor in zinc, but nuts (cashew, pecan, Brazil nut, almond, hazelnut, pistachio, and walnut) and squash seeds are good sources (Gharibzahedi & Jafari, 2017). As with calcium and iron, oxalates and phytates bind zinc and form insoluble precipitates, decreasing its availability for absorption.

19.2.8.11 Boron (B)

No estimated average requirements or dietary reference intakes have been set for boron, only a tolerable upper intake level of 20 mg/day for individuals aged $\geq$19 years (Białek, Czauderna, Krajewska, & Przybylski, 2019). In humans, boron plays important roles in growth and maintenance of bone tissue, improvement of wound healing, and calcium metabolism (enhanced gut absorption of calcium, calcification). Boron acts together with vitamin D, calcium, and magnesium in bone metabolism. Boron has antiinflammatory effects, influences central nervous system functions, and helps regulate the hormones testosterone, estrogen, insulin, triiodothyronine, and thyroxine. It increases biological half-life and bioavailability of estradiol and vitamin D. Boron raises the abundance of antioxidant enzymes, such as superoxide dismutase, catalase, glutathione peroxidase, glutathione-*S*-transferase, and glucose-6-phosphate dehydrogenase. It also detoxifies reactive oxygen and nitrogen species and reduces lipid peroxidation and DNA damage (Białek et al., 2019).

In vascular plants, boron forms strong complexes with different molecules carrying *cis*-diol groups in appropriate spatial configurations and is essential for correct formation and stabilization of primary cell walls. Most authors consider the formation of borate diester cross links with two chains of rhamnogalacturonan-II is an essential function for growth, development, and reproduction in vascular plants (Wimmer et al., 2020). Animals lack the capacity to metabolize inorganic boron compounds (like boric acid or borates) into mono- or di-sugar−borate esters (e.g., glucose and fructose borate esters), bis-sucrose borate esters, sugar alcohol borate esters (sorbitol, mannitol), or pectic polysaccharide borate esters. In contrast, plants can convert inorganic boron into dietary sugar-borate ester complexes, which are the best chemical form for assimilation into cells. In general, plants have higher boron concentrations (from 0.1 to 0.6 mg B/100 g) than animal-based foods (from 0.01 to 0.06 mg/100 g) (Białek et al., 2019). Fresh fruits (e.g., avocado, apple, banana, and red grape), leafy vegetables, flowering heads (broccoli), dried fruits (plums, apricots, and raisins), seeds, and nuts (pecans, almonds, and hazelnuts) are primary natural dietary sources of fructoborate esters, mainly calcium fructoborate complex—an excellent source of soluble boron with many beneficial physiological properties (Gharibzahedi & Jafari, 2017).

19.2.8.12 Selenium (Se)

The recommended dietary allowance for selenium is 55 μg/day (Davison, 2017). In humans, this trace mineral is associated with the endocrine system, the antioxidant defense, and the immune function. Iodothyronine deiodinases are selenium-dependent enzymes that convert inactive thyroxine to active thyroid hormone, triiodothyronine. Glutathione peroxidases are antioxidant seleno enzymes that protect against reactive oxygen and nitrogen species. The antioxidative effects of selenium and vitamin E may act together to protect from oxidative damage. At adequate doses, selenium protects plants from different abiotic stresses. It works as an antioxidant: it scavenges ROS by their dismutation and reduces metal-induced oxidative stress (Shahid et al., 2018). Fruits and vegetables typically contain small amounts of selenium. But, certain species, such as onions, garlic, broccoli, and cabbage, can accumulate selenium when grown on selenium-rich soils (Gharibzahedi & Jafari, 2017) (see also Chapter 7: Fresh-cut products—implications for postharvest).

19.2.8.13 Silicon (Si)

Silicon is suggested as an essential element for human health (Michalak & Chojnacka, 2018). Its essentiality is difficult to prove because silicon is very common (it is the second-most abundant element in the Earth's crust by mass, after oxygen); hence, deficiency symptoms are difficult to reproduce. In the human body, this mineral is associated with connective tissue formation in general: bone health (silicon can increase bone volume and density in patients with osteoporosis), elastin and collagen synthesis, and skin aging prevention. It is one of the nutrients sustaining good condition of nails and hair and is also involved in cardiovascular health (Michalak & Chojnacka, 2018).

In plants, silicon is useful for the healthy growth of many species, since it plays multiple roles to alleviate a wide variety of biotic and abiotic stresses. In fruit trees, it promotes root growth and development, prevents root rot and premature aging, improves photosynthesis, and regulates fruit absorption of different minerals (Etesami & Jeong, 2020). Plant-based foods are the major contributors to dietary silicon. Fruits (banana in particular) and vegetables (e.g., beetroot, carrot, potato, green beans, and spinach) are good sources of silicon (Farooq & Dietz, 2015). Little silicon was bioavailable from bananas (5.8%) and spinach (4.9%), despite their high silicon content (Robberecht, Van Dyck, Bosscher, & Van Cauwenbergh, 2008).

19.2.8.14 Sodium (Na)

In general, fruits are poor in sodium and are recommended for low-sodium diets. Low sodium is defined as 140 mg of sodium per serving and an ideal maximum intake of sodium for low sodium diet is 1500 mg/day (Davison, 2017). Sodium is important for electrolyte balance and blood pressure. Along with potassium, it coregulates ATP and is important in neuromuscular function. Table salt (NaCl) in the diet also provides chloride, which is part of gastric acid, the human digestive fluid required for proper digestion. Sodium intake from vegetables increased during the past few decades (Table 19.6) due to increased consumption of processed vegetables, largely tomatoes and white potatoes. Except for canned vegetables, food supply sodium estimates do not include sodium added in processing. Thus the relative contribution of vegetables to sodium in the food supply is likely overstated (Hiza & Bente, 2007). Olives and spinach are horticultural sources of sodium.

19.2.8.15 Molybdenum (Mo)

The recommended dietary allowance for molybdenum is set at 45 μg/day for adults. In both humans and plants, molybdenum must be complexed by a special cofactor to gain catalytic activity: it is bound to a pterin, forming molybdenum cofactor (Moco), the active compound at the catalytic site of molybdenum-containing enzymes. In the human body, there are four molybdenum-dependent enzymes (two mitochondrial and two cytosolic enzymes), each harboring a pterin-based molybdenum cofactor in the active site (Schwarz, 2016). In plants, different enzymes are molybdenum-dependent, including nitrate reductase. Molybdenum concentrations in plant foodstuffs are dependent on the soil content. In general, fruits and vegetables are poor sources, but nuts are rich in molybdenum (Novotny, 2011).

19.2.8.16 Nickel (Ni)

Nickel is an essential nutrient for plants, but there is no evidence that nickel is of nutritional value in humans (Genchi, Carocci, Lauria, Sinicropi, & Catalano, 2020). In plants, it plays roles in both primary and secondary metabolism. It is a key component of enzymes involved in nitrogen metabolism, among them, urease (Wood, 2015). High mean concentrations of nickel have been measured in nuts (e.g., walnuts, 3.6 mg/kg); moderately high concentrations were found in vegetables (742−753 μg/kg). Fruits are poorer sources of nickel (Mania, Rebeniak, & Postupolski, 2019).

19.2.8.17 Fluorine (F)

Most fruits and vegetables have low concentrations of fluorine (Mahmoud, Mutchnick, Svider, McLeod, & Fribley, 2020). Adequate intake of fluorine (which occurs naturally as the monoatomic anion fluoride, F^-) is 4 mg/day for adult males and 3 mg/day for females (Davison, 2017). Fluorine is important for the health of bones and teeth in humans but may be a toxic pollutant for plant metabolism. The main sources of human fluorine are treated drinking water, tea and other beverages, fish, and dental products.

19.2.8.18 Iodine (I)

The recommended dietary allowance for iodine is 150 μg/day (Davison, 2017). The thyroid gland concentrates 70%−80% of the human body's iodine and uses about 80 μg/day to synthesize thyroid hormones (triiodothyronine and thyroxine). These hormones are primarily responsible for regulation of metabolism, normal growth, neurological development, and reproduction. Some horticultural crops (cassava, sweet potatoes, turnips, and vegetables from the genus *Brassica* such as broccoli, Brussels sprouts, cabbage, and cauliflower) contain substances called goitrogens that interfere with iodine uptake or use by the thyroid gland (Langer, 2018). Most of these goitrogens can be inactivated by heat. They are of clinical importance only if consumed in large amounts and/or iodine supply is deficient. Fruits and vegetables are poor sources of iodine, but leafy vegetables such as lettuce are richer in iodine than other horticultural crops (Fuge & Johnson, 2015). Bananas, cranberries, dried prunes, and strawberries are good fruit sources of iodine (Gharibzahedi & Jafari, 2017). The use of iodine-biofortified vegetables such as *Brassica* genotypes may be a healthier alternative than iodine-fortified salt for preventing iodine deficiency and related human disorders (Gonnella, Renna, D'Imperio, Santamaria, & Serio, 2019).

19.2.8.19 Factors influencing mineral content of fruits and vegetables

19.2.8.19.1 Species and cultivar

Mineral composition varies widely in raw fruits (Table 19.7) and vegetables. Leafy vegetables have higher concentrations of nutrients that are less mobile in the plant (e.g., calcium) and depend on direct water flow rather than recycling from older leaves. Mineral concentrations may vary widely among cultivars. For example, both "Dwarf Brazilian" (Santa Catarina Prata, *Musa* sp. AAB) and "Williams" (Cavendish subgroup, Musa sp. AAA) bananas are considered good sources of potassium. Nevertheless, "Dwarf Brazilian" bananas have more P, Ca, Mg, Mn, and Zn than "Williams" bananas (Wall, 2006). As a result of the distribution of vascular tissue, sink characteristics, and metabolic rates, higher mineral concentrations are found in the skin and seeds than in the flesh of fruits. In "Rocha" pears, nitrogen, calcium, magnesium, manganese, iron, copper, zinc, and boron show radially decreasing concentrations from the fruit skin to the inner flesh tissues (Saquet, Streif, & Almeida, 2019). Tissues with higher metabolic rates (epicarp, core) may accumulate more nitrogen. Rapidly expanding or large-celled tissues are unlikely to have high calcium concentrations. Distal fruit tissue contains the least calcium and the greatest susceptibility to calcium deficiency disorders (Tonetto de Freitas & Mitcham, 2012).

19.2.8.19.2 Preharvest factors

Orchard location has important effects on fruit and vegetable mineral composition (Table 19.7). For example, potassium in bananas differs among locations/microclimates (Wall, 2006). Similar fluctuations in potassium among growing areas are seen in "Rainbow" papaya fruits (Wall, 2006). Mineral composition fluctuates widely in raw fruits and vegetables due to preharvest factors (soil fertility, including both pH and concentrations of nutrients, soil moisture, temperature) and cultural practices (amount and timing of fertilization and irrigation, application of plant growth regulators, pruning, and thinning of tree fruit species) (see also Chapter 7: Fresh-cut products—implications for postharvest). Most agricultural practices are established primarily to increase productivity, not to improve human health, horticultural crop postharvest life, or flavor (Crisosto & Mitchell, 2002). Most fertilizers are applied directly to the soil to raise nutrient concentrations that are inadequate for successful crop growth and to maintain soil fertility, which will decline if nutrient removal from the soil via crop uptake, leaching, volatilization, or denitrification exceeds nutrients added via weathering of minerals and mineralization of organic matter.

Nitrogen is the most frequently deficient element and most common fertilizer in orchards, while phosphorus and potassium are added when soil test results, plant response, or tissue analysis indicate a need. N−P−K addition with irrigation water has several advantages, including the ability to transport soluble nutrients directly to the root zone whenever water is applied to the plant. Calcium additions can be large when lime is applied to increase soil pH. Most micronutrients are rarely applied to soil but instead are sprayed directly on the canopy in dilute concentrations. In fruits, the quantity of nutrients absorbed through the waxy cuticle is often small, relative to nutrient demand, but can ameliorate deficiency symptoms and improve fruit quality.

An excessive supply of nutrients relative to photosynthesis develops when the rate of nutrient assimilation is high relative to net photosynthesis. When this happens, nutrients can accumulate in fruits and vegetables to concentrations that are toxic for the plant or consumers. Excessive nitrogen leads to potentially harmful accumulations of nitrate in leafy greens and potatoes (Pavlou, Ehaliotis, & Kavvadias, 2007). Such nutrient imbalances also affect crop quality. Nutrient transport and source−sink relations also affect nutrient accumulation. For example, altered water economy affects calcium uptake, since calcium is transported in the soil toward the roots and translocated to the shoots with the mass flow of water driven by transpiration and growth. Bagging fruit may decrease calcium concentrations and increase calcium-related disorders (Li, Han et al., 2020; Li, Cheng, Zhang, Wang, & Yang, 2020). Canopy position and crop load also influence calcium uptake. Fruit calcium uptake is determined by the calcium concentration in the xylem sap, and xylem/phloem ratio of fruit sap uptake, which is affected by the rates of leaf and fruit transpiration and growth (Tonetto de Freitas & Mitcham, 2012). Fruit from upper parts of the canopy tend to have less calcium (Ferguson & Triggs, 1990) and heavily cropped trees have fruit with more calcium and less potassium (Ferguson & Watkins, 1992). Gibberellins, auxins, abscisic acid, and cytokinins may help regulate calcium uptake and translocation to fruit tissues. Gibberellins affect cellular calcium partitioning and distribution, which increase fruit susceptibility to calcium deficiency disorders (Tonetto de Freitas & Mitcham, 2012). Treatment of tomato plants and apple trees with prohexadione-calcium, a gibberellin biosynthesis inhibitor, increases the total calcium in fruits (do Amarante et al., 2020). Pre- and postharvest treatments with different calcium sources have been used to maintain quality, extend shelf-life, and enhance the nutritional value of fresh fruits and vegetables (Martín-Diana et al., 2007).

Tree size, spacing, row orientation, canopy shape, and training system influence light distribution within fruit trees, which affects fruit mineral composition. In grapes, improving light penetration into the canopy increased anthocyanins and soluble phenols but reduced potassium (Prange & DeEll, 1997). In kiwifruit, light promoted calcium accumulation (Montanaro, Dichio, Xiloyannis, & Celano, 2006). This finding was not fully explained by fruit transpiration: regulation by phytohormones could help determine calcium concentrations. The effect of sunlight is not universal: avocado fruit from the sunny side of trees had the same calcium concentration as fruit from the shaded side (Witney, Hofman, & Wolstenholme, 1990). The mineral concentrations in some horticultural species are affected by intensive culture systems (glasshouse) or organic conditions. Tomato fruit contained more calcium and less potassium, magnesium, and sodium when grown in an organic compost/soil mix than in hydroponic substrates (Premuzic, Bargiela, García, Rendina, & Iorio, 1998).

Organic cultivation did not affect strawberry mineral concentrations consistently (Bedbabis, Ferrara, Rouina, & Boukhris, 2010; Hakala, Lapveteläinen, Huopalahti, Kallio, & Tahvonen, 2003). Organic crops overall contained 21.1% more iron, 29.3% more magnesium, and 13.6% more phosphorus than their conventional counterparts (Rembiałkowska, 2007).

There were higher concentrations of nitrogen, phosphorus, potassium, sulfur, calcium, magnesium, and boron in organically grown kiwifruits then in those grown under a conventional production system (Amodio, Colelli, Hasey, & Kader, 2007). In contrast, another study found no consistent differences in concentrations of nitrogen, phosphorus, potassium, and magnesium in kiwifruit grown under organic or conventional production systems and only calcium was more abundant in fruit from organic orchards (Benge, Banks, Tillman, & De Silva, 2000). Organic cropping systems may promote mineral content, but there are instances where differences are small or nonexistent (Mditshwa, Magwaza, Tesfay, & Mbili, 2017).

19.2.8.19.3 Harvest and postharvest practices

Mineral composition of some horticultural crops can be modified by harvest practices. In broccoli florets, changes in mineral content (floret:stalk ratio) may be dependent on stalk length (Guo et al., 2018). Postharvest treatments with minerals, primarily calcium, can increase the storage life and quality of some fruits and vegetables. In the last decade, the industry has been encouraged to fortify food and beverages with calcium. Increasing the calcium concentration of horticultural crops gives consumers' new ways to enhance calcium intake without supplements. Also, phosphorous-free sources of calcium can help provide a good balance of dietary calcium and phosphorus (Martín-Diana et al., 2007).

There are two primary ways to apply postharvest calcium to horticultural crops: (1) dipping-washing and (2) impregnation (Martín-Diana et al., 2007). Immersion treatments are used for fresh, sensitive products like leafy vegetables. Impregnation modifies the composition of food through partial water removal and replacement with solutes, without damaging integrity. The driving forces can be an osmotic gradient between sample and solution, application of vacuum followed by normal atmospheric pressure, or both. $CaCl_2$ is widely used as a firming agent for whole and fresh-cut fruits and vegetables. Mineral concentrations were similar in fresh, canned, and frozen fruit and vegetable products; this is expected, since these nutrients are inert and thus not sensitive to degradation by the thermal processes used in food preservation.

19.2.8.20 Incidence of minerals on fruit and vegetable quality and consumer acceptance

Many of these qualities are affected by mineral concentrations and are part of many factors leading to fruit and vegetable acceptability. Acceptability determines the consumption of many essential nutrients: vitamins, antioxidants, and fiber. Thus the effect of minerals on crop quality and consumer acceptance should be considered. The effect of minerals on color, flavor, firmness, and other attributes of specific horticultural commodities is described below.

Consumers buy certain products as good sources of specific minerals: potato and sweet potato for potassium, banana for magnesium and potassium, spinach for iron, potassium, magnesium, and as a nondairy source of calcium (see also Chapter 19: Nutritional quality of fruits and vegetables). Minerals are credence attributes because they cannot be detected by visual inspection or consumption. Thus there is no incentive to measure minerals in a quality control program unless specific nutritional claims can be made. To judge quality, consumers use purchase attributes (size, color, firmness, aroma, and absence of defects) and consumption attributes (flavor and mouth feel).

19.2.8.20.1 Effect of minerals on color

In apples and pears, both leaf and fruit nitrogen correlate positively with fruit green background color (Marsh, Volz, Cashmore, & Reay, 1996). Manganese is also associated with green ground color in apples (Deckers, Daemen, Lemmens, Missotten, & Val, 1997). Excessive nitrogen inhibits background color change from green to yellow, inhibits reddish blush development, and decreases edibility in peaches (Crisosto, Johnson, DeJong, & Day, 1997). In apples, correcting potassium deficiency can increase fruit red color, but applications in excess of need have no effect (Neilsen & Neilsen, 2003). In tomato, potassium deficiency is associated with less lycopene and increased β-carotene (Trudel & Ozbun, 1971), while selenium application to hydroponically grown plants decreased ethylene production and β-carotene accumulation (Pezzarossa, Rosellini, Borghesi, Tonutti, & Malorgio, 2014). In broccoli, foliar sprays of calcium, iron, zinc, or manganese during plant growth increase total chlorophyll content and reduce yellowing of harvested heads; moreover, calcium and manganese applications may enhance chlorophyll retention during postharvest cold storage (El-Mogy, Mahmoud, El-Sawy, & Parmar, 2019). In grapes, sprayings with calcium chloride throughout the fruiting season reduced anthocyanin content (pigments responsible for their red color) but increased total phenolic acids and flavonol (Martins, Billet, Garcia, Lanoue, & Gerós, 2020).

19.2.8.20.2 Effect of minerals on flavor

Nitrogen content shows negative correlation with soluble solids in apples (Dris, Bennett, & Bash, 1999). In contrast, soluble solids increased with increased nitrogen in tomatoes (Barringer, Bennett, & Bash, 1999). In mango, total soluble solids increased when zinc sulfate fertilizer was applied to the soil (Bahadur, Malhi, & Singh, 1998). In "Fino 49" lemon, salinity reduced juice percentage and impaired juice quality by decreasing soluble solid sugars and acidity (García-Sánchez, Carvajal, Porras, Botía, & Martínez, 2003) (see also Chapter 7: Fresh-cut products—implications for postharvest).

Preharvest calcium chloride sprays increase synthesis of key volatile compounds that contribute to overall flavor in ripe Ussurian pear (*Pyrus ussuriensis*), both at harvest and after a five-day storage. Calcium treatment promotes glucosidase activity that releases bound aroma compounds into free forms. Applied calcium also increases lipoxygenase, pyruvate decarboxylase, and alcohol dehydrogenase activities that boost synthesis of ethanol and acetaldehyde in fruit and also the amounts of metabolic unsaturated fatty acids that promote biosynthesis of ester compounds (Wei et al., 2017).

Minerals also affect production of several classes of volatile compounds in pomme fruit (reviewed in Mattheis & Fellman, 1999). In fresh onions, increased sulfur availability enhances pungency and total sulfur flavor, but decreases the concentrations of precursors for synthesis of volatiles, imparting "green" and "cabbage" notes (Randle, 1997). Selenite treatment improves postharvest quality of broccoli through changes in the volatile compound profile, particularly alcohols and sulfides (Lv et al., 2017) (see also Chapter 23).

19.2.8.20.3 Effect of minerals on firmness

Excess nitrogen can decrease tissue firmness (Prange & DeEll, 1997). The relationship between calcium and fruit firmness has been studied and reviewed extensively. Greater firmness and/or slower softening after harvest/storage are associated with higher calcium concentrations or calcium applications (Angeletti et al., 2010; Dong, Zhi, & Wang, 2019). Calcium foliar sprays on peaches and nectarines increased calcium (Manganaris, Vasilakakis, Mignani, Diamantidis, & Tzavella-Klonari, 2005; Manganaris, Vasilakakis, Diamantidis, & Mignani, 2006), while papaya fruit peel and pulp showed quadratic increases in calcium after foliar and fruit calcium chloride applications (Madani, Wall, Mirshekari, Bah, & Mohamed, 2015). In California, no consistent effect on the quality of mid- or late-season peaches and nectarines was found (reviewed in Crisosto et al., 1997).

Postharvest calcium treatments can retain fruit firmness in peaches (Manganaris, Vasilakakis, Diamantidis, & Mignani, 2005; Manganaris, Vasilakakis, Diamantidis, & Mignani, 2007) and lemons (Martínez-Romero, Valero, Serrano, & Riquelme, 1999), among other fruits. Calcium effects on fruit firmness are attributable to calcium's ability to cross-link with pectic polysaccharides by ionic association. Calcium binding may reduce the accessibility of cell wall-degrading enzymes to their substrates. Calcium applications are frequently combined with other physical or chemical treatments (Dong et al., 2019; Nguyen, Nguyen, & Nguyen, 2020).

Preharvest foliar and fruit application of selenium increases selenium concentrations in "Suncrest" peaches and "Conference" pears and enhances flesh firmness both at harvest and after a 14-day storage at 2°C (Pezzarossa, Remorini, Gentile, & Massai, 2012). In "Starking Delicious" apples, foliar application of selenium increases both leaf and fruit selenium concentration, enhances flesh fruit firmness, and lowers ethylene production throughout 6-month storage at 0°C (Babalar, Mohebbi, Zamani, & Askari, 2019). Postharvest applications of different sources of silicon can improve fruit keeping quality and delay softening in banana (Nikagolla, Udugala-Ganehenege, & Daundasekera, 2019) and apples (Ge et al., 2019). Sodium silicate treatment partially counteracted the increased total activity of the cell wall enzymes polygalacturonic acid transeliminase, pectin methyltranseliminase, pectin methylgalacturonase, polygalacturonase, cellulase, and β-galactosidase, which are involved in apple cell wall degradation and subsequent softening (Ge et al., 2019).

19.2.8.20.4 Effect of minerals on rots, physiological disorders, and nutritional value

Calcium-treated fruit has increased firmness and reduced rot incidence. Calcium may affect both processes through its role in strengthening plant cell walls (Manganaris, Vasilakakis, Mignani et al., 2005). High nitrogen increases susceptibility to decay caused by *Monilinia fructicola* (brown rot) in nectarines (Daane et al., 1995). Wounded and inoculated "Fantasia" and "Flavortop" nectarines from trees with >2.6% leaf nitrogen were more susceptible to *M. fructicola* than fruit from trees with less leaf nitrogen (Michailides, Ramirez, Morgan, Crisosto, & Johnson, 1993). Low phosphorus and nitrogen fruit concentrations increase the intensity and incidence of fruit flesh browning in "Grand Pearl" nectarines during cold storage (Olivos, Johnson, Xiaoqiong, & Crisosto, 2012).

Silicon alleviates biotic and abiotic stresses and increases plant resistance to pathogenic fungi. The efficacy of silicon in reducing the severity of several fungal diseases in fruit crops has been studied (Etesami & Jeong, 2020). Silicon, like calcium, plays a role in forming physical resistance barriers that make plant cells less susceptible to fungal pathogen invasion and subsequent enzymatic degradation. Additionally, silicon promotes defense-related enzyme activities in plant-pathogen interactions, which are connected to disease resistance. Silicon-treated muskmelons showed various defense responses (regulation of energy metabolism and ROS production) against *Trichothecium roseum* (Lyu et al., 2019). In sweet cherry fruit, silicon reduces decay and lesion diameter of blue mold and brown rot caused by *Penicillium expansum* and *Monilinia fructicola*, respectively (Qin & Tian, 2005). It also decreases the incidence and severity of postharvest carrot rot caused by *Sclerotinia sclerotiorum* (Elsherbiny & Taher, 2018). In banana, a postharvest silicon dip treatment delayed the time required for diseases (stalk end rot and anthracnose caused by *Lasiodiplodia* sp. and *Colletotichum* sp.) to cover 5% of total fruit area (Nikagolla et al., 2019).

Consumers consider that fruits have less predictable quality than manufactured snacks. The effect of nutrients on the final quality of horticultural products may not become evident until harvest, distribution, or consumption. The expression "latent damage" describes damage incurred at one step, but not apparent until a later step. Physiological disorders are a type of latent damage. Some physiological disorders are related to nutrient imbalance. Calcium deficiency is associated with postharvest disorders. Calcium deficiency is an important preharvest factor for fruit and vegetable physiological disorders such as bitter pit in pomme fruit, blossom-end rot in tomato, pepper, and watermelon, blackheart in celery, cracking and cavity spot in carrot, and tipburn in lettuce and cabbage (Ferguson, Volz, & Woolf, 1999), although total fruit tissue calcium content may not be the only cause of development of these disorders (Tonetto de Freitas & Mitcham, 2012). Apples and pears with low calcium concentrations develop more superficial scald than those with high concentrations (Li, Han et al., 2020; Li, Cheng et al., 2020). Preharvest applications of calcium, alone or in combination with other chemicals, can mitigate sweet cherry rain cracking, a major cause of crop loss worldwide (Correia, Schouten, Silva, & Gonçalves, 2018; Dong et al., 2019). Cracking, a physiological failure of the fruit peel caused by cell wall swelling, also manifests as fractures in the peel or cuticle of different susceptible fruits such as apple, grape, persimmon, avocado, pistachio, *Citrus*, and banana. Foliar calcium fertilization alleviated this disorder in species other than sweet cherry and preharvest applications of calcium decrease cracking in pomegranate (Davarpanah et al., 2018) and some plum cultivars (Vangdal, Lunde Knutsen, & Kvamm-Lichtenfeld, 2018). Other calcium-related disorders are associated with long-term cold storage, such as CI in muskmelon (Combrink, Jacobs, & Maree, 1995). Postharvest calcium applications limited the incidence of CI in peach fruit, expressed as flesh browning, after 4 weeks cold storage at 5°C and additional ripening at room temperature for 5 days (Manganaris et al., 2007). Nevertheless, preharvest calcium applications did not affect the onset of CI in peaches and nectarines (reviewed in Lurie & Crisosto, 2005). In apples, interaction of elements such as K/Ca, N/Ca, and Mg/Ca was more closely associated with bitter pit than those elements individually. Magnesium and potassium are part of an index to predict bitter pit (Autio, Bramlage, & Weis, 1986). "Rocha" pear fruits that developed disorders after a 22-week storage had been harvested mostly from orchards with lower Ca concentrations and higher K/Ca ratios; also, the (K + Mg)/Ca ratios were higher in fruit with internal disorders (Saquet et al., 2019).

Minerals can influence the concentrations of other nutrients in horticultural crops. In a field trial of mature papaya trees, preharvest applications of calcium chloride decreased magnesium concentrations in fruit peel and pulp (Madani et al., 2015). Nitrogen fertilizers applied at high rates decreased the concentration of vitamin C in fruits (citrus juices) and vegetables (potatoes, cauliflower, white cabbage, and crisphead lettuce), while increased potassium fertilization increases AsA (reviewed in Lee & Kader, 2000). Foliar applied calcium lactate enhanced sweet pepper quality attributes: vitamin C, fruit firmness, total soluble solids, carotenoids, total phenols, flavonoids, and antioxidant activity (Barzegar, Fateh, & Razavi, 2018). In persimmon, postharvest combined treatments with calcium lactate and hot water maintained fruit quality and antioxidant capacity and increased soluble tannins and AsA during cold storage (Naser, Rabiei, Razavi, & Khademi, 2018). In grapes, sprayings with calcium chloride throughout the fruiting season stimulated synthesis of stilbenoids (Martins et al., 2020).

19.3 Antioxidants

19.3.1 Oxidative damage and antioxidants

ROS are reduced forms of oxygen such as singlet oxygen, hydrogen peroxide (H_2O_2), superoxide ($O_2^{-\bullet}$), or hydroxyl radical ($OH^{-\bullet}$). ROS cause deleterious modifications in proteins, lipids, and nucleic acids by altering normal metabolism in living organisms (Waris & Ahsan, 2006). The protective effects of fruit and vegetables against ROS are linked to the presence of antioxidants. Such compounds, able to prevent uncontrolled cellular oxidation (Dragsted, 2003) are present in all plant organs and include diverse metabolites including AsA, carotenoids, vitamin E, phenolics, glucosinolates, and thiosulfinates (Fig. 19.3, Table 19.8).

19.3.2 Carotenoids, ascorbic acid, tocopherols and tocotrienols

Besides on their role as vitamins these compounds play a key role in the regulation of cell redox status (Järvinen, Knekt, Hakulinen, Rissanen, & Heliövaara, 2001; Rao & Rao, 2007; Tan et al., 2010). The general properties of these compounds were described in Section 19.2.7.

19.3.3 Phenolic compounds

Phenolics are diverse compounds derived from aromatic amino acids. Many phenolic compounds have been identified in plants. They are grouped into subclasses such as phenolic acids, flavonoids, lignans, stilbenes, tannins, coumarins, and lignin (Vuolo, Lima, & Junior, 2019). Their distinctive feature is the presence of aromatic rings with variable degrees of hydroxylation. Phenolics contribute to fruit pigmentation and act as predator deterrents and antimicrobials. They may provide astringency or bitter taste to some products (Zhang et al., 2020). During processing or storage many phenolics are readily oxidized by plant peroxidases (PODs) and polyphenol oxidases (PPOs), leading to undesirable tissue browning.

Phenolic compounds are generally present at low concentrations but in blueberry can be over 0.1%. Phenolics accumulate preferentially in the peel, but this varies depending on species and chemical group. Eggplant anthocyanins are concentrated in the peel, while chlorogenic acid, the primary antioxidant, predominates in the pulp, surrounding the

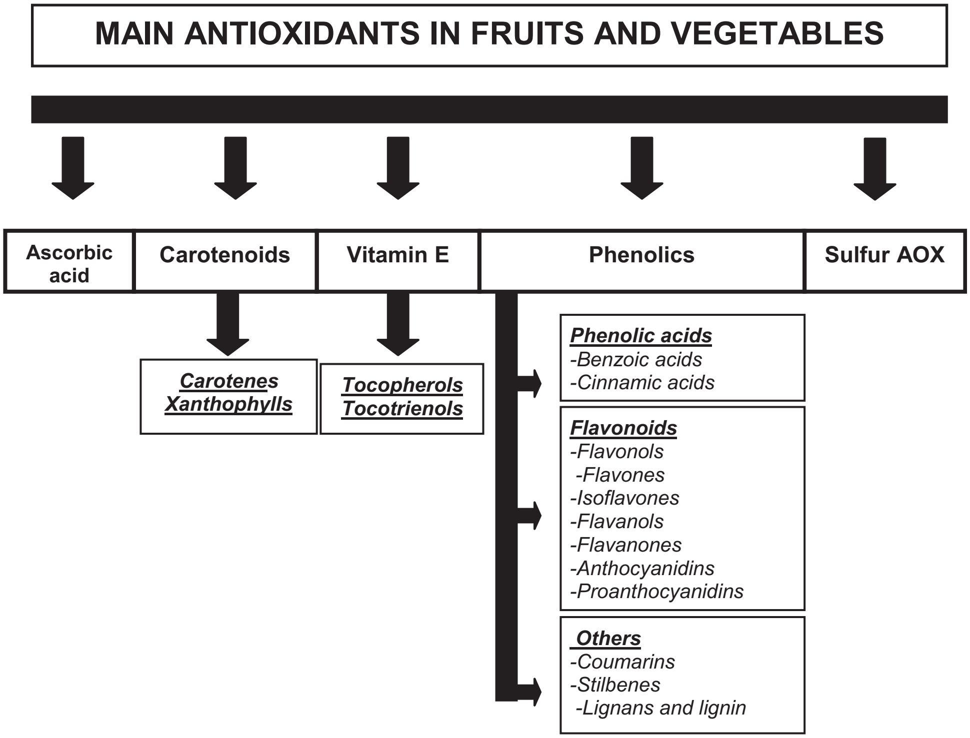


FIGURE 19.3 Main dietary antioxidants present in fruits and vegetables.

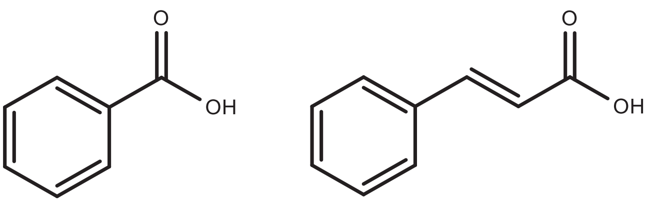


FIGURE 19.4 Structure of benzoic acid (left) and cinnamic acid (right), precursors of the two main classes of phenolic acids present in fruits and vegetables.

seeds (Zaro, Chaves, Vicente, & Concellón, 2014). As with other compounds, the health-promoting effects of phenolics depend on their bioavailability, but their concentration in plasma is very low (Konic-Ristic et al., 2011).

19.3.3.1 Phenolic acids

Phenolic acids are derivatives of benzoic and cinnamic acids (Benbrook, 2005) (Fig. 19.4). The most abundant benzoic acid derivatives are *p*-hydroxybenzoic, vanillic, syringic, and gallic acids. Common cinnamic acid derivatives include *p*-coumaric, caffeic, ferulic, and sinapic acids. The derivatives differ in the degree of hydroxylation and methoxylation of the aromatic ring. Caffeic acid is the most abundant in berry fruits (Mattila, Hellstrom, & Torronen, 2006), while coumaric is present at lower concentrations. Ferulic acid is 90% of total phenolic acids in cereals. Frying and roasting readily degrade phenolic acids (Rashmi & Negi, 2020). Improved retention is observed under frozen storage.

19.3.3.2 Flavonoids

They are a large group of phenolic compounds with two aromatic rings associated by a C3-oxygenated heterocycle. Flavonoids are further divided in subclasses: flavones and flavonols, flavanones and flavanols, isoflavones, proanthocyanidins, and anthocyanidins (Thakur et al., 2020).

19.3.3.2.1 Flavones and flavonols

Flavonols have a central 3-hydroxypyran-4-one ring. Flavones lack the OH in position 3 (Fig. 19.5). Rutin, luteolin, and apigenin are common flavones, while the most abundant flavonols are quercetin and kampferol (Manach, Scalbert, Morand, Remesy, & Jimenez, 2004). Onions are rich in quercetin. Blueberry also has high concentrations, especially in peel, because their biosynthesis is stimulated by light exposure. Celery is a good source of flavones. In citrus, they are also abundant, in the peel and high concentrations are also present in herbs (Slimestad, Fossen, & Brede, 2020).

19.3.3.2.2 Flavanones and flavanols

Flavanones have no double bond in position 2,3 of the central ring, while flavanols lack a carbonyl group at position 4 (Fig. 19.6). The genus *Citrus* accumulates flavanone glycosides. Orange juice contains the flavanone glycoside hesperidin (Tripoli, La Guardia, Giammanco, Di Majo, & Giammanco, 2007). The flavanols catechin and epicatechin are common in grape, capers, and parsley (Faggio et al., 2017).

19.3.3.2.3 Proanthocyanidins

Proanthocyanidins are oligomeric flavonoids (oligomers of catechin and epicatechin). They are common in grape peel, seeds, and wine, in which they are related to astringency (Basalekou et al., 2019). Sources of proanthocyanidins include apple, almond, and blueberry (Bodoira & Maestri, 2020; Li, Han et al., 2020; Li, Cheng et al., 2020).

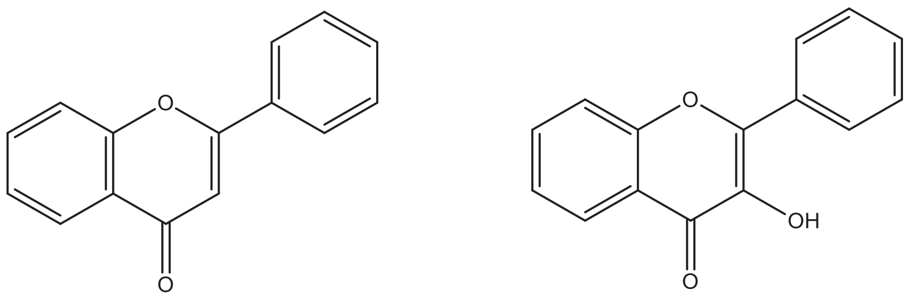


FIGURE 19.5 General structure of flavones (left) and flavonols (right).

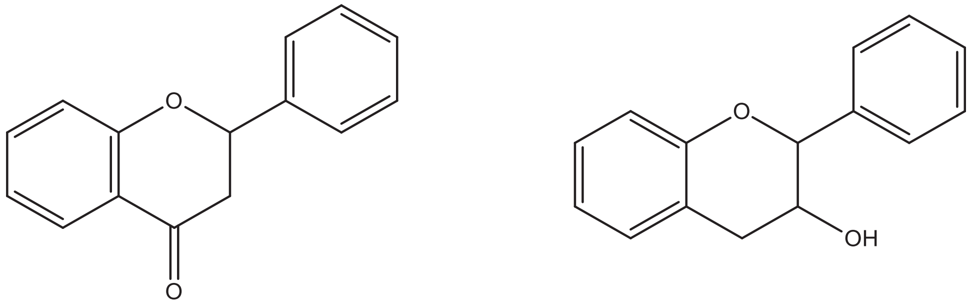


FIGURE 19.6 General structure of flavanones (left) and flavanols (right).

19.3.3.2.4 Anthocyanidins

The term anthocyanin derives from the Greek words *anthos* and *cyan*, meaning flower and blue. They provide characteristic red or purple colors to some fruits (Faggio et al., 2017). Yet, some forms are uncolored. Anthocyanidins contribute to the antioxidant capacity of fruits and vegetables. Because of their widespread distribution, anthocyanins are common antioxidants in the human diet. The antioxidant capacity of anthocyanins relies on their ability to donate H from aromatic hydroxyls to free radicals and to delocalize unpaired electrons. The basic structure of anthocyanidins derives from the flavilium cation (2-phenyl-benzopyril). Owing to their polarity, anthocyanins are water soluble. Six anthocyanidins are found in fruits and vegetables: pelargonidin, cyanidin, delphinidin, peonidin, petunidin, and malvidin. They differ in the substituents (OH, H, or OCH_3) associated with the phenolic rings. Their distribution in fruits iscyanidin: 30%; delphinidin: 22%; pelargonidin: 18%; peonidin: 7.5%; malvidin: 7.5%; and petunidin: 5% (Andersen & Jordheim, 2006). Hydroxyl distribution influences both the hue and antioxidant capacity of anthocyanidins. As a general rule, hydroxylation induces a shift of the visible max toward longer wavelengths (bathochromic effect, also known as blueing effect) (Gómez-Míguez, González-Manzano, Escribano-Bailón, Heredia, & Santos-Buelga, 2006). Methylation of hydroxyl groups causes the reverse trend. Consequently, the anthocyanidins with more hydroxyls are bluish, while those with methoxyl groups are red (Delgado-Vargas & Paredes-López, 2003). They are glycosylated or acylated, which increases or reduces solubility, respectively. Sugars may be present as mono-, di-, or trisaccharides. A major form of anthocyanins in most fruits is the monoglycoside (70%−100% of the total). Glucose, galactose, rhamnose, and arabinose are the most common sugars in anthocyanins. Acylating agents include caffeic, *p*-coumaric, ferulic, and sinapic acids (Castañeda-Ovando, Pacheco-Hernandez, Paez-Hernandez, Rodriguez, & Galan-Vidal, 2009). Anthocyanins form copigments with some metallic ions or colorless organic compounds in complex associations. Such interaction may change pigment hues and increase intensity (Boulton, 2001). Anthocyanin color is affected by pH. At low pH, the flavylium cation contributes purple and red colors. At higher pH, the quinoidal blue species predominate. Anthocyanin concentrations range from undetectable up to 611 mg/100 g FW in bilberry (Table 19.9) (Faggio et al., 2017).

TABLE 19.9 Anthocyanidin concentrations in common fruits. (Bhagwat, Haytowitz, and Holden, 2011).

Fruit	Content (mg/100 g FW)
Acai	53.6
Acerola	22.6
Apple, Fuji	0.7
Apple, Gala	1.1
Apple, Red Delicious	3.8
Avocado	0.3
Blackberry	90.6
Blueberry	141.0
Cherry	27.7
Cranberry	85.5
Currant, black	154.8
Currant, red	75.0
Eldberry	485.3
Grape, Concord	65.6
Grape, red	44.0
Nectarine and peach	1.8
Pear	12.2
Plum red	7.0
Plum black	39.7
Plum yellow	0.3
Raspberry	40.9
Strawberry	23.8

Adapted from Bhagwat, S., Haytowitz, D. B. & Holden, J. M. (2011). 'USDA database for the flavonoid content of selected foods', Release 3. *Nutrient Data Laboratory, Beltsville Human Nutrition Research Center, Agricultural Research Service, U.S. Department of Agriculture.*

19.3.3.3 Others

Lignans are diphenolic structures formed by the association of two cinnamic acid derivatives. They are present in linseed, cereals, and legumes, but not significantly in fruits and vegetables. The main dietary sources of lignans are linseed, soybean, and whole cereals and berries among fruits (Durazzo et al., 2019). Stilbenes have received great attention due to their suggested anticarcinogenic properties (Fig. 19.7). Resveratrol belongs to this group; it accumulates in response to pathogens and other stresses in grapes (González-

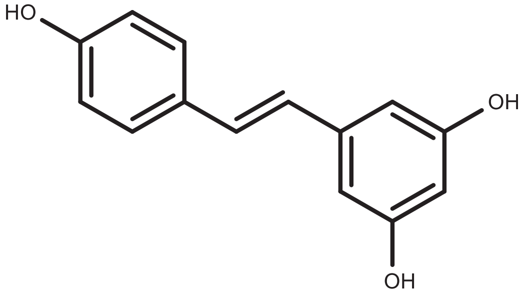


FIGURE 19.7 Structure of resveratrol. This compound has been studied in detail in grapes and may have anticarcinogenic properties.

Barrio et al., 2006). Stilbenes are present at high concentrations in grape, almond, bean, blueberry, bilberry, peanut, cranberry, plum, and wine (El Khawand, Courtois, Valls, Richard, & Krisa, 2018). It has also been identified in other fruits, such as blueberry. Lignin was described in Section 19.2.6.1. Due to its very low solubility and digestibility, its contribution to antioxidant activity is negligible.

19.3.3.4 Association between phenolic structures and antioxidant capacity

The structure of phenolic compounds is directly related to their antioxidant properties. A higher degree of hydroxylation of the aromatic rings increases antioxidant activity of hydroxycinnamic acids (Fan et al., 2009). More hydroxyls in the B ring also increases antioxidant activity of anthocyanins (Cao, Sofic, & Prior, 1997). Hydroxyls in *ortho* configuration enhance antioxidant activity (Zheng & Wang, 2003). The antioxidant activity of phenolic acids is enhanced by other electron-donating groups associated with the rings (Jing et al., 2012).

Glycosylation has variable effects on the antioxidant capacity of phenolic compounds. Often anthocyanins have similar antioxidant activity than the corresponding anthocyanidin. Cyanidin, delphinidin, and malvidin have similar antioxidant (AOX) capacity to their glycosylated derivatives. Yet, arabinose and rutinoside glycosides and diglucosides have less antioxidant capacity than monoglucosides (Zheng & Wang, 2003). Flavonols are more potent antioxidants than anthocyanins, due to a 2,3 double bond associated with a 4-oxo function (Melidou, Riganakos, & Galaris, 2005).

19.3.4 Sulfur antioxidants

Sulfoxides and glucosinolates are among the most important sulfur antioxidants present in vegetables. Sulfoxides are common in vegetables of the genus *Allium*, particularly garlic (*Allium sativum*), one of the oldest medicinal plants. The major sulfur compounds in intact garlic are δ-glutamyl-*S*-allyl-L-cysteine and *S*-allyl-L-cysteine sulfoxide (alliin) (Butt, Sultan, Butt, & Iqbal, 2009). When raw garlic is chopped, the sulfoxides are converted to unstable thiosulfinates like allicin. Other thiosulfinates include allylmethyl-, methylallyl-, and trans-1-propenyl-thiosulfinate. Glucosinolates are present in plants of the order Brassicales. They have received great attention because their degradation products are powerful anticarcinogenic compounds. They consist of a β-D-thioglucose group, a sulfonated oxime moiety and a side chain derived from methionine, an aromatic, or a branched amino acid. In broccoli, the most abundant is glucoraphanin (80%), followed by glucobrassicin. Sinigrin is predominant in Brussels sprouts and mustard seeds (Bischoff, 2016).

19.3.5 Factors regulating the concentrations of antioxidants in fruits and vegetables

Several factors influence the accumulation of antioxidants in fruits and vegetables. Changes in composition from harvest to consumption depend on the compound, commodity, cultural practices, postharvest handling, processing, and home cooking conditions (Fig. 19.8).

19.3.5.1 Genetic factors

19.3.5.1.1 Species

The species determines the prevalence of specific antioxidants. With some exceptions, most fruits accumulate typical antioxidants (Table 19.6). Berries and artichokes are rich in phenolics (Avio et al., 2020; Bouali et al., 2020; Zheng & Wang, 2003). In ripe blueberry, AsA contributes only 0.4%−9.0% of total antioxidant capacity (Kalt, Forney, Martin, & Prior, 1999). The distribution of antioxidants varies among the tissues of a fruit. Water-soluble polyphenolic compounds are found primarily in skins of peaches, pears, and apples (Ain, Saeed, Barrow, Dunshea, & Suleria, 2020).

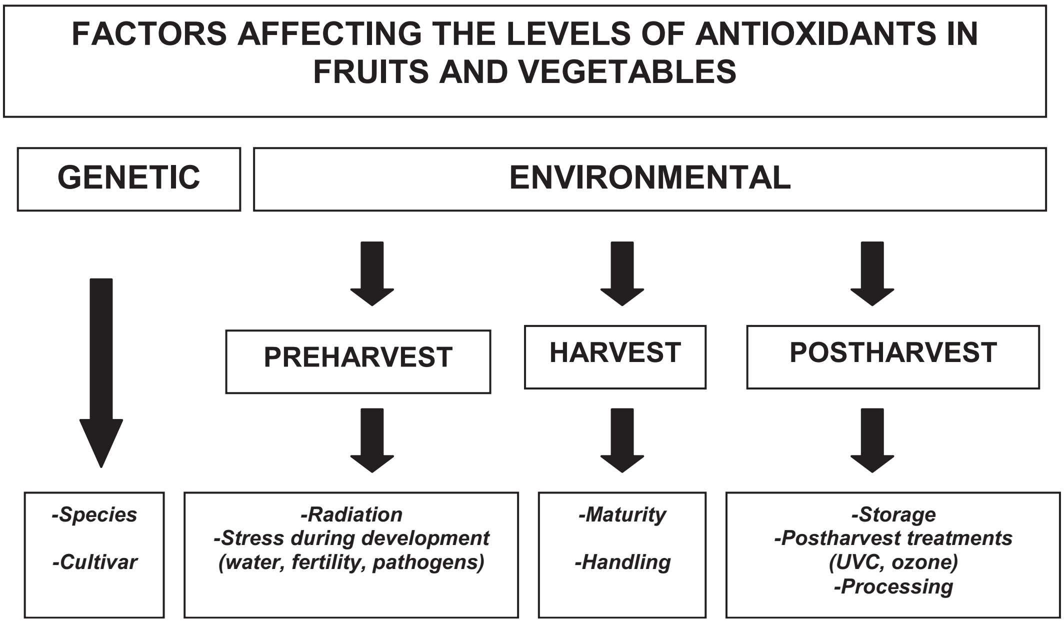


FIGURE 19.8 Factors affecting the concentrations of antioxidants in fruits and vegetables.

19.3.5.1.2 Cultivar

For a given species, antioxidant concentrations vary by cultivar (Wang & Lin, 2000). The identification of lines or mutants that accumulate antioxidants might be useful in breeding programs to improve the nutritional value of fruits and vegetables. Overexpression of high-pigment (*hp*) in tomato increased carotenoid accumulation (Liu et al., 2004). Also, in tomato, overexpression of phytoene synthase and lycopene cyclase increased β-carotene and lycopene (D'Ambrosio et al., 2004). In carrot, overexpression of β-carotene ketolase from *Haematococcus pluvialis* led to accumulation of the ketocarotenoid astaxanthin (Jayaraj, Devlin, & Punja, 2007). Transgenic approaches have increased the concentrations of phenolic compounds. Transformation of tomato with a *Petunia* gene for chalcone isomerase increased the flavonol concentration in the peel 80-fold (Muir et al., 2001). While the biosynthetic pathway for AsA is established and most of its genes have been cloned and expressed in various plant species, these strategies have had limited success (Tripodi et al., 2018).

19.3.5.2 Environmental factors

19.3.5.2.1 Radiation

Modifications in the concentrations of phenolic compounds, AsA, and carotenoids are associated with changes in sunlight exposure. Fruit location within the canopy and thus sun exposure can affect the concentrations of bioactive compounds (Ali, Ejaz, Anjum, Nawaz, & Ahmad, 2020). Sun-exposed fruit sides have more phenolics and vitamin C than shaded regions (Olale, Walyambillah, Mohammed, Sila, & Shepherd, 2019). In leafy vegetables, there are 10 times more flavonols in surface leaves than in internal leaves. Total phenolics doubled in tomato plants exposed to more light. These plants also accumulated more carotenoids and AsA (Gautier et al., 2008). Thus radiation interception is important to obtain commodities with increased antioxidants. But, the optimal irradiance to maximize accumulation of different antioxidants in fruits and vegetables is not established.

19.3.5.2.2 Cultivation practices

Several works analyzed the effect of cultural practices on antioxidants. Strawberries grown with plastic mulch had greater antioxidant capacity than fruits from uncovered beds (Wang, Zheng, & Galletta, 2002). High nitrogen is associated with reduced AsA (Lee & Kader, 2000). Adding compost as a soil supplement significantly enhanced AsA (Wang & Lin, 2003). Vitamin C accumulation is inversely correlated with rainfall (Toivonen, Zebarth, & Bowen, 1994). Some studies found that organic products accumulated more antioxidants and vitamins than conventionally grown commodities (Asami, Hong, Barrett, & Mitchell, 2003; Chassy, Bui, Renaud, Van Horn, & Mitchell, 2006). Other studies found no differences or opposite results (Barrett, Weakley, Diaz, & Watnik, 2007). It is not possible to conclude that organically grown products are nutritionally superior to conventional commodities (see also Chapter 19: Nutritional quality of fruits and vegetables). Antioxidant accumulation is also dependent on plant nutritional status (Sonntag et al., 2020). The roostock/cultivar combination also modulates antioxidant accumulation in plums (Radović et al., 2020).

19.3.5.2.3 Maturity at harvest

Fruit developmental stage has a large impact on total antioxidant capacity. These changes depended on the commodity. In tomato and pepper, total antioxidant capacity increases as carotenoids and vitamin C accumulate during ripening. Total anthocyanin increases during ripening in all berries (Wang & Lin, 2000). Yet, the antioxidant capacity peaks in other species early in development. During berry ripening, anthocyanins accumulate while phenolic acids decrease (Lin et al., 2020; Wang & Lin, 2000). Carotenoids increase during development in pepper, tomato, mango, and *Prunus* species (Kim et al., 2020). In products in which anthocyanins or chlorophylls dominate, carotenoids decrease during development. In cherry, AsA accumulates during ripening (Xu et al., 2020).

19.3.5.2.4 Wounding

Tissue damage greatly affects total antioxidant concentration. Cell disruption exacerbates turnover of AsA and phenolic compounds. Eliminating cellular compartmentalization triggers oxidation of preexisting phenolics by PPOs and increases hydrogen peroxide, providing the cosubstrate for POD-mediated degradation. Wounding also alters phenolic biosynthesis (Hussein, Fawole, & Opara, 2020). In lettuce, cutting induced phenylalanine ammonia lyase and led to accumulation of chlorogenic acid (Choi, Tomás-Barberán, & Saltveit, 2005). Carotenoid turnover is also accelerated by oxygen, but they are more stable than other AOX groups. Careful handling reduces antioxidant losses (Erkan & Dogan, 2019).

19.3.5.2.5 Storage

Refrigeration slows deterioration of vitamin C. Except for broccoli and banana; most commodities lose visual quality before significant loss of antioxidant capacity occurs (Kevers et al., 2007). Improper temperature management significantly reduces visual quality and thus, consumer acceptance. Ethylene induces accumulation of the bitter compound iso-coumarin 6-methoxymellein. After extended storage, both membrane disruption causing loss of cell compartmentation and the increase in ROS have been linked to antioxidant degradation (Tao, Wang, Zhang, Jiang, & Lv, 2019).

19.3.5.2.6 Other treatments

Biosynthesis of phenolics is triggered by elicitors like ultraviolet radiation or ozone. In grape, postharvest UV-C and ozone increased accumulation of resveratrol (González-Barrio et al., 2006). In strawberry, UV-C also increased phenolic compounds and antioxidant potency (Li et al., 2019). UV-B exposure increased accumulation of glucosinolates in broccoli, with the changes dependent on the combination of radiation intensity and dose applied (Darré et al., 2017; Duarte-Sierra, Hasan, Angers, & Arul, 2020).

19.3.5.2.7 Processing

Processing operations greatly affect antioxidant concentrations of fruits and vegetables (Nayak, Liu, & Tang, 2015). Effects of processing on the amount and bioavailability of antioxidants depend on treatment intensity and the specific compound (Bernhardt & Schlich, 2006). Washing and peeling may result in loss of water-soluble AOXs. In general, freezing does not reduce antioxidants, but these responses may be cultivar-dependent. Four raspberry cultivars showed contradictory results during 1 year of frozen storage, from no change to a 12% increase and decreases of 21% and 28%, respectively (Rickman, Barrett, & Bruhn, 2007). Fat-soluble nutrients such as carotenoids and vitamin E may be released from their cellular matrices by thermal, freezing, high-pressure, or other preservation treatments. In carrot and spinach, vapor cooking increases carotenoid bioaccesibility by disrupting its complexes with proteins. Similarly, the bioavailability of lycopene increases in heat-treated tomato (Nayak et al., 2015). But, cooking can isomerize β-carotene to *cis* forms with less provitamin A activity (Deming, Baker, & Erdman, 2002; Deming, Teixeira, & Erdman, 2002). Heat, light, and oxygen accelerate carotenoid degradation (Von Elbe & Schwartz, 1996). AsA is one of the most labile antioxidants (Lee & Kader, 2000). Heat treatments degrade vitamin C and may cause leaching into the liquid medium. Blanching or even freezing and thawing can cause losses of up to 25%. More drastic treatments destroy 90% of AsA. Factors affecting AsA loss include the severity of heating, the exposed surface (which affects lixiviation in the cooking medium), oxygen availability, and pH (Eitenmiller & Landen, 1999). AsA is more stable at acidic pH, under reduced oxygen, in darkness, and in the presence of chelating agents. Consumption of fresh foods is the best way to minimize AsA losses. Processing can decrease phenolic antioxidants (Tiwari & Cummins, 2013). Peeling or cutting reduces quercetin by only 1%, but water cooking might destroy 75%. Strawberry processing into jams decreased ellagic acid and flavonols by 20% (Häkkinen, Heinonen et al., 1999; Häkkinen, Karenlampi, Heinonen, Mykkanen, & Torronen, 1999). During drying, anthocyanins were more readily degraded than other phenolics. Anthocyanin losses in processed berries are reduced by blanching, indicating enzymatic degradation (Sablani et al., 2010).

Although processing does not increase the concentration of antioxidants, it may make them more easily extracted and bioavailable. Increased free ellagic acid was found in heated raspberry pulp. This was likely released from insoluble ellagitannins. After canning, total anthocyanins decreased up to 44%, but phenolic concentrations and antioxidant activity increased by 50% and 53%, respectively (Sablani et al., 2010). AOXs is present in foods mostly as esters, glycosides, or polymers, which are not absorbed directly. Hydrolysis of aglycones may increase their bioavailability (Hollman & Katan, 1997).

19.4 Allergens

Allergies are exaggerated immune reactions to substances that are then known as allergens (Remington et al., 2020). The first stage of allergic responses, sensitization, involves the production of immunoglobulin E antibodies as a defense response. Subsequent episodes result in the release of other substances such as histamine, leukotrienes, and cytokines that can induce observable responses. Symptoms appear immediately or after a short term of ingestion or contact. Food allergies may be induced either by consumption or contact. Consumption allergies are associated with a variety of symptoms, including but not limited to oral or general pruritus (itching), sneezing, tearing or redness of the skin, digestive symptoms (abdominal pain, vomiting, or diarrhea), urticaria, choking, dizziness, and hypotension (Skypala, 2019). Contact allergies more often lead to urticaria, contact dermatitis, conjunctivitis, or respiratory symptoms such as rhinitis or asthma. Sometimes, lip erythema swelling of the lips and tongue (angioedema) may also appear

(Muluk & Cingi, 2018). In severe cases, allergies may lead to systemic disease (anaphylaxis) and death (Remington et al., 2020). Food allergenicity depends on several factors, including the individual susceptibility, the type of allergenic substance and its concentration (Skypala, 2019). The threshold dose is dependent on age (Turner et al., 2016). Exercise, alcohol, or certain nonsteroidal antiinflammatory drugs can often be cofactors of the allergic reaction (Skypala, 2019). This has been seldom addressed with regard to fresh fruit and vegetables. Many different foods, including fruits and vegetables may contain allergenic substances (Skypala, 2019).

19.4.1 Allergens in fruits

One important source of allergic reaction in fruit is in latex-containing species. Such responses are linked to chitinases (Righetti et al., 2015; Sompornrattanaphan et al., 2019). Banana has one of the highest allergenic capacities (Nikolić et al., 2018). Kiwifruit has the most allergens identified, with 13 proteins (Le et al., 2013). Fruits belonging to the *Rosaceae* family have identified allergens. Apple is the fruit most implicated in exercise-induced anaphylaxis (Skypala, 2019). It has four identified allergens: Mal d 1 (pathogenesis-related protein,), Mal d 2 (thaumatin-like protein), Mal d 3 (nonspecific lipid transfer protein), and Mal d 4 (profilin) (www.allergen.org). Apple processing, including heat treatment and its combination with reducing agents such as sulfur, may reduce allergenicity (Marzban et al., 2014). Sweet cherry (*Prunus avium*) has five identified allergens. Cherry cultivation under cover favored antioxidant accumulation without increasing the allergen Pru av 1 (Schmitz-Eiberger & Blanke, 2012). Peach fruit contains six identified allergens, but two of them (Pru p 3, nonspecific lipid transfer protein and Pru p 7, gibberellin-regulated protein) are more frequently linked to allergic episodes. Allergen concentrations change depending on the variety and maturity stage (Jin et al., 2020). Pru p 3 is more problematic, since it is the most resistant to the gastrointestinal tract and heat treatment (Tuppo et al., 2014). Peach packaging in opaque bags reduced the amount of allergens (Ma et al., 2018). The application of high hydrostatic pressures and pulsed electric fields treatments has been evaluated as a method to reduce allergenicity in processed peach (Tobajas et al., 2020).

19.4.2 Allergens in vegetables

One of the most frequent causes of adverse allergenic events is celery, for which six allergens have been identified (www.allergen.org). The concentration of allergens, as in fruit, varies depending on cultivar (Dölle et al., 2018). Celery allergies have been linked to exercise-induced anaphylaxis. Some technological factors can decrease the reactivity of allergens in celery, such as pH and heat treatment (Rib-Schmidt et al., 2018). Tomato plant and fruit can cause contact dermatitis and allergic reactions upon consumption (Martín-Pedraza et al., 2016). Seven allergenic proteins have been identified in this species. (Kurze, Lo Scalzo, Campanelli, & Schwab, 2018). Particularly, Sola l 4 is sensitive to heat treatment and can be reduced by drying (Kurze et al., 2018). An eggplant 17 kDa protein (Sola m 1) has been identified as a proteic allergen (Maity, Bhakta, Bhowmik, Sircar, & Bhattacharya, 2020). Also, this fruit is rich in histamine, which can eventually cause contact dermatitis, followed by systemic manifestations in the digestive or respiratory tracts (Kiran Kumar, Harish Babu, & Venkatesh, 2009). In lettuce, lipid transfer protein allergen (Lac s 1) has been identified (Bascones, Rodríguez-Pérez, Juste, Moneo, & Caballero, 2009). Food allergy is the most frequent allergic reaction to lettuce (Paulsen & Andersen, 2015). Chicory may cause contact dermatitis (Herman & Baeck, 2017).

19.5 Conclusion

In this chapter, we reviewed the main components present in fruits and vegetables in relation to their nutritional and quality value in postharvest systems. Fruit and vegetable consumption makes a major contribution of nutritionally relevant components such as water, fiber, some minerals, and vitamins (especially C and provitamin A). In addition, they are an important source of dietary antioxidants and bioactive molecules. Major advances have been made in the characterization of the isolated metabolites. However, the interaction between the different components is far from being understood. Both the level and bioavailability of fruit and vegetable components show wide variation depending on the commodity, production, and postharvest processing conditions considered. Growing evidence supports the central role of fruits and vegetables in the protection against several chronic and degenerative diseases as well as in the prevention of some types of cancer. Recent works also point out several other relevant benefits, such as the modulating the immune system and regulating the gut microbiota. All such findings increasingly stress the relevance of promoting fruit and vegetable consumption, especially considering that fruit and vegetable intake is still well below the current WHO recommendation. Efficient postharvest systems must also have a key role preventing losses of the large set of highly valuable compounds present in fruits and vegetables.

References

Aaron, K. J., & Sanders, P. W. (2013). Role of dietary salt and potassium intake in cardiovascular health and disease: A review of the evidence. *Mayo Clinic Proceedings*, *88*, 987−995.

Abbaspour, N., Hurrell, R., & Kelishadi, R. (2014). Review on iron and its importance for human health. *Journal of Research in Medical Science*, *19*, 164−174.

Ain, H. B. U., Saeed, F., Barrow, C. J., Dunshea, F. R., & Suleria, H. A. R. (2020). Food processing waste: A potential source for bioactive compounds. *Bioactive Compounds in Underutilized Fruits and Nuts* (pp. 625−649). Springer International Publishing, Springer Nature Switzerland AG.

Alasalvar, C., Salvadó, J. S., & Ros, E. (2020). Bioactives and health benefits of nuts and dried fruits. *Food Chemistry*, *314*, 126192.

Ali, S., Ejaz, S., Anjum, M. A., Nawaz, A., & Ahmad, S. (2020). Impact of climate change on postharvest physiology of edible plant products. In I. M. Hasanuzzaman (Ed.), *Plant ecophysiology and adaptation under climate change: Mechanisms and perspectives* (pp. 87−115). Singapore: Springer. Available from http://doi.org/10.1007/978-981-15-2156-0.

Amodio, M. L., Colelli, G., Hasey, J. K., & Kader, A. A. (2007). A comparative study of composition and postharvest performance of organically and conventionally grown kiwifruits. *Journal of the Science of Food and Agriculture*, *87*, 1228−1236.

Amtmann, A., Armengaud, P., & Volkov, V. (2004). Potassium nutrition and salt stress. In M. R. Blatt (Ed.), *Membrane transport in plants annual plant reviews* (15, pp. 293−332). Oxford: Blackwell.

Andersen, Ø. M., & Jordheim, M. (2006). The anthocyanins. In Ø. M. Andersen, & K. R. Markham (Eds.), *Flavonoids: Chemistry, biochemistry and applications* (pp. 471–552). Boca Raton, FL: CRC Press.

Angeletti, P., Castagnasso, H., Miceli, E., Terminiello, L., Concellón, A., Chaves, A., & Vicente, A. R. (2010). Effect of preharvest calcium applications on postharvest quality, softening and cell wall degradation of two blueberry (*Vaccinium corymbosum*) varieties. *Postharvest Biology and Technology*, *58*, 98–103.

Asami, D. K., Hong, Y. H., Barrett, D. M., & Mitchell, A. E. (2003). A comparison of the total phenolic and ascorbic acid contents of freeze-dried and air-dried marionberry, strawberry and corn grown using conventional, organic and sustainable agricultural practices. *Journal of Agricultural and Food Chemistry*, *51*, 1237–1241.

Asl, P. J., Niazmand, R., & Jahani, M. (2020). Theoretical and experimental assessment of supercritical CO_2 in the extraction of phytosterols from rapeseed oil deodorizer distillates. *Journal of Food Engineering*, *269*, 109748.

Autio, W. R., Bramlage, W. J., & Weis, S. A. (1986). Predicting disorders of 'Cox's Orange Pippin' and 'Bramley's Seedling' apples by regression equations. *Journal of the American Society for Horticultural Science*, *111*, 738–742.

Avio, L., Maggini, R., Ujvári, G., Incrocci, L., Giovannetti, M., & Turrini, A. (2020). Phenolics content and antioxidant activity in the leaves of two artichoke cultivars are differentially affected by six mycorrhizalsymbionts. *Scientia Horticulturae*, *264*, 109153.

Ayour, J., Le Bourvellec, C., Gouble, B., Audergon, J. M., Benichou, M., & Renard, C. M. (2020). Changes in cell wall neutral sugar composition related to pectinolytic enzyme activities and intra-flesh textural property during ripening of ten apricot clones. *Food Chemistry*, *339*, 128096.

Babalar, M., Mohebbi, S., Zamani, Z., & Askari, M. A. (2019). Effect of foliar application with sodium selenate on selenium biofortification and fruit quality maintenance of 'Starking Delicious' apple during storage. *Journal of the Science of Food and Agriculture*, *99*, 5149–5156.

Bahadur, L., Malhi, C. S., & Singh, Z. (1998). Effect of foliar and soil applications of zinc sulphate on zinc uptake, tree size, yield, and fruit quality of mango. *Journal of Plant Nutrition*, *21*, 589–600.

Bailey, R. L., Dodd, K. W., Goldman, J. A., Gahche, J. J., Dwyer, J. T., Moshfegh, A. J., Picciano, M. F., et al. (2010). Estimation of total usual calcium and vitamin D intakes in the United States. *Nutrition Journal*, *140*(4), 817–822.

Barrett, D. M., Weakley, C., Diaz, J. V., & Watnik, M. (2007). Qualitative and nutritional differences in processing tomatoes grown under commercial organic and conventional production systems. *Journal of Food Science*, *72*, C441–C450.

Barringer, S. A., Bennett, M. A., & Bash, W. D. (1999). Effect of fruit maturity and nitrogen fertilizer levels on tomato peeling efficiency. *Journal of Vegetable Crop Production*, *5*, 3–11.

Barzegar, T., Fateh, M., & Razavi, F. (2018). Enhancement of postharvest sensory quality and antioxidant capacity of sweet pepper fruits by foliar applying calcium lactate and ascorbic acid. *Scientia Horticulturae*, *241*, 293–303.

Basalekou, M., Kyraleou, M., Pappas, C., Tarantilis, P., Kotseridis, Y., & Kallithraka, S. (2019). Proanthocyanidin content as an astringency estimation tool and maturation index in red and white winemaking technology. *Food Chemistry*, *299*, 125135.

Bascones, O., Rodríguez-Pérez, R., Juste, S., Moneo, I., & Caballero, M. L. (2009). Lettuce-induced anaphylaxis. Identification of the allergen involved. *Journal of Investigational Allergology and Clinical Immunology*, *19*, 154–157.

Bedbabis, S., Ferrara, G., Rouina, B. B., & Boukhris, M. (2010). Effects of irrigation with treated wastewater on olive tree growth, yield and leaf mineral elements at short term. *Scientia Horticulturae*, *126*(3), 345–350.

Benbrook, C. M. (2005).'*Elevating antioxidant levels in food through organic farming and food processing. An organic center state of science review*', in www.organic-center.org/reportfiles/Antioxidant_SSR.pdf.

Benge, J., Banks, N., Tillman, R., & De Silva, H. N. (2000). Pairwise comparison of the storage potential of kiwifruit from organic and conventional production systems. *New Zealand Journal of Crops and Horticultural Science*, *28*, 147–152.

Bernhardt, S., & Schlich, E. (2006). Impact of different cooking methods on food quality: Retention of lipophilic vitamins in fresh and frozen vegetables. *Journal of Food Engineering*, *77*, 327–333.

Bhagwat, S., Haytowitz, D. B. & Holden, J. M. (2011).'*USDA database for the flavonoid content of selected foods*', *Release 3*. Nutrient Data Laboratory, Beltsville Human Nutrition Research Center, Agricultural Research Service, U.S. Department of Agriculture.

Białek, M., Czauderna, M., Krajewska, K. A., & Przybylski, W. (2019). Selected physiological effects of boron compounds for animals and humans. A review. *Journal of Animal and Feed Sciences*, *28*(4), 307–320.

Bischoff, K. L. (2016). Glucosinolates. *Nutraceuticals* (pp. 551–554). Academic Press, eds.

Bodoira, R., & Maestri, D. (2020). Phenolic compounds from nuts: Extraction, chemical profiles, and bioactivity. *Journal of Agricultural and Food Chemistry*, *68*(4), 927–942.

Borel, P., Caillaud, D., & Cano, N. J. (2015). Vitamin D bioavailability: State of the art. *Critical Review in Food Science and Nutrition*, *55*(9), 1193–1205.

Bouali, I., Tsafouros, A., Ntanos, E., Albouchi, A., Boukhchina, S., & Roussos, P. A. (2020). Inter-cultivar and temporal variation of phenolic compounds, antioxidant activity and carbohydrate composition of pecan (*Caryailllinoinensis*) kernels grown in Tunisia. *Horticulture Environment and Biotechnology*, *61*(1), 183–196.

Boulton, R. (2001). The copigmentation of anthocyanins and its role in the color of red wine: A critical review. *American Journal of Enology and Viticulture*, *52*, 67–87.

Briat, J. F., & Lobreaux, S. (1997). Iron transport and storage. *Trends in Plant Science*, *2*, 187–193.

Butt, M. S., Sultan, M. T., Butt, M. S., & Iqbal, J. (2009). Garlic: Nature's protection against physiological threats. *Critical Reviews in Food Science and Nutrition*, *49*(6), 538–551.

Byeon, S. E., & Lee, J. (2020). Differential responses of fruit quality and major targeted metabolites in three different cultivars of cold-stored figs (*Ficuscarica* L.). *Scientia Horticulturae*, *260*, 108877.

Cabot, C., Martos, S., Llugany, M., Gallego, B., Tolrà, R., & Poschenrieder, C. (2019). A role for zinc in plant defense against pathogens and herbivores. *Frontiers in Plant Science*, *10*, 1171.

Canteri, M. H., Renard, C. M., Le Bourvellec, C., & Bureau, S. (2020). ATR-FTIR spectroscopy to determine cell wall composition: Application on a large diversity of fruits and vegetables. *Carbohydrate Polymers*, *235*(212), 186–196.

Cao, G., Sofic, E., & Prior, R. L. (1997). Antioxidant and prooxidant behavior of flavonoids: Structure–activity relationships. *Free Radical Biology and Medicine*, *22*, 749–760.

Carpita, N., & McCann, M. (2015). The plant cell wall. In B. Buchanan, W. Gruissem, & R. Jones (Eds.), *Biochemistry and molecular biology of plants* (2nd ed., pp. 45–110). American Society of Plant Physiologists.

Castañeda-Ovando, A., Pacheco-Hernandez, M. D. L., Paez-Hernandez, M. E., Rodriguez, J. A., & Galan-Vidal, C. A. (2009). Chemical studies of anthocyanins: A review. *Food Chemistry*, *113*, 859–871.

Chahardoli, A., Jalilian, F., Memariani, Z., Farzaei, M. H., & Shokoohinia, Y. (2020). Chapter 26. Analysis of organic acids. *Recent advances in natural products analysis* (pp. 767–823). Elsevier.

Chassy, A., Bui, L., Renaud, E. N. C., Van Horn, M., & Mitchell, A. (2006). Three-year comparison of the content of antioxidant microconstituents and several quality characteristics in organic and conventionally managed tomatoes and bell peppers. *Journal of Agricultural and Food Chemistry*, *54*, 8244–8252.

Chen, P., Bornhorst, J., & Aschner, M. (2018). Manganese metabolism in humans. *Frontiers in Bioscience-Landmark*, *23*, 1655–1679.

Chijiiwa, R., Hosokawa, M., Kogawa, M., Nishikawa, Y., Ide, K., Sakanashi, C., … Takeyama, H. (2020). Single-cell genomics of uncultured bacteria reveals dietary fiber responders in the mouse gut microbiota. *Microbiome*, *8*, 5.

Choi, Y. J., Tomás-Barberán, F. A., & Saltveit, M. E. (2005). Wound-induced phenolic accumulation and browning in lettuce (*Lactuca sativa* L.) leaf tissue is reduced by exposure to *n*-alcohols. *Postharvest Biology and Technology*, *37*, 47–55.

Cohen, A. J., & Roe, F. J. C. (2000). Review of risk factors for osteoporosis with particular reference to a possible aetiological role of dietary salt. *Food and Chemistry Toxicology*, *38*, 237–253.

Coleman, C. M., & Ferreira, D. (2020). Oligosaccharides and complex carbohydrates: A new paradigm for cranberry bioactivity. *Molecules (Basel, Switzerland)*, *25*(4), 881.

Collins, J. F. (2017). Copper: Basic physiological and nutritional aspects. In J. F. Collins (Ed.), *Molecular, genetic, and nutritional aspects of major and trace minerals* (pp. 69–83). San Diego, CA: Elsevier.

Combrink, N. J. J., Jacobs, G., & Maree, P. C. J. (1995). The effect of calcium and boron on the quality of muskmelons. *Journal of South African Society for Horticultural Sciences*, *5*, 33–38.

Correia, S., Schouten, R., Silva, A. P., & Gonçalves, B. (2018). Sweet cherry fruit cracking mechanisms and prevention strategies: A review. *Scientia Horticulturae*, *240*, 369–377.

Crisosto, C. H., Johnson, R. S., DeJong, T., & Day, K. R. (1997). Orchard factors affecting postharvest stone fruit quality. *HortScience: A Publication of the American Society for Horticultural Science*, *32*, 820–823.

Crisosto, C. H., & Mitchell, J. P. (2002). Preharvest factors affecting fruit vegetable quality. In A. A. Kader (Ed.), *Postharvest technology of horticultural crops* (pp. 49–54). Berkeley, CA: University of California, Agriculture and Natural Resources, Publication 3311.

D'Ambrosio, C., Giorio, G., Marino, I., Merendino, A., Petrozza, A., Salfi, L., Stigliani, A. L., et al. (2004). Virtually complete conversion of lycopene into β-carotene in fruits of tomato plants transformed with the tomato lycopene β-cyclase (tlcy-b) cDNA. *Plant Science*, *166*, 207–214.

Daane, K. M., Johnson, R. S., Michailides, T. J., Crisosto, C. H., Dlott, J. W., Ramirez, H. T., Yokota, G., et al. (1995). Excess nitrogen raises nectarine susceptibility to disease and insects. *California Agriculture*, *49*(4), 13–17.

Dahl, W. J., & Alvarez, M. M. (2019). Whole pulses and pulse fiber: Modulating gastrointestinal function and the microbiome. *Health benefits of pulses* (pp. 91–108). Cham: Springer, Ed.

Darré, M., Valerga, L., Araque, L. C. O., Lemoine, M. L., Demkura, P. V., Vicente, A. R., & Concellón, A. (2017). Role of UV-B irradiation dose and intensity on color retention and antioxidant elicitation in broccoli florets (*Brassica oleracea* var. Italica). *Postharvest Biology and Technology*, *128*, 76–82.

Davarpanah, S., Tehranifar, A., Abadía, J., Val, J., Davarynejad, G., Aran, M., & Khorassani, R. (2018). Foliar calcium fertilization reduces fruit cracking in pomegranate (*Punica granatum* cv. Ardestani). *Scientia Horticulturae*, *230*, 86–91.

Davison, K. M. (2017). Mineral nutrients: From macro-level to ultra trace. *Nutrition guide for physicians and related healthcare professionals* (pp. 261–272). Cham: Humana Press.

de Assis, R. C., Soares, R. D. L. G., Siqueira, A. C. P., de Rosso, V. V., de Sousa, P. H. M., Mendes, A. E. P., & Maia, C. S. C. (2020). Determination of water-soluble vitamins and carotenoids in Brazilian tropical fruits by high performance liquid chromatography. *Heliyon*, *6*, e05307.

Debar, L. L., Rittenbaugh, C., Vuckovik, N., Stevens, V. J., Aickin, M., Elliot, D., Moe, E., et al. (2004). YOUTH: Decisions and challenges in designing an osteoporosis prevention intervention for teen girls. *Preventive Medicine*, *39*, 1047–1055.

Deckers, T., Daemen, E., Lemmens, K., Missotten, C., & Val, J. (1997). Influence of foliar applications on Mn during summer on the fruit quality of Jonagold. *Acta Horticulture*, *448*, 467–473.

Delgado-Vargas, F., & Paredes-López, O. (2003). *Natural colorants for food and nutraceutical uses*. Boca Raton, FL: CRC Press.

Deming, D. M., Baker, D. H., & Erdman, J. W. (2002). The relative vitamin A value of 9-cis β-carotene is less and that of 13-cis β-carotene may be greater than the accepted 50% that of all-trans β-carotene in gerbils. *Journal of Nutrition*, *132*, 2709–2712.

Deming, D. M., Teixeira, S. R., & Erdman, J. W. (2002). All-trans-β-carotene appears to be more biovailable than 9-cis or 13-cis-β-carotene in gerbils given single oral doses of each isomer. *Journal of Nutrition*, *132*, 2700–2708.

Dimeglio, L. A., White, K. E., & Econs, M. J. (2000). Disorders of phosphate metabolism. *Endocrinology and Metabolism Clinics of North America*, *29*, 591–609.

do Amarante, C. V., Silveira, J. P. G., Steffens, C. A., de Freitas, S. T., Mitcham, E. J., & Miqueloto, A. (2020). Postbloom and preharvest treatment of 'Braeburn'apple trees with prohexadione-calcium and GA_4 affects vegetative growth and postharvest incidence of calcium-related physiological disorders and decay in the fruit. *Scientia Horticulturae*, *261*, 108919.

Dölle, S., Welter, S., Ruppel, E., Lehmann, K., Schwarz, D., Jensen-Jarolim, E., Zieglmayer, P., et al. (2018). Clinical reactivity of celery cultivars in allergic patients: Role of Api g 1. *Clinical and Experimental Allergy*, *48*, 424–432.

Dong, Y., Zhi, H., & Wang, Y. (2019). Cooperative effects of pre-harvest calcium and gibberellic acid on tissue calcium content, quality attributes, and in relation to postharvest disorders of late-maturing sweet cherry. *Scientia Horticulturae*, *246*, 123–128.

Dragsted, L. O. (2003). Antioxidant actions of polyphenols in humans. *International Journal for Vitamin and Nutrition Research*, *73*, 112–119.

Dris, R., Bennett, M. A., & Bash, E. (1999). Relationship between leaf and fruit minerals and fruit quality attributes of apples grown under northern conditions. *Journal of Plant Nutrition*, *22*, 1839–1851.

Duarte-Sierra, A., Hasan, S. M. M., Angers, P., & Arul, J. (2020). UV-B radiation hormesis in broccoli florets: Glucosinolates and hydroxy-cinnamates are enhanced by UV-B in florets during storage. *Postharvest Biology and Technology*, *168*, 111278.

Durazzo, A., Lucarini, M., Souto, E. B., Cicala, C., Caiazzo, E., Izzo, A. A., Santini, A., et al. (2019). Polyphenols: A concise overview on the chemistry, occurrence, and human health. *Phytotherapy Research*, *33*. Available from https://doi.org/10.1002/ptr.6419.

Eitenmiller, R. R., & Landen, W. O. (1999). *Vitamin analysis for the health and food sciences* (pp. 223–270). Boca Raton, London, New York, Washington: CRC Press.

El Khawand, T., Courtois, A., Valls, J., Richard, T., & Krisa, S. (2018). A review of dietary stilbenes: Sources and bioavailability. *Phytochemistry Reviews*, *17*, 1007−1029. Available from https://doi.org/10.1007/s11101-018-9578-9.

El-Aal, Y. A. A., Abdel-Fattah, D. M., & Ahmed, K. E. D. (2019). Some biochemical studies on trans fatty acid-containing diet. *Diabetes and Metabolic Syndrome*, *13*, 1753−1757.

El-Mogy, M. M., Mahmoud, A. W. M., El-Sawy, M. B. I., & Parmar, A. (2019). Pre-harvest foliar application of mineral nutrients to retard chlorophyll degradation and preserve bio-active compounds in broccoli. *Agronomy*, *9*, 711.

Elsherbiny, E. A., & Taher, M. A. (2018). Silicon induces resistance to postharvest rot of carrot caused by *Sclerotinia sclerotiorum* and the possible of defense mechanisms. *Postharvest Biology and Technology*, *140*, 11−17.

Erkan, M., & Dogan, A. (2019). Harvesting of horticultural commodities. *Postharvest technology of perishable horticultural commodities* (pp. 129−159). Woodhead Publishing.

Etesami, H., & Jeong, B. R. (2020). Importance of silicon in fruit nutrition: Agronomic and physiological implications. In A. K. Srivastava, & C. Hu (Eds.), *Fruit crops: Diagnosis and management of nutrient constraints* (pp. 255−277). Amsterdam: Elsevier.

Faggio, C., Sureda, A., Morabito, S., Sanches-Silvade Andrei, A., Seyed, N., Seyed, F. N., & Nabavi, M. (2017). Flavonoids and platelet aggregation: A brief review. *European Journal of Pharmacology*, *807*, 91−101.

Fan, G. J., Jin, X. L., Qian, Y. P., Wang, Q., Yang, R. T., Dai, F., Tang, J. J., et al. (2009). Hydroxycinnamic acids as DNA-cleaving agents in the presence of CuII ions: Mechanism, structure-activity relationship, and biological implications. *Chemistry: A European Journal*, *15*, 12889−12899.

Farooq, M. A., & Dietz, K. J. (2015). Silicon as versatile player in plant and human biology: Overlooked and poorly understood. *Frontiers in Plant Science*, *6*, 994.

Ferguson, I., Volz, R., & Woolf, A. (1999). Preharvest factors affecting physiological disorders of fruit. *Postharvest Biology and Technology*, *15*, 255−262.

Ferguson, I. B., & Triggs, C. M. (1990). Sampling factors affecting the use of mineral analysis of apple fruit for prediction of bitter pit. *New Zealand Journal of Crop Horticulture Science*, *18*, 147−152.

Ferguson, I. B., & Watkins, C. B. (1992). Crop load affects mineral concentrations and incidence of bitter pit in 'Cox's Orange Pippin' apple fruit. *Journal of the American Society for Horticultural Science*, *117*, 373−376.

Freeland-Graves, J. H., Mousa, T. Y., & Kim, S. (2016). International variability in diet and requirements of manganese: Causes and consequences. *Journal of Trace Elements in Medicine and Biology*, *38*, 24−32.

Fuge, R., & Johnson, C. C. (2015). Iodine and human health, the role of environmental geochemistry and diet, a review. *Applied Geochemistry: Journal of the International Association of Geochemistry and Cosmochemistry*, *63*, 282−302.

García-Salinas, C., Ramos-Parra, P. A., & de la Garza, R. I. D. (2016). Ethylene treatment induces changes in folate profiles in climacteric fruit during postharvest ripening. *Postharvest Biology and Technology*, *118*, 43−50.

García-Sánchez, F., Carvajal, M., Porras, I., Botía, P., & Martínez, V. (2003). Effects of salinity and rate of irrigation on yield, fruit quality and mineral composition of 'Fino 49' lemon. *European Journal of Agronomy*, *19*, 427−437.

Gautier, H., Diakou-Verdin, V., Bernard, C., Reich, M., Buret, M., Bourgaud, R., . . . Genard, M. (2008). How does tomato quality (sugar, acid, and nutritional quality) vary with ripening stage, temperature, and irradiance? *Journal of Agricultural and Food Chemistry*, *56*, 1241−1250.

Ge, Y., Duan, B., Li, C., Wei, M., Chen, Y., Li, X., & Tang, Q. (2019). Application of sodium silicate retards apple softening by suppressing the activity of enzymes related to cell wall degradation. *Journal of Science and Food and Agriculture*, *99*, 1828−1833.

Genchi, G., Carocci, A., Lauria, G., Sinicropi, M. S., & Catalano, A. (2020). Nickel: Human health and environmental toxicology. *International Journal of Environmental Research and Public Health*, *17*, 679.

Georgiadou, E. C., Koubouris, G., Goulas, V., Sergentani, C., Nikoloudakis, N., Manganaris, G. A., et al. (2019). Genotype-dependent regulation of vitamin E biosynthesis in olive fruits as revealed through metabolic and transcriptional profiles. *Plant Biology*, *21*(4), 604−614.

Gharibzahedi, S. M. T., & MahdiJafari, S. (2017). The importance of minerals in human nutrition: Bioavailability, food fortification, processing effects and nanoencapsulation. *Trends in Food Science & Technology*, *62*, 119−132.

Godswill, A. G., Somtochukwu, I. V., Ikechukwu, A. O., & Kate, E. C. (2020). Health benefits of micronutrients (vitamins and minerals) and their associated deficiency diseases: A systematic review. *International Journal of Food Science*, *3*(1), 1−32.

Gómez-Míguez, M., González-Manzano, S., Escribano-Bailón, M. T., Heredia, F. J., & Santos-Buelga, C. (2006). Influence of different phenolic copigments on the color of malvidin 3-glucoside. *Journal of Agricultural Food Chemistry*, *54*, 5422−5429.

Gonnella, M., Renna, M., D'Imperio, M., Santamaria, P., & Serio, F. (2019). Iodine biofortification of four *Brassica* genotypes is effective already at low rates of potassium iodate. *Nutrients*, *11*, 451.

González-Barrio, R., Beltrán, D., Cantos, E., Gil, M. I., Espín, J. C., & Tomás-Barberán, F. A. (2006). Comparison of ozone and UV-C treatments on the postharvest stilbenoid monomer, dimer, and trimer induction in var. 'Superior' white table grapes. *Journal of Agricultural and Food Chemistry*, *54*, 4222−4228.

Guillon, F., & Champ, M. (2000). Structural and physical properties of dietary fibres, and consequences of processing on human physiology. *Food Research International*, *33*, 233−245.

Guo, Y., Wang, L., Chen, Y., Yun, L., Liu, S., & Li, Y. (2018). Stalk length affects the mineral distribution and floret quality of broccoli (*Brassica oleracea* L. var. *italica*) heads during storage. *Postharvest Biology and Technology*, *145*, 166−171.

Hakala, M., Lapveteläinen, A., Huopalahti, R., Kallio, H., & Tahvonen, R. (2003). Effects of varieties and cultivation conditions on the composition of strawberries. *Journal of Food Composition and Analysis*, *16*, 67−80.

Häkkinen, S., Heinonen, M., Kärenlampi, S., Mykkänen, H., Ruuskanen, J., & Törrönen, R. (1999). Screening of selected flavonoids and phenolic acids in 19 berries. *Food Research International*, *32*, 345−353.

Häkkinen, S. H., Karenlampi, S. O., Heinonen, M., Mykkanen, H. M., & Torronen, A. R. (1999). Content of the flavonols quercetin, myricetin, and kaemferol in 25 edible berries. *Journal of Agriculture and Food Chemistry*, *47*, 2274−2279.

Hancock, R. D., & Viola, R. (2005). Improving the nutritional value of crops through enhancement of L-ascorbic acid (vitamin C) content: Rationale and biotechnological opportunities. *Journal of Agricultural and Food Chemistry*, *53*, 5248−5257.

Herman, A., & Baeck, M. (2017). Airborne contact dermatitis in a patient with type I and IV sensitivity to chicory. *Contact Dermatitis*, *77*, 325−351.

Hiza, H. A. B. & Bente, L. (2007). Nutrient content of the U.S. food supply, 1909−2004: A summary report. *Home economics research report number 57*. Washington, DC: U.S. Department of Agriculture, Center for Nutrition Policy and Promotion.

Hollman, P. C., & Katan, M. B. (1997). Absorption, metabolism and health effects of dietary flavonoids in man. *Biomedicine and Pharmacotherapy*, *51*, 305−310.

Huang, W., Zhu, N., Zhu, C., Wu, D., & Chen, K. (2019). Morphology and cell wall composition changes in lignified cells from loquat fruit during postharvest storage. *Postharvest Biology and Technology*, *157*, 110975.

Hussein, Z., Fawole, O. A., & Opara, U. O. (2020). Effects of bruising and storage duration on physiological response and quality attributes of pomegranate fruit. *Scientia Horticulturae*, *267*, 109306.

Ignarro, L. J., Balestrieri, M. L., & Napoli, C. (2007). Nutrition, physical activity, and cardiovascular disease: An update. *Cardiovascular Research*, *73*, 326−340.

Itkin, M., Heinig, U., Tzfadia, O., Bhide, A. J., Shinde, B., Cardenas, P. D., Bocobza, S. E., et al. (2018). In silico assessment data of allergenicity and cross-reactivity of NP24 epitopes from *Solanum lycopersicum* (tomato) fruit. *Data In Brief*, *21*, 660−674.

Jamakhani, M., Lele, S. S., & Rekadwad, B. (2018). *In silico* assessment data of allergenicity and cross-reactivity of NP24 epitopes from *Solanum lycopersicum* (tomato) fruit. *Data In Brief*, *21*, 660−674.

Järvinen, R., Knekt, P., Hakulinen, T., Rissanen, H., & Heliövaara, M. (2001). Dietary fat, cholesterol and colorectal cancer in a prospective study. *British Journal of Cancer*, *85*(3), 357−361.

Jayaraj, J., Devlin, R., & Punja, Z. (2007). Metabolic engineering of novel ketocarotenoid production in carrot plants. *Transgenic Research*. Available from https://doi.org/10.1007/s11248-007-9120-0.

Jin, J., Gao, L., Zhao, L., Gao, Z., Li, X., Xie, H., Ni, J., et al. (2020). Selection of Pru p 3 hypoallergenic peach and nectarine varieties. *Allergy*, *75*, 1256−1260.

Jing, P., Zhao, S. J., Jian, W. J., Qian, B. J., Dong, Y., & Pang, J. (2012). Quantitative studies on structure-DPPH scavenging activity relationships of food phenolic acids. *Molecules (Basel, Switzerland)*, *17*, 12910−12924.

Johnson, L. E. (2020). *Vitamin K deficiency*. In: https://www.msdmanuals.com/professional/nutritional-disorders/vitamin-deficiency-dependency-and-toxicity/vitamin-k-deficiency.

Kalt, W., Forney, C. F., Martin, A., & Prior, R. L. (1999). Antioxidant capacity, vitamin C, phenolics, and anthocyanins after fresh storage of small fruits. *Journal of Agricultural and Food Chemistry*, *47*, 4638−4644.

Kang, C. H., Yoon, E. K., Muthusamy, M., Kim, J. A., Jeong, M. J., & Lee, S. I. (2020). Blue LED light irradiation enhances L-ascorbic acid content while reducing reactive oxygen species accumulation in Chinese cabbage seedlings. *Scientia Horticulturae*, *261*, 108924.

Kays, S. J. (1997). *Postharvest physiology of perishables plant products*. Athens, GA: Exon Press.

Kevers, C., Falkowski, M., Tabart, J., Defraigne, J. O., Dommes, J., & Pincemail, J. (2007). Evolution of antioxidant capacity during storage of selected fruits and vegetables. *Journal of Agricultural Food Chemistry*, *55*, 8596−8603.

Khanum, F., Swamy, M. S., Krishna, K. S., Santhanam, K., & Viswanathan, K. R. (2000). Dietary fiber content of commonly fresh and cooked vegetables consumed in India. *Plant Foods for Human Nutrition*, *55*, 207−218.

Khedmat, L., Izadi, A., Mofid, V., & Mojtahedi, S. Y. (2020). Recent advances in extracting pectin by single and combined ultrasound techniques: A review of techno-functional and bioactive health-promoting aspects. *Carbohydrate Polymers*, *229*, 115474.

Kim, T. J., Hyeon, H., Park, N. I., Yi, T. G., Lim, S. H., Park, S. Y., Kim, J. K., et al. (2020). A high-throughput platform for interpretation of metabolite profile data from pepper (*Capsicum*) fruits of 13 phenotypes associated with different fruit maturity states. *Food Chemistry*, 127286.

Kiran Kumar, M. N., Harish Babu, B. N., & Venkatesh, Y. P. (2009). Higher histamine sensitivityin non-atopic subjectsby skin prick test may resultin misdiagnosis of eggplant allergy. *Immunological Investigations*, *38*, 93−103.

Konic-Ristic, A., Šavikin, K., Zdunic, G., Tankovic, T., Juranic, Z., Menkovic, N., & Stankovic, I. (2011). Biological activity and chemical composition of different berry juices. *Food Chemistry*, *125*, 1412−1417.

Kurze, E., Lo Scalzo, R., Campanelli, G., & Schwab, W. (2018). Effect of tomato variety, cultivation, climate and processing on Sola l 4, an allergen from *Solanum lycopersicum*. *PLoS One*, *13*, e0197971.

Langer, P. (2018). Naturally occurring food toxicants: Goitrogens. In M. Rechcigl (Ed.), *Handbook of naturally occurring food toxicants* (pp. 101−130). Boca Raton, FL: CRC Press.

Lanham-New, S. A., Lambert, H., & Frassetto, L. (2012). Potassium. *Advances in Nutrition*, *3*, 820−821.

Le, T., Bublin, M., Breiteneder, H., Fernández-Rivas, M., Asero, R., Ballmer-Weber, B., Barreales, L., et al. (2013). Kiwifruit allergy across Europe: Clinical manifestation and IgE recognition patterns to kiwifruit allergens. *Journal of Allergy and Clinical Immunology*, *131*, 164−171.

Lee, S. K., & Kader, A. A. (2000). Preharvest and postharvest factors influencing vitamin C content of horticultural crops. *Postharvest Biology and Technology*, *20*, 207−220.

Leong, S. Y., & Oey, I. (2012). Effects of processing on anthocyanins, carotenoids and vitamin C in summer fruits and vegetables. *Food Chemistry*, *133*(4), 1577−1587.

Leszczuk, A., Kalaitzis, P., Blazakis, K. N., & Zdunek, A. (2020). The role of arabinogalactan proteins (AGPs) in fruit ripening—A review. *Horticulture Research*, *7*, 1−12.

Levine, M., Wang, Y. H., Padayatty, S. J., & Morrow, J. (2001). A new recommended dietary allowance of vitamin C for healthy young women. *Proceeding of the National Academy of Sciences of the United States of America*, *98*, 9842−9846.

Lewiecki, E. M., Ortendahl, J. D., Vanderpuye-Orgle, J., Grauer, A., Arellano, J., Lemay, J., Harmon, A. L., et al. (2019). Healthcare policy changes in osteoporosis can improve outcomes and reduce costs in the United States. *JBMR Plus*, *3*, e10192.

Li, B. W., Andrews, K. W., & Pehrsson, P. R. (2002). Individual sugars, soluble, and insoluble dietary fiber contents of 70 high consumption foods. *Journal of Food Composition and Analysis*, *15*, 715−723.

Li, H., Han, M., Yu, L., Wang, S., Zhang, J., Tian, J., & Yao, Y. (2020). Transcriptome analysis identifies two ethylene response factors that regulate proanthocyanidin biosynthesis during *Malus* crabapple fruit development. *Frontiers in Plant Science*, *11*, 76.

Li, M., Li, X., Han, C., Ji, N., Jin, P., & Zheng, Y. (2019). UV-C treatment maintains quality and enhances antioxidant capacity of fresh-cut strawberries. *Postharvest Biology and Technology*, *156*, 110945.

Li, Q., Cheng, C., Zhang, X., Wang, C., & Yang, S. (2020). Preharvest bagging and postharvest calcium treatment affects superficial scald incidence and calcium nutrition during storage of 'Chili' pear (*Pyrus bretschneideri*) fruit. *Postharvest Biology and Technology*, *163*, 111149.

Lin, P. H., Aickin, M., Champagne, C., Craddick, S., Sacks, F. M., McCarron, P., Most-Windhauser, M. M., et al. (2003). Food group sources of nutrients in the dietary patterns of the DASH-Sodium trial. *Journal of the American Dietetic Association*, *103*, 488−496.

Lin, Y., Huang, G., Zhang, Q., Wang, Y., Dia, V. P., & Meng, X. (2020). Ripening affects the physicochemical properties, phytochemicals and antioxidant capacities of two blueberry cultivars. *Postharvest Biology and Technolgy*, *162*, 111097.

Liu, Y., Roof, S., Ye, Z., Barry, C., van Tuinen, A., Vrebalov, J., . . . Giovannoni, J. (2004). Manipulation of light signal transduction as a means of modifying fruit nutritional quality in tomato. *Proceeding of the National Academy of Sciences of the United States of America*, *101*, 9897−9902.

Lo, D., Wang, H. I., Wu, W. J., & Yang, R. Y. (2018). Anti-nutrient components and their concentrations in edible parts in vegetable families. *CAB Reviews*, *13*(015), 1–30.

Lurie, S., & Crisosto, C. H. (2005). Chilling injury in peach and nectarine. *Postharvest Biology and Technology*, *37*, 195–208.

Lv, J., Wu, J., Zuo, J., Fan, L., Shi, J., Gao, L., . . . Wang, Q. (2017). Effect of Se treatment on the volatile compounds in broccoli. *Food Chemistry*, *216*, 225–233.

Lwin, W. W., Srilaong, V., Boonyaritthongchai, P., Wongs-Aree, C., & Pongprasert, N. (2020). Electrostatic atomised water particles reduce postharvest lignification and maintain asparagus quality. *Scientia Horticulturae*, *271*, 109487.

Lyu, L., Bi, Y., Li, S., Xue, H., Li, Y., & Prusky, D. B. (2019). Sodium silicate prime defense responses in harvested muskmelon by regulating mitochondrial energy metabolism and reactive oxygen species production. *Food Chemistry*, *289*, 369–376.

Ma, Y., Zhao, X., Ren, H., Wu, H., Guo, M., Zhang, Y., He, Z., et al. (2018). Fruit bagging with opaque paper significantly reduced the expression of peach (*Prunus persica* L. Batsch) allergen-encoding genes. *Journal of Agriculture and Food Chemistry*, *66*, 4051–4061.

Madani, B., Wall, M., Mirshekari, A., Bah, A., & Mohamed, M. T. M. (2015). Influence of calcium foliar fertilization on plant growth, nutrient concentrations, and fruit quality of papaya. *HortTechnology*, *25*, 496–504.

Maestri, D., Cittadini, M. C., Bodoira, R., & Martínez, M. (2020). Tree nut oils: Chemical profiles, extraction, stability, and quality concerns. *European Journal of Lipid Science and Technology*, *122*, 1900450.

Mahmoud, N., Mutchnick, S. A., Svider, P. F., McLeod, T. M., & Fribley, A. M. (2020). Fluorine in human metabolism, health and disease. In G. J. Brewer, S. Ananda, & A. S. Prasad (Eds.), *Essential and toxic trace elements and vitamins in human health* (pp. 153–162). San Diego, CA: Academic Press.

Maity, S., Bhakta, S., Bhowmik, M., Sircar, G., & Bhattacharya, S. G. (2020). Identification, cloning, and immunological studies on a major eggplant(*Solanum melongena* L.) allergen Sola m 1: A new member of profilin allergen family. *Molecular Immunology*, *118*, 210–221.

Manach, C., Scalbert, A., Morand, C., Remesy, C., & Jimenez, L. (2004). Polyphenols: Food sources and bioavailability. *American Journal of Clinical Nutrition*, *79*, 727–747.

Manganaris, G. A., Vasilakakis, M., Diamantidis, G., & Mignani, I. (2006). Effect of in-season calcium applications on cell wall physicochemical properties of nectarine fruit (*Prunus persica* var. nectarina Ait. Maxim) after harvest or cold storage. *Journal of the Science and Food Agriculture*, *86*, 2597–2602.

Manganaris, G. A., Vasilakakis, M., Diamantidis, G., & Mignani, I. (2005). Effect of post-harvest calcium treatments on the physicochemical properties of cell wall pectin in nectarine fruit during ripening after harvest or cold storage. *Journal of Horticultural Science and Biotechnology*, *80*, 611–617.

Manganaris, G. A., Vasilakakis, M., Diamantidis, G., & Mignani, I. (2007). The effect of postharvest calcium application on tissue calcium concentration, quality attributes, incidence of flesh browning and cell wall physicochemical aspects of peach fruits. *Food Chemistry*, *100*, 1385–1392.

Manganaris, G. A., Vasilakakis, M., Mignani, I., Diamantidis, G., & Tzavella-Klonari, K. (2005). The effect of preharvest calcium sprays on quality attributes, physicochemical aspects of cell wall components and susceptibility to brown rot of peach fruits (*Prunus persica* L. cv. Andross). *Scientia Horticulturae*, *107*, 43–50.

Mania, M., Rebeniak, M., & Postupolski, J. (2019). Food as a source of exposure to nickel. *Roczniki Państwowego Zakładu Higieny*, *70*, 393–399.

Maqsood, S., Adiamo, O., Ahmad, M., & Mudgil, P. (2020). Bioactive compounds from date fruit and seed as potential nutraceutical and functional food ingredients. *Food Chemistry*, *308*, 125522.

Marlett, J. A., & Longacre, M. J. (1997). Comparisons of *in vitro* and *in vivo* measures of resistant starch in selected grain products. *Cereal Chemistry*, *73*, 63–68.

Marlett, J. A., McBurney, M. I., & Slavin, J. L. (2002). Position of the American Dietetic Association health implications of dietary fiber. *Journal of the American Dietetic Association*, *102*, 993–1000.

Marsh, K. B., Volz, R. K., Cashmore, W., & Reay, P. (1996). Fruit colour, leaf nitrogen level, and tree vigour in 'Fuji' apples. *New Zealand Journal of Crop Horticultural Science*, *24*, 393–399.

Martin, C., Butelli, E., Petroni, K., & Tonelli, C. (2011). How can research on plants contribute to promoting human health? *The Plant Cell*, *23*, 1685–1699.

Martin, C., Zhang, Y., Tonelli, C., & Petroni, K. (2013). Plants, diet, and health. *Annual Review of Plant Biology*, *64*, 19–46.

Martín-Diana, A. B., Rico, D., Frías, J. M., Barat, J. M., Henehan, G. T. M., & Barry-Ryan, C. (2007). Calcium for extending the shelf life of fresh whole and minimally processed fruits and vegetables: A review. *Trends in Food Science and Technology*, *18*, 210−218.
Martínez-Romero, D., Valero, D., Serrano, M., & Riquelme, F. (1999). Effects of postharvest putrescine and calcium treatments on reducing mechanical damage and polyamine and ABA levels during lemon storage. *Journal of the Science of Food and Agriculture*, *79*, 1589−1595.
Martín-Pedraza, L., González, M., Gómez, F., Blanca-López, N., Garrido-Arandia, M., Rodríguez, R., Torres, M. J., et al. (2016). Two nonspecific lipid transfer proteins (nsLTPs) from tomato seeds are associated to severe symptoms of tomato-allergic patients. *Molecular Nutrition & Food Research*, *60*, 1172−1182.
Martins, V., Billet, K., Garcia, A., Lanoue, A., & Gerós, H. (2020). Exogenous calcium deflects grape berry metabolism towards the production of more stilbenoids and less anthocyanins. *Food Chemistry*, *313*, 126123.
Marzban, G., Kinaciyan, T., Maghuly, F., Brunner, R., Gruber, C., Hahn, R., Jensen-Jarolim, E., et al. (2014). Impact of sulfur and vitamin C on the allergenicity of Mal d 2 from apple (*Malus domestica*). *Journal of Agricultural and Food*, *62*, 7622−7630.
Mattheis, J. P., & Fellman, J. K. (1999). Preharvest factors influencing flavor of fresh fruit and vegetables. *Postharvest Biology and Technology*, *15*, 227−232.
Mattila, P., Hellstrom, J., & Torronen, R. (2006). Phenolic acids in berries, fruits, and beverages. *Journal of Agricultural and Food Chemistry*, *54*, 7193−7199.
Mayer, J. E., Pfeiffer, W. H., & Beyer, P. (2008). Biofortified crops to alleviate micronutrient malnutrition. *Current Opinion in Plant Biology*, *11*, 166−170.
Mccarron, D. A., & Reusser, M. E. (2001). Are low intakes of calcium and potassium important causes of cardiovascular disease? *American Journal of Hypertension*, *14*, 206S−212S.
McClure, S. T., Chang, A. R., Selvin, E., Rebholz, C. M., & Appel, L. J. (2017). Dietary sources of phosphorus among adults in the United States: Results from NHANES 2001−2014. *Nutrients*, *9*, 95.
Mditshwa, A., Magwaza, L. S., Tesfay, S. Z., & Mbili, N. (2017). Postharvest quality and composition of organically and conventionally produced fruits: A review. *Scientia Horticulturae*, *216*, 148−159.
Melidou, M., Riganakos, K., & Galaris, D. (2005). Protection against nuclear DNA damage offered by flavonoids in cells exposed to hydrogen peroxide: The role of iron chelation. *Free Radical Biology and Medicine*, *39*(12), 1591−1600.
Mellidou, I., Georgiadou, E. C., Kaloudas, D., Kalaitzis, P., Fotopoulos, V., & Kanellis, A. K. (2018). Vitamins. *Postharvest physiology and biochemistry of fruits and vegetables* (pp. 359−383). .
Michailides, T. J., Ramirez, H. T., Morgan, D. P., Crisosto, C. H., & Johnson, R. S. (1993). Effects of nitrogen fertilization on susceptibility of stone fruits (peach and nectarine) to brown rot. *1992 research reports for California peaches and nectarines*. California Tree Fruit Agreement, ed.
Michalak, I., & Chojnacka, K. (2018). Fluorine and silicon as essential and toxic trace elements. In K. Chojnacka, & A. Saeid (Eds.), *Recent advances in trace elements* (pp. 207−218). Oxford: John Wiley and Sons.
Montanaro, G., Dichio, B., Xiloyannis, C., & Celano, G. (2006). Light influences transpiration and calcium accumulation in fruit of kiwifruit plants (*Actinidia deliciosa* var. deliciosa). *Plant Science*, *170*, 520−527.
Muir, S. R., Collins, G. J., Robinson, S., Hughes, S., Bovy, A., Ric De Vos, C. H., van Tunen, A. J., et al. (2001). Overexpression of petunia chalcone isomerase in tomato results in fruit containing increased levels of flavonols. *National Biotechnology*, *19*, 470−474.
Muley, A. B., & Singhal, R. S. (2020). Extension of postharvest shelf life of strawberries (*Fragariaananassa*) using a coating of chitosan-whey protein isolate conjugate. *Food Chemistry*, *329*, 127213.
Muluk, N. B., & Cingi, C. (2018). Oral allergy syndrome. *American Journal of Rhinology & Allergy*, *32*, 27−30.
Myhrstad, M. C. W., Tunsjø, H., Charnock, C., & Telle-Hansen, V. H. (2020). Dietary fiber, gut microbiota, and metabolic regulation—Current status in human randomized trials. *Nutrients*, *12*, 859.
Narayan, V., Thompson, E. W., Demissei, B., Ho, J. E., Januzzi, J. L., Jr, & Ky, B. (2020). Mechanistic biomarkers informative of both cancer and cardiovascular disease: JACC state-of-the-art review. *Journal of the American College of Cardiology*, *75*(21), 2726−2737.
Naser, F., Rabiei, V., Razavi, F., & Khademi, O. (2018). Effect of calcium lactate in combination with hot water treatment on the nutritional quality of persimmon fruit during cold storage. *Scientia Horticulturae*, *233*, 114−123.

Nayak, B., Liu, R. H., & Tang, J. (2015). Effect of processing on phenolic antioxidants of fruits, vegetables, and grains—A review. *Critical Reviews in Food Science and Nutrition*, *55*(7), 887–918.

Neilsen, G. H., & Neilsen, D. (2003). Nutritional requirements of apple. In D. C. Ferree, & I. J. Warrington (Eds.), *Apples: Botany, production and uses* (pp. 267–302). Wallingford, Oxon: CABI Publishing.

Nguyen, V. T., Nguyen, D. H., & Nguyen, H. V. (2020). Combination effects of calcium chloride and nano-chitosan on the postharvest quality of strawberry (*Fragaria* x *ananassa* Duch.). *Postharvest Biology and Technology*, *162*, 111103.

Nikagolla, N. G. D. N., Udugala-Ganehenege, M. Y., & Daundasekera, W. A. M. (2019). Postharvest application of potassium silicate improves keeping quality of banana. *Journal of Horticultural Science and Biotechnology*, *94*, 735–743.

Nikolić, J., Nešić, A., Kull, S., Schocker, F., Jappe, U., & Gavrović-Jankulović, M. (2018). Employment of proteomic and immunological based methods for the identification of catalase as novel allergen from banana. *Proteomics*, *175*, 87–94.

Novotny, J. A. (2011). Molybdenum nutriture in humans. *Journal of Evidence-Based Complementary and Alternative Medicine*, *16*, 164–168.

Nowak, D., Gośliński, M., Wojtowicz, E., & Przygoński, K. (2018). Antioxidant properties and phenolic compounds of vitamin C-rich juices. *Journal of Food Science*, *83*(8), 2237–2246.6.

Olale, K., Walyambillah, W., Mohammed, S. A., Sila, A., & Shepherd, K. (2019). FTIR-DRIFTS-based prediction of β-carotene, α-tocopherol and l-ascorbic acid in mango (*Mangifera indica* L.) fruit pulp. *Applied Sciences*, *1*(3), 279.

Olivos, A., Johnson, S., Xiaoqiong, Q., & Crisosto, C. H. (2012). Fruit phosphorous and nitrogen deficiencies affect 'Grand Pearl'nectarine flesh browning. *HortScience: A Publication of the American Society for Horticultural Science*, *47*, 391–394.

Ostlund, R. E., Jr (2002). Phytosterols in human nutrition. *Annual Review of Nutrition*, *22*, 533–549.

Öztür, S., & Mutlu, S. (2019). Chapter 8 - Physicochemical properties, modifications, and applications of resistant starches. In: Starches for Food Application. Chemical, Technological and Health Properties. Elsevier. ISBN 9780128094402. pp 297–332.

Palafox-Carlos, H., Ayala-Zavala, J. F., & González-Aguilar, G. A. (2011). The role of dietary fiber in the bioaccessibility and bioavailability of fruit and vegetable antioxidants. *Journal of Food Science*, *7 6*, R6–R15.

Pantelidis, G. E., Vasilakakis, M., Manganaris, G. A., & Diamantidis, G. (2007). Antioxidant capacity, phenol, anthocyanin and ascorbic acid contents in raspberries, blackberries, red currants, gooseberries and cornelian cherries. *Food Chemistry*, *102*, 777–783.

Paulsen, E., & Andersen, K. E. (2015). Lettuce contact allergy. *Contact Dermatitis*, *74*, 67–75.

Pavlou, G. C., Ehaliotis, C. D., & Kavvadias, V. A. (2007). Effect of organic and inorganic fertilizers applied during successive crop seasons on growth and nitrate accumulation in lettuce. *Scientia Horticulturae*, *111*(4), 319–325.

Pezzarossa, B., Remorini, D., Gentile, M. L., & Massai, R. (2012). Effects of foliar and fruit addition of sodium selenate on selenium accumulation and fruit quality. *Journal of the Science of Food and Agriculture*, *92*, 781–786.

Pezzarossa, B., Rosellini, I., Borghesi, E., Tonutti, P., & Malorgio, F. (2014). Effects of Se-enrichment on yield, fruit composition and ripening of tomato (*Solanum lycopersicum*) plants grown in hydroponics. *Scientia Horticulturae*, *165*, 106–110.

Prange, R., & DeEll, J. R. (1997). Preharvest factors affecting quality of berry crops. *HortScience*, *32*, 824–830.

Prasad, A. S. (2017). Discovery of zinc for human health and biomarkers of zinc deficiency. In J. F. Collins (Ed.), *Molecular, genetic, and nutritional aspects of major and trace minerals* (pp. 241–260). San Diego, CA: Elsevier.

Premuzic, Z., Bargiela, M., García, A., Rendina, A., & Iorio, A. (1998). Calcium, iron, potassium, phosphorus, and vitamin C content of organic and hydroponic tomatoes. *HortScience: A Publication of the American Society for Horticultural Science*, *33*, 255–257.

Price, M. Y., & Preedy, V. R. (2020). Vitamin k status in nutritionally compromised circumstances. In *Handbook of Famine, Starvation, and Nutrient Deprivation*, (pp. 1753–1768). Springer.

Qin, G. Z., & Tian, S. P. (2005). Enhancement of biocontrol activity of *Cryptococcus laurentii* by silicon and the possible mechanisms involved. *Phytopathology*, *95*, 69–75.

Quintero-Castaño, V. D., Castellanos-Galeano, F. J., Álvarez-Barreto, C. I., Bello-Pérez, L. A., & Alvarez-Ramirez, J. (2020). *In vitro* digestibility of octenyl succinic anhydride-starch from the fruit of three Colombian Musa. *Food Hydrocolloids*, *101*, 105566.

Radović, M., Milatović, D., Tešić, Ž., Tosti, T., Gašić, U., Dojčinović, B., & Zagorac, D. D. (2020). Influence of rootstocks on the chemical composition of the fruits of plum cultivars. *Journal of Food Composition and Analysis*, *92*, 103480.

Ramulu, P., & Rao, P. U. (2003). Total, insoluble and soluble dietary fiber contents of Indian fruits. *Journal of Food Composition and Analysis*, *16*, 677−685.

Randle, W. (1997). Onion flavor chemistry and factors influencing flavor intensity. In S. J. Risch, & C. T. Ho (Eds.), *Spices: Flavor chemistry and antioxidant properties* (pp. 41−52). Washington, DC: ACS Press, ACS Symposium Series 660.

Rao, A. V., & Rao, L. G. (2007). Carotenoids and human health. *Pharmacological Research: The Official Journal of the Italian Pharmacological Society*, *55*, 207−216.

Rashmi, H. B., & Negi, P. S. (2020). Phenolic acids from vegetables: A review on processing stability and health benefits. *Food Research International*, *109298*.

Rembiałkowska, E. (2007). Quality of plant products from organic agriculture. *Journal of the Science of Food and Agriculture*, *87*, 2757−2762.

Remington, B. C., Westerhout, J., Meima, M. Y., Blom, W. M., Kruizinga, A. G., Wheeler, M. W., Taylor, S. L., et al. (2020). Updated population minimal eliciting dose distributions for use in risk assessment of 14 priority food allergens. *Food Chemistry and Toxicology*, *139*, 111259.

Rib-Schmidt, C., Riedl, P., Meisinger, V., Schwaben, L., Schulenborg, T., Reuter, A., Schiller, D., et al. (2018). pH and heat resistance of the major celery allergen Api g 1. *Molecular Nutrition and Food Research*, *62*, 1700886.

Rickman, B., Barrett, D. M., & Bruhn, C. M. (2007). Nutritional comparison of fresh, frozen and canned fruits and vegetables. Part 1. Vitamins C and B and phenolic compounds. *Journal of the Science of Food and Agriculture*, *87*, 930−944.

Righetti, P. G., Esteve, C., D'Amato, A., Fasoli, E., Marina, M. L., & García, M. C. (2015). A sarabande of tropical fruit proteomics: Avocado, banana, and mango. *Proteomics*, *15*, 1639−1645.

Rinaldo, D. (2020). Carbohydrate and bioactive compounds composition of starchy tropical fruits and tubers, in relation to pre and postharvest conditions: A review. *Journal of Food Science*, *85*(2), 249−259.

Robberecht, H., Van Dyck, K., Bosscher, D., & Van Cauwenbergh, R. (2008). Silicon in foods: Content and bioavailability. *International Journal of Food Properties*, *11*, 638−645.

Rodriguez-Amaya, D. B. (2001). *A guide to carotenoid analysis in foods* (20005-5802, p. 64). Washington, DC, Circle, NW: ILSI Human Nutrition Institute. One Thomas.

Roman, G. C., Jackson, R. E., Gadhia, R., Roman, A. N., & Reis, J. (2019). Mediterranean diet: The role of long-chain ω-3 fatty acids in fish; polyphenols in fruits, vegetables, cereals, coffee, tea, cacao and wine; probiotics and vitamins in prevention of stroke, age-related cognitive decline, and Alzheimer disease. *Revue Neurologique (Paris)*, *175*, 724−741.

Sablani, S. S., Andrews, P. K., Davies, N. M., Walters, T., Saez, H., Syamaladevi, R. M., & Mohekar, P. R. (2010). Effect of thermal treatments on phytochemicals in conventionally and organically grown berries. *Journal of the Science of Food and Agriculture*, *90*, 769−778.

Saini, R. K., Nile, S. H., & Keum, Y. S. (2016). Food science and technology for management of iron deficiency in humans: A review. *Trends in Food Science and Technology*, *53*, 13−22.

Saldívar, S. O. S., & Soto, F. E. A. (2020). Chemical composition and biosynthesis of dietary fiber components. In J. Welti-Chanes, S. Serna-Saldívar, O. Campanella, & V. A. Tejada Ortigoza (Eds.), *Science and technology of fibers in food systems* (pp. 15−43). Cham: Springer Nature.

Salunkhe, D. K., Bolin, H. R., & Reddy, N. R. (Eds.), (1991). *Storage, processing, and nutritional quality of fruits and vegetables. Volume I. Fresh fruits and vegetables*. Boston, MA: CRC Press.

Sanmartin, M., Pateraki, I., Chatzopoulou, F., & Kanellis, A. K. (2007). Differential expression of the ascorbate oxidase multigene family during fruit development and in response to stress. *Planta*, *225*, 873−885.

Saquet, A. A., Streif, J., & Almeida, D. P. (2019). Mineral composition and distribution within 'Rocha'pear in relation to internal storage disorders. *Postharvest Biology and Technology*, *158*, 111002.

Sarker, U., Hossain, M. M., & Oba, S. (2020). Nutritional and antioxidant components and antioxidant capacity in green morph *Amaranthus* leafy vegetable. *Scientific Reports*, *10*(1), 1−10.

Schmitz-Eiberger, M. A., & Blanke, M. M. (2012). Bioactive components in forced sweet cherry fruit (*Prunus avium* L.), antioxidative capacity and allergenic potential as dependent on cultivation under cover. *LWT − Food Science and Technology*, *46*, 388−392.

Schwarz, G. (2016). Molybdenum cofactor and human disease. *Current Option in Chemical Biology*, *31*, 179−187.

Shahid, M., Niazi, N. K., Khalid, S., Murtaza, B., Bibi, I., & Rashid, M. I. (2018). A critical review of selenium biogeochemical behavior in soil-plant system with an inference to human health. *Environmental Pollution*, *234*, 915–934.

Shahzad, N., Khan, W., Shadab, M. D., Ali, A., Saluja, S. S., Sharma, S., Afify, M. A., et al. (2017). Phytosterols as a natural anticancer agent: Current status and future perspective. *Biomedicine & Pharmacotherapy = Biomedecine & Pharmacotherapie*, *88*, 786–794.

Sigman-Grant, M., Warland, R., & Hsieh, G. (2003). Selected lower-fat foods positively impact nutrient quality in diets of free-living Americans. *Journal of the American Dietetic Association*, *103*, 570–576.

Skypala, I. J. (2019). Food-induced anaphylaxis: Role of hidden allergens and cofactors. *Frontiers in Immunology*, *10*, 673.

Slavin, J. L., & Lloyd, B. (2012). Health benefits of fruits and vegetables. *Advances in Nutrition*, *3*, 506–516.

Slimestad, R., Fossen, T., & Brede, C. (2020). Flavonoids and other phenolics in herbs commonly used in Norwegian commercial kitchens. *Food Chemistry*, *309*, 125678.

Soliman, G. A. (2019). Dietary fiber, atherosclerosis, and cardiovascular disease. *Nutrients*, *11*, 1155.

Sompornrattanaphan, M., Kreetapirom, P., Srinoulprasertc, Y., Kanistanon, D., Klinniyom, A., Wongsa, C., & Thongngarm, T. (2019). Severe anaphylaxis after pelvic examination: A case report of dual latex and chlorhexidine allergies. *Allergy, Asthma, and Clinical Immunology*, *15*, 19.

Sonntag, F., Bunzel, D., Kulling, S., Porath, I., Pach, F., Pawelzik, E., Naumann, M., et al. (2020). Effect of potassium fertilization on the concentration of antioxidants in two cocktail tomato cultivars. *Journal of Applied Botany and Food Quality*, *93*, 34.

Sozzi, G. O. (2001). Caper bush: Botany and horticulture. *Horticultural Reviews*, *27*, 125–188.

Sozzi, G. O., Greve, L. C., Prody, G. A., & Labavitch, J. M. (2002). Gibberellic acid, synthetic auxins, and ethylene differentially modulate α-l-arabinofuranosidase activities in antisense 1-aminocyclopropane-1-carboxylic synthase pericarp discs. *Plant Physiology*, *129*, 1330–1340.

Tan, H. L., Thomas-Ahner, J. M., Grainger, E. M., Wan, L., Francis, D. M., Schwartz, S. J., Erdman, J. W., Jr., et al. (2010). Tomato-based food products for prostate cancer prevention: What have we learned? *Cancer and Metastasis Review*, *29*, 553–568.

Tang, R. J., & Luan, S. (2017). Regulation of calcium and magnesium homeostasis in plants: From transporters to signaling network. *Current Opinion in Plant Biology*, *39*, 97–105.

Tao, D., Wang, J., Zhang, L., Jiang, Y., & Lv, M. (2019). 1-Methylcyclopropene alleviates peel browning of 'Nanguo'pears by regulating energy, antioxidant and lipid metabolisms after long term refrigeration. *Scientia Horticulturae*, *247*, 254–263.

Thakur, N., Raigond, P., Singh, Y., Mishra, T., Singh, B., Lal, M. K., & Dutt, S. (2020). Recent updates on bioaccessibility of phytonutrients. *Trends in Food Science and Technology*, *97*, 366–380.

Thor, K. (2019). Calcium—Nutrient and messenger. *Frontiers in Plant Science*, *10*, 440.

Titchenal, C. A., & Dobbs, J. (2007). A system to assess the quality of food sources of calcium. *Journal of Food Composition and Analysis*, *20*, 717–724.

Tiwari, U., & Cummins, E. (2013). Factors influencing levels of phytochemicals in selected fruit and vegetables during pre-and post-harvest food processing operations. *International Food Research Journal*, *50*(2), 497–506.

Tobajas, A. P., Agulló-García, A., Cubero, J. L., Colás, C., Segura-Gila, I., Sánchez, L., ... Pérez, M. D. (2020). Effect of high pressure and pulsed electric field on denaturation and allergenicity of Pru p 3 protein from peach. *Food Chemistry*, *321*, 126745.

Toivonen, P. M. A., Zebarth, B. J., & Bowen, P. A. (1994). Effect of nitrogen fertilization on head size, vitamin C content and storage life of broccoli (*Brassica oleracea* var. italica). *Canadian Journal of Plant Science*, *74*, 607–610.

Tomé-Carneiro, J., Crespo, M. C., López de Las Hazas, M. C., Visioli, F., & Dávalos, A. (2020). Olive oil consumption and its repercussions on lipid metabolism. *Nutrition Reviews*, *78*. Available from https://doi.org/10.1093/nutrit/nuaa014.

Tonetto de Freitas, S., & Mitcham, E. J. (2012). Factors involved in fruit calcium deficiency disorders. *Horticultural Reviews*, *40*, 107–146.

Tripodi, P., Cardi, T., Bianchi, G., Migliori, C. A., Schiavi, M., Rotino, G. L., & Scalzo, R. L. (2018). Genetic and environmental factors underlying variation in yield performance and bioactive compound content of hot pepper varieties (*Capsicum annuum*) cultivated in two contrasting Italian locations. *European Food Researchand Technology*, *244*(9), 1555–1567.

Tripoli, E., La Guardia, M., Giammanco, S., Di Majo, D., & Giammanco, M. (2007). Citrus flavonoids: Molecular structure, biological activity and nutritional properties: A review. *Food Chemistry*, *104*, 466–479.

Trudel, M. J., & Ozbun, J. L. (1971). Influence of potassium on carotenoid content of tomato fruit. *Journal of the American Society for Horticultural Science*, *96*, 763–765.

Tuppo, L., Spadaccini, R., Alessandri, C., Wienk, H., Boelens, R., Giangrieco, I., Tamburrini, M., et al. (2014). Structure, stability, and IgE binding of the peach allergen peamaclein (Pru p 7). *Peptide Science*, *102*, 416–425.

Turner, P. J., Baumert, J. L., Beyer, K., Boyle, R. J., Chan, C. H., Clark, A. T., Crevel, R. W. R., et al. (2016). Can we identify patients at risk of life-threatening allergic reactions to food? *Allergy*, *71*, 1241–1255.

U.S. Department of Agriculture (2008).*'Composition of foods, raw, processed, prepared' USDA national nutrient database for standard reference, release 20*. Beltsville, MD: USDA-ARS, Beltsville Human Nutrition Research Center, Nutrient Data Laboratory. <http://www.ars.usda.gov/nutrientdata>. Accessed 04/2008.

U.S. Department of Health and Human Services and U.S. Department of Agriculture. (2005). *Dietary guidelines for Americans* (6th ed.). Washington, DC: U.S. Government Printing Office, 2005.

Uluisik, S., & Seymour, G. B. (2020). Pectatelyases: Their role in plants and importance in fruit ripening. *Food Chemistry*, *309*, 125559.

Uriu-Adams, J. Y., & Keen, C. L. (2005). Copper, oxidative stress, and human health. *Molecular Aspects of Medicine*, *26*, 268–298.

Vainik, U., García-García, I., & Dagher, A. (2019). Uncontrolled eating: A unifying heritable trait linked with obesity, overeating, personality and the brain. *European Journal of Neuroscience*, *50*(3), 2430–2445.

Van de Poll, M. C. G., Dejong, C. H. C., & Soeters, P. B. (2006). Adequate range for sulfur-containing amino acids and biomarkers for their excess: Lessons from enteral and parenteral nutrition. *Journal of Nutrition*, *136*, 1694S–1700S.

Vangdal, E., Lunde Knutsen, I., & Kvamm-Lichtenfeld, K. (2018). Fertilization and susceptibility to fruit cracking in plums (*Prunus domestica* L.). *Acta Horticulturae*, *1194*, 25–30.

Vanholme, R., De Meester, B., Ralph, J., & Boerjan, W. (2019). Lignin biosynthesis and its integration into metabolism. *Current Opinion in Biotechnology*, *56*, 230–239.

Vicente, A. R., Ortugno, C., Rosli, H., Powell, A. L. T., Greve, C., & Labavitch, J. M. L. (2007). Temporal sequence of cell wall disassembly events in developing fruits. 2. Analysis of blueberry (*Vaccinium Species*). *Journal of Agriculture and Food Chemistry*, *55*, 4125–4130.

Vicente, A. R., Saladié, M., Rose, J. K. C., & Labavitch, J. M. (2007). The linkage between cell wall metabolism and fruit softening: Looking to the future. *Journal of the Science and Food Agriculture*, *87*, 1435–1448.

Von Elbe, J. H., & Schwartz, S. J. (1996). Colorants. In O. R. Fennema (Ed.), *Food chemistry* (3rd ed.). New York: Marcel Dekker.

Vuolo, M. M., Lima, V. S., & Junior, M. R. M. (2019). Phenolic compounds: Structure, classification, and antioxidant power. *Current bioactive compounds* (pp. 33–50). Woodhead Publishing.

Wall, M. M. (2006). Ascorbic acid, vitamin A, and mineral composition of banana (*Musa sp.*) and papaya (*Carica papaya*) cultivars grown in Hawaii. *Journal of Food Composition and Analysis*, *19*, 434–445.

Walsh, J. H., Wyse, B. W., & Hansen, R. G. (1981). Pantothenic acid content of 75 processed and cooked foods. *Journal of the American Dietetic Association*, *78*, 140.

Wang, S. Y., & Lin, H. S. (2000). Antioxidant activity in fruits and leaves of blackberry, raspberry, and strawberry varies with cultivar and developmental stage. *Journal of Agriculture and Food Chemistry*, *48*, 140–146.

Wang, S. Y., & Lin, H. S. (2003). Compost as a soil supplement increases the level of antioxidant compounds and oxygen radical absorbance capacity in strawberries. *Journal of Agriculture and Food Chemistry*, *51*, 6844–6850.

Wang, S. Y., Zheng, W., & Galletta, G. J. (2002). Cultural system affects fruit quality and antioxidant capacity in strawberries. *Journal of Agriculture and Food Chemistry*, *50*, 6534–6542.

Wang, X., Ouyang, Y., Liu, J., Zhu, M., Zhao, G., Bao, W., & Hu, F. B. (2014). Fruit and vegetable consumption and mortality from all causes, cardiovascular disease, and cancer: Systematic review and dose-response meta-analysis of prospective cohort studies. *British Medical Journal*, *349*, g4490.

Waris, G., & Ahsan, H. (2006). Reactive oxygen species: Role in the development of cancer and various chronic conditions. *Journal of Carcinogenesis*, *6*, 14–21.

Watkins, J. L., & Pogson, B. J. (2020). Prospects for carotenoid biofortification targeting retention and catabolism. *Trends in Plant Science*, *25*(5), 501–512.

Wei, S., Qin, G., Zhang, H., Tao, S., Wu, J., Wang, S., & Zhang, S. (2017). Calcium treatments promote the aroma volatiles emission of pear (*Pyrus ussuriensis* 'Nanguoli') fruit during post-harvest ripening process. *Scientia Horticulturae*, *215*, 102−111.

Wimmer, M. A., Abreu, I., Bell, R. W., Bienert, M. D., Brown, P. H., Dell, B., Fujiwara, T., et al. (2020). Boron: An essential element for vascular plants. *New Phytologist*, *226*, 1232−1237.

Witney, G. W., Hofman, P. M., & Wolstenholme, B. N. (1990). Effect of cultivar, tree vigourand fruit position on calcium accumulation in avocado fruits. *Scientia Horticulturae*, *44*, 269−278.

Wood, B. W. (2015). Nickel. In A. V. Barker, & D. J. Pilbeam (Eds.), *Handbook of plant nutrition* (2nd ed., pp. 511−535). New York: CRS Press.

Xu, M., Shen, C., Zheng, H., Xu, Y., Xue, C., Zhu, B., & Hu, J. (2020). Metabolomic analysis of acerola cherry (*Malpighiaemarginata*) fruit during ripening development via UPLC-Q-TOF and contribution to the antioxidant activity. *Food Research International*, *130*, 108915.

Yuan, J., Yu, Z., Lin, T., Wang, L., Chen, X., Liu, T., Li, Y., et al. (2020). BcERF070, a novel ERF (ethylene-response factor) transcription factor from non-heading Chinese cabbage, affects the accumulation of ascorbic acid by regulating ascorbic acid-related genes. *Molecular Plant Breeding*, *40*(1), 1−18.

Zaro, M. J., Chaves, A. R., Vicente, A. R., & Concellón, A. (2014). Distribution, stability and fate of phenolic compounds in white and purple eggplants (*Solanummelongena* L.). *Postharvest Biology and Technology*, *92*, 70−78.

Zerwekh, J. E., Odvina, C. V., Wuermser, L. A., & Pak, C. Y. C. (2007). Reduction of renal stone risk by potassium-magnesium citrate during 5 weeks of bed rest. *Journal of Urology*, *177*, 2179−2184.

Zhang, Q., Chen, T., Wang, X., Zhao, P., Lei, X., Liu, P., Guo, Y., et al. (2020). Influence of simulated grape crushing process on phenolic compounds extraction, astringency and color of Cabernet Sauvignon model wine. *LWT − Food Science and Technology*, *128*, 109514.

Zheng, W., & Wang, S. W. (2003). Oxygen radical absorbing capacity of phenolics in blueberries, cranberries, chokeberries, and lingonberries. *Journal of Agriculture and Food Chemistry*, *51*, 502−509.

This page intentionally left blank

CHAPTER

20

Mitigating contamination of fresh and fresh-cut produce

Elazar Fallik[1] *and Zoran Ilic*[2]

[1]ARO—The Volcani Institute, Department of Postharvest Science, Rishon LeZiyyon, Israel

[2]University of Priština-Kosovska Mitrovica, Faculty of Agriculture, Lešak, Serbia

Abbreviations

AA	acetic acid
ARB	antibiotic-resistant bacteria
CAPP	cold atmospheric-pressure plasma
CFU	colony forming units
DDVP	dichlorvos
EO	essential oil
FBD	foodborne diseases
FDA	Food and Drug Administration
GRAS	generally recognized as safe
HSI	hyperspectral imaging
LA	levulinic acid
LFD	lateral flow disk
LOD	limit of detection
MAP	modified atmosphere packaging
NGS	next-generation sequencing
PA	peracetic acid
PAA	peroxyacetic acid
PCR	polymerase chain reaction
PET	polyethylene terephthalate
PL	pulse light
PM	packaging materials
TAB	total aerobic bacteria
UV	ultra violet
WPL	water-assisted PL

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00020-8

20.1 Introduction

According to dietary guidelines, a balanced and healthy diet should include daily intake of fruit and vegetables. Phytochemicals are abundant in fresh produce and may promote human health, reduce the risk of heart diseases, and prevent diseases such as cancer (Formica-Oliveira, Martínez-Hernández, Díaz-López, Artés, & Artés-Hernández, 2017). However, all fresh fruits and vegetables, as well as fresh-cut produce are exposed to microbial contamination and spoilage, either before harvest or after harvesting and processing.

Fresh produce may become contaminated with spoilage pathogens or inorganic pollutants at many points during production and along supply chains. Apart from animal manure (Atidegla, Huat, Agbossou, Saint-Macary, & Kakai, 2016), the key sources of pathogens in the farm are soil, irrigation water (Decol et al., 2017), and feces of wild and domestic animals. Fecal contamination of water that is used to irrigate, to distribute fertilizer, pesticides or fungicides, or to wash food crops has the potential to disperse pathogenic bacteria like *Campylobacter* spp., *Escherichia coli* O157:H7, *Salmonella* spp., and *Listeria monocytogenes* widely among the produce (Wadamori, Gooneratne, & Hussain, 2017; Yeni, Yavas, Alpas, & Soyer, 2016). Poor or absent hygiene practices during processing, distribution, retail, and consumption, as well as at home in our refrigerators, are additional causes of contamination (Bhilwadikar, Pounraj, Manivannan, Rastogi, & Negi, 2019; Jung, Jang, & Matthews, 2014; Maffei et al., 2019; Sant'Ana, Silva, Maffei, & Franco, 2014).

Foodborne infections that elicit gastrointestinal disturbances are most commonly due to pathogens such as *Salmonella*, *Novovirus*, *Staphylococcus aureus*, *Shigella*, and *Campylobacter*. The foodborne illnesses caused by *Clostridium botulinum*, pathogenic *E. coli* O157:H7 and O104:H4, *Listeria* spp., and *Vibrio* spp. were reported to be much more severe, causing symptoms extending from bloody diarrhea to death, in new-born infants and in some acutely infected adults. Also, molds and pesticides have caused adverse health conditions such as cancer, birth defects, and neurodevelopmental disorders (Bhilwadikar et al., 2019). According to the WHO (2018), every year approximately 600 million people become ill after consuming contaminated food. Among these victims, an estimated 420,000 die, including 125,000 children under the age of 5 years. However, cases of foodborne diseases (FBD) often are not reported, generally because of nonidentification or absence of symptoms—in contrast to the effects of attacks by pathogenic microorganisms—or in cases of diseases that elicit temporary symptoms for which people do not seek health care (Zanin, da Cunha, de Rosso, Carpiles, & Stedefeldt, 2017). Between January 2017 and March 2018 in South Africa, there were 978 laboratory-identified listeriosis cases, with 674 illnesses confirmed (WHO, 2018), and about 30% of these patients died (WHO, 2018). This represents a case fatality rate that is higher than that recorded for the European Union in 2015 (Kurpas & Wieczorek, 2018).

The annual cost of foodborne pathogens has been estimated at between \$14 billion and \$36 billion (Minor et al., 2015). During 2018 in the United States, the US Food and Drug Administration (FDA) reported over 1000 illnesses and 5 deaths linked to multistate outbreaks in melons, vegetable trays, lettuce-based salad mixes, and romaine lettuce (Astill, Minor, & Thornsbury, 2019). Therefore industry was encouraged to develop best practices for fresh and fresh-cut products, in parallel with US Federal Government efforts to standardize food safety practices that include FDA initiatives such as good agricultural practices and, more recently, the Food Safety Modernization Act (Astill et al., 2019).

Thus, the goal of the present chapter is to summarize the latest information—accumulated during recent years—on prestorage or processing treatments designed to reduce or eliminate the presence of spoilage microorganisms, foodborne pathogens, and chemical pollutants on fresh and fresh-cut products and to review the detection technologies that are available, known, or used today.

20.2 Treatments to reduce microbial load

The many types of disinfecting treatments include: chemical treatments based on chlorine, hydrogen peroxide, ozone, cold plasma, electrolyzed water, and organic acids; irradiation with ultra violet (UV), and heat treatments (HTs). The following paragraphs describe and discuss some of these treatments. Individual packinghouses, companies, or even domestic consumers use a variety of procedures for washing fresh or fresh-cut produce. Differences in these procedures can affect the design of processing lines, specific processing machinery, and management of the postharvest treatments, which may include single- or double-washing, open or closed flumes and tanks, number and location of nozzles and of rinsing steps, water replenishment policy, and whether to use single or combined treatments (Yoon & Lee, 2019).

20.2.1 Sodium hypochlorite

Chlorine (Cl_2) and hypochlorite (OCl^-) in solution are the most used aqueous sanitizers in the food industry and for drinking water disinfection, because of their efficacy against pathogens. For commercial disinfection purposes, chlorine gas, sodium hypochlorite (NaOCl) solutions, or calcium hypochlorite [$Ca(ClO)_2$] are used to make aqueous hypochlorite solutions (Feliziani, Lichter, Smilanick, & Ippolito, 2016). For disinfecting surfaces, chlorine has been applied at concentrations that ensure the presence of chlorine in the hypochlorous acid formed but do not promote excessive corrosion of equipment, that is, total active ingredient concentration of 50−200 ppm for 1−2 min; pH between 6 and 7.5 (Yoon & Lee, 2019). However, the occurrence in the wash water and finished produce of chlorate derived from chlorine-based antimicrobials has been highlighted as a health risk for consumers (Garrido, Marin, Tudela, Allende, & Gil, 2019). In the European Union, the default maximum residue level for chlorate in food is 0.01 mg/kg.

Recently, Tudela et al. (2019) reported that a lower free chlorine concentration operational limit based on total aerobic bacteria (TAB) counts of 10 mg/L was effective for onion, and they established levels up to 20−25 mg/L for lettuce and cabbage; however, the levels of TAB in process wash water of baby leaves were not controlled, even at the highest tested free chlorine concentration of 30 mg/L. Dharmarha et al. (2019) questioned the effectiveness of standard postharvest interventions, sanitizer washing, and cold storage to reduce antibiotic-resistant bacteria (ARB) on raw carrots. These ARBs included antibiotic-resistant strains of the human pathogen *E. coli* O15:H7 and a common spoilage bacterium *Pseudomonas*. Results of this study indicate that sodium hypochlorite (50 ppm free chlorine) in wash water, followed by storage at 2°C, might provide an effective strategy to prevent regrowth of pathogenic *E. coli* O157:H7 and to reduce levels of bacteria resistant to certain antibiotics on carrots.

Because chlorine is a powerful oxidant, it can oxidize chemical compounds and produce various chlorination byproducts. Washing for 5 min in chlorinated tap water containing chlorine at 0.1 mg/L reduced systemic and nonsystemic pesticides and reduced the levels of alpha-cypermethrin, azoxystrobin, boscalid, chlorpyrifos, fludioxonil, and iprodione pesticides on broccoli, black currants, strawberries, and tomatoes by more than 40% (Lozowicka & Jankowska, 2016). In contrast, washing with chlorinated tap water containing available chlorine at 2 ppm removed only 16%−30% of dichlorvos (DDVP) ($C_4H_7Cl_2O_4P$) residues from tomatoes (Heshmati & Nazemi, 2017).

20.2.2 Hydrogen peroxide (H_2O_2)

Hydrogen peroxide (H_2O_2) is classified as generally recognized as safe (GRAS) for use in food products. It is a strong oxidizer and is offered as an alternative means to decontaminate fruits and vegetables because of its low toxicity and safe decomposition products. It exhibits both bacteristatic and bactericidal activity (Ali, Yeoh, Forney, & Siddiqui, 2018); it has been shown to damage bacterial proteins, DNA, and cellular membranes of microbial cells, and to remove protein from the coats of bacterial spores; its action is affected by organic load but not by pH (Van Haute, Tryland, Veys, & Sampers, 2015).

Hydrogen peroxide (10%) fumes reduced *E. coli*, *Salmonella typhimurium*, and *L. monocytogenes* counts on lettuce leaves by 3 log colony forming unit (CFU)/g after 10 min of treatment (Back, Ha, & Kang, 2014). Aerosolized H_2O_2 treatment on smooth tomato surfaces reduced *E. coli* to undetectable levels and reduced their populations by 4.9 log CFU/g on cantaloupe rind and by 1.5 log CFU/g on spinach leaf surfaces (Jiang et al., 2017). Use of a mist of 5% H_2O_2 in rooms designated for the food industry was found to be effective against *L. monocytogenes* (Moretro, Fanebust, Fagerlund, & Langsrud, 2019). Le Toquin, Faure, Orange, and Gas (2018) compared the decontamination efficiency of an aqueous foam containing hydrogen peroxide at 5.5%, with that of disinfectant in the liquid form on vertical surfaces contaminated by *Bacillus thurengiensis* spores; the foam enabled reduction of the spores by a factor of more than 6 log within 30 min of contact. This technology can be used in cooling rooms, in fresh-produce containers, and in other facilities.

20.2.3 Ozone

Several promising technologies based on ozone have been evaluated. The application of ozone, in both gaseous and aqueous phases, as a direct food additive for processing, treatment, and storage of food was approved by the FDA in 2001. There are two main forms of ozone treatments for food: gaseous ozone and aqueous ozone washing or rinsing. Gaseous ozone is more stable than the aqueous solution, because ozone has a longer half-life in air than in water. Ozone has a strong oxidizing capacity, but it is not stable and quickly degrades to oxygen and free radicals, leaving no chemical residue. It can destroy cell membranes, oxidize vital cell components such as enzymes and nucleic acids of microorganisms, and lead to cell death (Tokala, Singh, & Payne, 2018).

One promising approach involves gaseous ozone treatment (forced air-ozone). This technology involves introducing ozone into an airstream that passes through the batch of produce to be treated, thereby ensuring contact of the antimicrobial gas with individual fruits. Spinach leaves were vacuum cooled at 4°C in a custom-made vessel and then were subjected to a gaseous ozone treatment at 9°C for 30 min, with 1.5 g of ozone per kg of gas mixture. The gaseous ozone used during vacuum cooling was effective against *E. coli* O157:H7 (Yesil, Kasler, Huang, & Yousef, 2017).

Continuous low-dosage (50–87 ppb) ozone treatment of Fuji apples reduced *Listeria innocua* by ~5.0 log CFU/fruit during 30 weeks in controlled atmosphere storage at 0°C without impairing fruit visual quality (Sheng et al., 2018). Murray, Moyer, Wu, Goyette, and Warriner (2018) showed that optimized forced air-ozone treatment reduced *L. monocytogenes* by 2.12–3.07 log CFU independently of the apple position within the 30-cm depth of the fruit column.

Treating tomato fruits with ozone at 6.85 mg/L for 2 and 4 h reduced *Salmonella* populations per fruit by approximately 2 log CFU on both smooth surface and stem scar areas of the fruit after 21 days at 10°C; however, this treatment impaired fruit quality (Wang, Fan, Sokorai, & Sites, 2019).

The removal of residues of the herbicide linuron and the fungicide difenoconazole from carrots by treatment with ozone has been demonstrated by de Souza et al. (2018), following dipping in ozonated water (10 ppm) at 14°C for 60 min the carrots showed the removal of 96% and 79.8% of difenoconazole and linuron, respectively, and gaseous ozone (5 ppm in air) treatment achieved more than 95% reduction of both chemicals. Tomatoes sprayed with DDVP in water at 2 mL/L and then washed for 15 min in ozonated water at 2, 4, or 6 ppm showed removal of 71.9%, 88.6%, or 91.9%, respectively, of DDVP residues (Heshmati & Nazemi, 2017).

20.2.4 Organic acids

Organic acids are GRAS and can be used as sanitizers of fresh produce because of their bactericidal activity.

Hassenberg, Schuhmann, Ulrichs, Herppich, and Huyskens-Keil (2018) treated sweet cherries with acetic acid (AA) vapor against pathogenic microorganisms: low AA vapor concentrations (3 mg/L) reduced mold counts to near the detection limit, and low-temperature storage then delayed or prevented mold regrowth. Higher AA vapor concentrations (>3 mg/L) sustainably reduced yeast counts during storage at 4°C, and AA vapor treatment moderately and temporarily decreased bacteria counts. However, the efficacy of AA fumigation varied between two tested cultivars: AA fumigation was found particularly helpful against mold-caused spoilage in fruit of both cultivars, and Hassenberg et al. (2018) recommended a minimum AA concentration of 6 mg/L to achieve highly efficient treatments.

Chen, Zhang, and Zhong (2019b) reported that washing for 3 min in acidified sodium benzoate (NaB) solution at 3000 ppm and pH 2.0 was the most effective in reducing the population of *E. coli* O157:H7, *Salmonella enterica*, and *L. monocytogenes* cocktails on cherry tomatoes by >4 log CFU/g after 15 days at 4°C and 21°C. NaB was more effective than free chlorine ($P < .05$) in reducing the two Gram-negative bacteria on tomatoes, whereas the reductions of Gram-positive *L. monocytogenes* by NaB (5.49 log CFU/g) and by chlorine (4.98 log CFU/g) were similar ($P > .05$) (Chen et al., 2019b).

Nicolau-Lapena et al. (2019) compared the disinfection capacity of peracetic acid (PA) at concentrations of 20, 40, and 80 ppm, and washing times of 1 and 2 min with those of sodium hypochlorite (NaClO) at 200 ppm and of a water control, on strawberries; they found washing time irrelevant in reduction of epiphytic microbiota and *L. innocua* populations. Aerobic mesophylls were reduced similarly by PA and NaClO washes. All PA washing treatments reduced the *L. innocua* populations by 4 log units. *L. innocua* counts in PA washing solutions were 4-log units lower than they were in control water. Sanitization had no impact on fruit quality or biochemical characterization (Nicolau-Lapena et al., 2019).

20.2.5 Chlorine dioxide (ClO_2)

Chlorine dioxide (ClO_2) is another chlorine-based compound that has been approved by the US FDA for use as a food sanitizer; it can be used at up to 3 ppm to sanitize raw fruits and vegetables. A synthetic green-yellowish gas, ClO_2 is a water-soluble strong oxidant with an oxidation capability 2.5 times higher than that of diatomic chlorine. It is extremely effective, with a short treatment time at low concentrations over a wide pH range, without formation of trihalomethanes or other halogenated organic compounds (Sun, Baldwin, & Bai, 2019). Chlorine dioxide gas (ClO_2 [g]) can be generated by reacting $NaClO_2$ with an acid such as hydrogen chloride (HCl) (Murray, Wu, Shi, Xue, & Warriner, 2017). Gaseous ClO_2 has many advantages over its aqueous formulations in addition to being less corrosive; they include ease of mixing with air, rapid diffusion, and the ability to penetrate permeable surfaces and biofilms. A combination of washing with aqueous sanitizer and application of gaseous ClO_2 can enhance decontamination of both foodborne and plant pathogens (Sun et al., 2019). However, Park, Ahn, and Kang (2018) found that the effectiveness of gaseous ClO_2 was temperature-dependent: as the temperature during treatment was increased ClO_2 became less effective in deactivating *E. coli*, *Salmonella*, and *Listeria*.

Spinach and tomato treated with gaseous ClO_2 at 0.05−0.08 mg/L showed strong antimicrobial activity against *E. coli* O157:H7, *Salmonella*, and *L. monocytogenes* after 20- to 30-min treatments (Park & Kang, 2018). Gaseous ClO_2 was also effective against Tulane virus, achieving a 2.2 log reduction after 20 min at 0.6 mg/L (Kingsley, Perez-Perez, Niemira, & Fan, 2018). Exposure to ClO_2 at 0.15 mg/g for 5.0 h reduced populations of viable *E. coli*, *Salmonella*, and *Listeria* on tomatoes and of *E. coli* on carrots below the detection limit (<1 log CFU/g); such a concentration did not bleach the plant tissues (Bridges, Rane, & Wu, 2018).

20.2.6 Modified atmosphere packaging

Modified atmosphere packaging (MAP) and controlled atmosphere storage can delay quality impairment and thus extend storability and shelf life of fresh, minimally processed, or fresh-cut produce, because of the low oxygen and high carbon dioxide levels inside the package. MAP of fruits can reduce respiratory activity, delay softening and ripening, and reduce incidence of various physiological disorders and pathogenic infestations

(Mphahlele, Fawole, & Opara, 2016; Pinela et al., 2016). Generally, O_2 and CO_2 concentrations below and above atmospheric, at 6% and 10%, respectively, can improve microbial control and extend the shelf life of fresh fruits (Oliveira et al., 2015).

Alsawmahi et al. (2018) evaluated polypropylene (PP) and polyethylene (PE) plastics with varied perforation sizes (0, 50, 100, and 150 μm) for storage of fresh Barhi dates at the Khalal (yellow) stage, at temperatures of 1°C, 5°C, 15°C, and 25°C, for up to 45 days. They found that PP date packages with 150-μm perforations and stored at 5°C for 2 weeks had the lowest acidity and microbial load.

Hyun and Lee (2018) reported that MAP using 100% CO_2 gas resulted in reduced levels of total mesophilic bacteria, *E. coli*/coliform, and yeast/mold in the fresh produce, compared with those in air packaging; in particular, MAP using CO_2 gas effectively maintained low levels of yeast and mold on grapes, soybean sprouts, and lotus roots during 21 days of storage at 4°C ± 2°C. Low-density PE packaging material (PM) that contained nano-Ag (30% (w/w), nano-TiO_2 [25% (w/w)], nano-SiO_2 [10% (w/w)], and attapulgite [10% (w/w)] was prepared and its effect on storage stability of mushrooms was investigated. After 14 days at 4°C ± 1°C, the results showed that the nanocomposite-based PMs regulated oxygen and carbon dioxide levels, eliminated ethylene, and inhibited the growth of microbes, and thus improved the quality preservation of mushrooms compared with packaging in the normal PE material (Donglu et al., 2016).

20.2.7 Essential oils

Essential oils (EOs) from aromatic plants have been considered as potential agents for disinfection and preservation of vegetable quality, because of their antimicrobial and antioxidant properties. The antifungal activities of EOs are related to the associated disintegration of fungal hyphae caused by the mono- and sesquiterpene compounds present in EOs. Moreover, EOs enhance membrane permeability because such compounds can dissolve in cell membranes and cause them to swell, thereby impairing their function. Additionally, the lipophilic property of EOs promotes their antifungal activity because it enables them to penetrate cell walls and affect the enzymes involved in cell-wall synthesis and thereby alter the morphological characteristics of the fungi (Pandey, Kumar, Singh, Tripathi, & Bajpai, 2017; Tzortzakis, Chrysargyris, Sivakumar, & Loulakakis, 2016; Xylia, Chrysargyris, Botsaris, & Tzortzakis, 2018).

Xylia, Clark, Chrysargyris, and Romanazzi (2019) studied the effects of washing with various aqueous solutions of EOs on the quality of shredded carrot stored at 4°C for 9 days. The studied EOs were marjoram EO at 1:1500 (v:v), marjoram hydrosol (Hyd) at 1:15 (v:v), AA at 1%, and their respective combinations. Decay incidence, as indicated by the total viable counts and counts of yeast and filamentous fungi, was decreased by separate or combined treatments during storage. Ascorbic acid, alone or in combination with Hyd or EO, maintained quality and preservation of processed carrots.

The application of carvacrol (Car):peppermint [80:20 (v:v)] vapor at 8 mg/L under vacuum in an industrial installation may extend the shelf life of fresh cilantro—a culinary herb—beyond 12 days at 2°C and thereby ensure its microbial and visual quality. However, EO vapors at concentrations below 0.5 mg/L did not achieve mold reductions greater than 0.2 log units, whereas at concentrations ≥ 10 mg/L, they did not increase the antifungal activity (Lopez-Gomez et al., 2019).

The use of EO compounds against *E. coli* O157:H7 was studied on fresh-cut lettuce by Yuan, Teo, and Yuk (2019), who found minimal inhibitory concentrations (MICs) of thymol (Thy), Car, *trans*-cinnamaldehyde, eugenol (Eug), and vanillin ranging from 0.63 to 2.5 mg/mL, whereas citral and linalool were ineffective, with MICs > 10 mg/mL. They obtained stronger antimicrobial efficacy by using combinations of EOs and attributed this effect to increased membrane damage. Application of Thy/Eug and Car/Eug o fresh-cut lettuce as a decontamination rinse caused a significant ($P < .05$) decrease in bacterial count, compared with a water rinse. However, this resulted in color-darkening and texture-softening in treated lettuce.

20.2.8 Cold plasma

Physical treatments based on nonthermal technology include exposure to cold atmospheric-pressure plasma (CAPP). Plasma, known as the fourth state of matter, is an ionized gas comprising molecules, atoms, ions, and free electrons. It forms an emerging technology in the field of food processing and has great potential in microbial load reduction on food product surfaces (Schottroff et al., 2018). The microbial inactivation mechanism of CAPP is attributed to the oxidation of vital cellular components. The oxidation exposes bacterial membranes to attack and leads to degradation of cell lipids, proteins, and DNA, which, in turn, leads to microbial death or cell injury (Bourke, Ziuzina, Han, Cullen, & Gilmore, 2017; Pignata, D'Angelo, Fea, & Gilli, 2017; Sarangapani, Patange, Bourke, Keener, & Cullen, 2018).

Berries are not only consumed in fresh or frozen states but also are available as processed products such as juices, preserves, jams, fruit pulp, purées, nectars, and dried fruits. They are highly perishable commodities, mainly because of their susceptibility to mechanical damage, water loss, and fungal decay. However, CAPP has shown great potential as an alternative food decontamination method, and it can be used to improve antimicrobial quality and enhance the food safety of berries, but treatment parameters need to be optimized for each berry type (Bovi, Frohling, Pathak, Vladramidis, & Schluter, 2019). Dong and Yang (2019) evaluated use of a cold-air plasma at atmospheric pressure as a pretreatment for prolonging the shelf life and improving the quality of blueberries. After plasma treatment for 10 min, the numbers of bacteria and fungi decreased by 93.0% and 25.8%, respectively, and fruit quality was maintained for 2 weeks at 25°C.

Schnabel et al. (2019) found that the native microbial load on fresh-cut lettuce and in the wash-up water was inactivated by microwave plasma-processed tap water (PPtW) during a common washing process. The use of PPtW in three different steps led to the highest reductions of microbial loads on the lettuce and in the washing water. Ziuzina, Han, Cullen, and Bourke (2015) reported rapid inactivation of *Salmonella*, *L. monocytogenes*, and *E. coli* suspended in lettuce broth within 30 s of plasma treatment; however, 5 min of treatment were required to reduce bacterial biofilm populations on lettuce. Shah et al. (2019) evaluated use of cold plasma-treated mist in disinfection of baby kale leaves and observed its effects on color values and cuticle composition after 12 days at 4°C: levels of *E. coli* O157:H7 were reduced below the detection limit of 5.5×10^3 CFU/mL with no significant color change, after plasma treatment for 300 s.

20.2.9 UV-C light/pulsed light

UV irradiation—a nonthermal, cost-effective technique—minimizes or inhibits microbial growth. It has been introduced as a promising technology for maintaining food quality and safety. UV treatment in postharvest processing involves exposing product to UV-C irradiation (190−280 nm) with a maximum wavelength (λ_{max}) of 254 nm, for a specified period. Although UV-C has lethal effects on various microorganisms, it does not sterilize food. However, some studies have found that use of this method to inhibit microorganism growth did reduce microbial flora and disinfected fruit and vegetable surfaces (Diao et al., 2015; Gabriel, Tongco, & Barnes, 2017).

Hosseini, Akhavan, Maghsoudi, Hajumohammadi-Farimani, and Balvardi (2019) exposed fresh pistachios to UV-C irradiation at 2.1 and 4.5 kJ/m^2 from seven germicidal UV-C lamps in a rotating cylindrical system and immediately packed them in perforated and unperforated PE terephthalate (PET); UV-C irradiation at 2.1 kJ/m^2 of produce packed in unperforated PET reduced microbial growth and, consequently, sensory changes in samples stored at 4°C.

Oviedo, Navarro, and Ltamiranda (2018) applied various UV-C doses to strawberry fruits for 7.5 min and found that 30 cm—the distance correctly used by industry—was the most effective distance from the source for decreasing microbial growth.

The effect of UV-C radiation on postharvest quality of pineapple cv. "Phulae" was investigated by Sari, Setha, and Naradison (2016) who found that this radiation significantly ($P < .05$) reduced disease incidence and internal browning in pineapple during storage at 10°C for 28 days. The lowest disease incidence was observed at the highest UV-C radiation dose, as provided by 30 min UV-C irradiation at 39.6 kJ/m^2.

Pulsed light (PL) also has been described as high-intensity pulsed UV light, pulsed UV light, high-intensity broad-spectrum UV light, intense light pulsed, and pulsed white light (Schottroff et al., 2018). Mannozzi et al. (2018) used PL as a nonthermal processing method to preserve the natural quality of food products. In principle, PL disinfection efficacy depends on accumulation of high-voltage energy in a capacitor from which it is discharged in ultrashort bursts through a xenon-filled light source, which typically emits a broad-spectrum light flash in the range of approximately 200−1100 nm, of which approximately 25% is in the UV range (Garvey & Rowan, 2019). The short pulses of electricity used in pulsed electric fields treatment can inactivate microorganisms and enhance their mass-transfer processes. In PL, the electric field strength creates transient pores in biological membranes, leading to irreversible cell disruption, which helps to kill the microorganisms (Gabric et al., 2018; Gomez et al., 2019; Rowen, 2019).

Fully ripe blueberries are susceptible to contamination by various pathogens and have a short shelf life. Cao, Huang, and Chen (2017) evaluated the effects of PL in inactivation of *Salmonella* on blueberries, and its impacts on shelf life, quality attributes, and health-promoting contents. Blueberries were stored at room temperature for 3 days or at 5°C for 7 days after dry PL at 6 J/cm^2; water-assisted PL in which samples were agitated in water during PL treatment at 9 J/cm^2; and two controls, dry control (untreated), and water washing without PL. In *Salmonella* inactivation, dry PL treatment achieved 0.9 and 0.6 log reductions of *Salmonella* in spot and dip inoculation, respectively; and water-assisted PL reduced Salmonella by 4.4 and 0.8 log in spot and dip inoculation, respectively. The treatment caused minimal or zero impact on the shelf life, quality attributes, and health-promoting contents of the fruit (Cao et al., 2017).

Holck, Liland, Dromtorp, Carlehog, and McLeod (2018) have shown that PL effectively inactivated *Salmonella*, *Listeria*, *Bacillus*, and *E. coli* species on chicken meat, fruit, and vegetables. They exposed bacterial cells to UV-C light at fluences from 0.05 to 3.0 J/cm^2 (i.e., 10 mW/cm^2, for 5−300 s) and to pulsed UV light at fluences ranging from 1.25 to 18.0 J/cm^2 and achieved reductions of 1.6−3.8 log, depending on working conditions. The PL exposure induced no unwanted by-products or damage to food sensory qualities and thus provided a safe, green, economic alternative means of ensuring food safety.

20.2.10 Heat

HTs are widely used in food processing, often to reduce or eliminate spoilage microorganisms and pathogens in food products. The efficacy of using heat to control microorganisms is challenged by the naturally diverse heat robustness of microorganisms. The efficacy of an HT in inactivating microorganisms depends on the heating temperature and time of exposure and on the heat resistance of the microorganisms (den Besten, Wells-Bennik, & Zwietering, 2018). For many years postharvest HTs have been known to be effective in managing postharvest diseases and physiological disorders; these treatments are completely safe for humans and the environment, that is, they are residue-free and environment-friendly, and feasibly can be used without constraints imposed by regulators (Sivakumar & Fallik, 2013; Usall, Ippolito, Sisquella, & Neri, 2016).

Poubol, Techavuthiporn, and Kanlayanarat (2018) investigated the effect of hot water treatment on microbiological quality of fresh-cut guava fruits, cv. "Kimju" and "Pan Srithong," which were treated with hot water at 40°C, 50°C, or 60°C for 10 or 30 min. Total microbial count, coliforms, lactic acid bacteria, and fungi were enumerated by Poubol et al. (2018) after processing and during storage at 10°C for 6 days. The results showed that the hot water treatments at 50°C for 10 and 30 min significantly reduced total microbial and coliform counts on guava cv. "Kimju," with greatest reduction achieved with higher temperature and longer immersion. Lactic acid bacteria and fungi were below the detection level during 4 days of storage at 10°C, after which they increased after 6 days of storage. Internal and external fruit quality were maintained during storage.

Chalupowicz, Alkalai-Tuvia, Zaaroor-Presman, and Fallik (2018) very successfully applied hot water rinsing and brushing (HWRB) at 54°C for 15 s on acorn squash; this treatment significantly maintained commodity quality for 3.5 months, as indicated by higher fruit firmness, lower decay incidence, and improved retention of green skin color compared with untreated fruit.

Calçots are the immature floral stems of second-year onion resprouts of the onion landrace; they are economically important in northeast Spain. Calçots subjected to a mild HT of 55°C for 60 s presented the highest reduction of aerobic mesophilic bacteria; they showed higher fresh weight loss (around 3%) and obtained the highest visual quality scores after 15 days of storage, with good consumer acceptance (Zudaire, Vinas, Abadias, Simo, & Aguilo-Aguayo, 2018).

A hot water treatment of 55°C for 0.5−2.0 min efficiently reduced the natural microflora and artificially inoculated microbes on apple peel by 2−3 log steps (i.e., 100- to 1000-fold) and yielded the best balance between preservation of the fruit and effective sanitation

(Kabelitz & Hassenberg, 2018). Similar results were reported by Kabelitz, Schmidt, Herppich, and Hassenberg (2019), who found that dipping at 55°C for 30 s effectively sanitized apple fruits.

Alicea, Annous, Mendez, Burke, and Orellana (2018) inoculated cantaloupes with *S. enterica* and then treated them with a solution containing free chlorine at 200 ppm for 40 min, with gaseous ClO_2 at 5 mg/L for 4.5 h, or with hot water at 76.1°C for 3 min, before cutting the fruit into pieces as fresh-cut and storing them for 21 days at 4°C. In the present study, the most effective treatment for reduction of *S. enterica* and preservation of the sensory quality of fresh-cut cantaloupes was hot water treatment of whole fruits at 76.1°C for 3 min.

Lotus root is one of the functional food vegetables with the greatest export volume from China. Li et al. (2018b) found that HT of fresh lotus root at 40°C, 50°C, or 60°C for 30 min effectively prevented moisture loss, browning and microbial growth but increased soluble solids, total volatile compounds, and firmness during storage at 25°C for 15 days. Total bacterial populations on the lotus after 15 days of storage at 25°C were lower by 1.3−1.6 log CFU/g on hot-water-treated samples than on control samples. However, on day 15, Li et al. (2018b) found no significant difference between samples treated at 40°C or 60°C.

Ceylan, McMahon, and Garren (2017) evaluated thermal inactivation with hot water and steam of *L. monocytogenes* and *Salmonella* on peas, spinach, broccoli, potatoes, and carrots. The vegetables were treated with hot water at 85°C or 87.8°C and with steam at 85°C or 96.7°C for up to 3.5 min. A greater than 5-log reduction of *L. monocytogenes* and *Salmonella* was achieved on all products within 0.5 min by hot-water blanching at 85°C and 87.8°C. Steam blanching at 85°C reduced *Salmonella* populations by more than 5-log on spinach and peas within 2 min and on carrots and broccoli within 3.5 min. Populations of *Salmonella* were reduced by more than 5 log within 1 min on carrot, spinach, and broccoli and within 2 min on peas by steam blanching at 96.7°C. Steam blanching at 85°C reduced *L. monocytogenes* populations by more than 5 log on carrots and spinach within 2 min and on broccoli and peas within 3.5 min. Populations of *L. monocytogenes* on carrot, spinach, pea, and broccoli were reduced by more than 5 log within 1 min by steam blanching at 96.7°C (Ceylan et al., 2017).

Ban and Kang (2018) used saturated steam at 100°C or superheated steam at 125°C, 150°C, 175°C, or 200°C for various periods to treat cherry tomatoes and oranges inoculated with the three foodborne pathogens *E. coli* O157:H7, *S. typhimurium*, and *L. monocytogenes*. After the fruits were exposed to superheated steam at 200°C for 3 or 20 s, all tested pathogens were reduced below the detection limit (i.e., by 1 or 1.7 log, respectively) without significant changes ($P>.05$) in fruit color, texture, vitamin C content, or poststorage antioxidant capacity at 4°C for up to 9 days.

Tang et al. (2017) indicated that HT of citrus fruit cv. Ponkan in water at 55°C for 20 s reduced the decay rate of the fruit, and a combination of HT with 25% of the normal commercial dose of iminoctadine tris (albesilate), 2,4-dichlorophenoxyacetic acid, and imazalil (IMZ) significantly reduced the decay rate without affecting fruit quality.

Nasef (2018), investigating the influence of hot water treatment on cucumbers (*Cucumis sativus* L.), found that a 5-min treatment at 55°C totally inhibited decay development and maintained fruit quality after 2 weeks of storage at 4°C followed by 2 days at 20°C.

Zhao and Yin (2018) studied the effects of biological control by *Pichia guilliermondii* at 1×10^8 CFU/mL and hot air treatment at 38°C for 4 days, both separately and in combination, on Red "Fuji" apple fruits infected by three major postharvest diseases: *Botrytis cinerea*, *Penicillium expansum*, and *Colletotrichum gloeosporioides*. Their results showed that the combined treatment inhibited the infection of apple fruit wounds by these diseases without affecting fruit quality during storage for up to 20 days at 20°C.

In a more recent study, Diep et al. (2019) proposed a validation protocol for efficacy of the thermal processing technology that is widely applied for food preservation, especially of ready-to-eat products processed at ultrahigh temperature and aseptically filled—products that are extensively consumed because of their convenience. Sterilization and aseptic filling are critical steps in such processing, and food business operators must verify their efficacy by demonstrating commercial sterility. The proposed validation protocol is based on inclusivity and limit of detection (LOD_{95}) as performance criteria (Diep et al., 2019). The LOD_{95} results indicated that methods based on cellular metabolisms were much more sensitive ($LOD_{95} < 1 \log_{10}$ CFU/mL) than cell counts and ATP-based methods ($LOD_{95} > 3 \log_{10}$ CFU/mL).

20.2.11 Irradiation/illumination

Irradiation following pasteurization is efficient and leaves no residue. During this process, the food is exposed to ionizing radiation, which eliminates microorganisms or insects, and thereby preserves its sensory and nutritional properties. Ionizing radiation such as gamma rays, UV irradiation, and electron beams are used to preserve the quality of fresh and processed produce. The United State Department of Agriculture and FDA approved the use of irradiation treatment for fruits and vegetables up to doses of 3.0−4.0 kGy for insect disinfestation and improved food safety (US FDA, 2018). Such radiation can penetrate the product and eliminate the microorganisms that are present in seeds and vegetables, and that harbor the pathogens; the food can be treated either before or after packaging (Cook, Knight, & Richards, 2016; Shahbaz, Akram, Ahn, & Kwon, 2016). Depending on the type of food and the desired effect, three dose levels can be designated. Low dose—up to 1 kGy—is used to delay ripening or sprouting of fresh fruits and vegetables and to control insects and foodborne parasites in cereals and pulses, fresh and dried fruits, dried fish and meat, etc.; Medium dose—1−10 kGy—is used to reduce spoilage and pathogenic microorganisms on fresh fish, strawberries, mushrooms, fresh and frozen seafood, and raw or frozen poultry and meat, and thereby to improve technological properties by, for example, reducing cooking times for dehydrated vegetables and extending shelf lives. High dose—greater than 10 kGy (10−50 kGy)—is used to sterilize meat, poultry, seafood, and other prepared foods (Shahbaz et al., 2016).

Pimenta, Margaca, and Verde (2019) inoculated fresh strawberries and raspberries, either with murine norovirus type 1 (MuNoV; as a human norovirus surrogate) or human adenovirus type 5 (HAdV) applied individually, or as a viral pool of both viruses, and irradiated the fruits in a Co-60 device at doses of 1−11 kGy; they achieved a 2 log PFU/g reduction in MuNoV and HAdV titers in both fruits after treatment with a dose of 4 kGy. However, they obtained nonlinear inactivation-survival curves for MuNoV and HAdV in fresh fruits, which led to detection of infective viral particles at a dose of 11 kGy. The irradiation process indicated virucidal potential, although the estimated gamma radiation dose to attain food safety

(>7 kGy) would compromise the preservation of food quality (Pimenta et al., 2019). Applying a 1-kGy irradiation dose to strawberries supported a 4 log CFU reduction of Shiga-toxin-producing *E. coli* levels (Shayanfar, Mena, & Pillai, 2017). Guerreiro et al. (2016) previously had found a 2-log reduction of the microbial load of cherry tomatoes after gamma irradiation at 3.2 kGy followed by 14 days of storage at 4°C.

Irradiation technologies all have differing physical properties but, from a processing point of view, can be differentiated as high-penetration (gamma radiation and X-rays) and low-penetration (electron beam). Another difference is that the e-beam dose rate is about 100 times higher than that of gamma radiation, which results in very short product irradiation exposure (Guerreiro et al., 2016; Lung et al., 2015). Madureira et al. (2019) studied e-beam inactivation of the microbiota of natural cherry tomatoes and of inoculated potential foodborne pathogens (*S. enterica*, *E. coli*, and *L. monocytogenes*) before and after irradiation, and after storage for 14 days at 4°C; they achieved a 4-log reduction of the mesophilic bacterial population and detected no filamentous fungi or foodborne inoculated pathogens after e-beam treatment at 3.6 kGy and storage. Ramakrishnan et al. (2019) studied the effects on quality of grapefruit and lemons, of low e-beam doses (0, 0.4, and 1 kGy) applied directly after irradiation or during exposure to simulated transport and storage conditions for 20 days at 4°C. Overall, a 1-kGy e-beam used for phytosanitation of grapefruit and lemons minimized quality deterioration during storage (Ramakrishnan et al., 2019). In a study by Nam, Ramakrishnan, and Kwon (2019) e-beam irradiation at 0.4 kGy, of mandarins that were stored for 15 days at 4°C, provided microbial decontamination and did not affect the major constituents or physical quality of the fruit.

20.2.12 Electrolyzed water

Slightly acidic electrolyzed water (SAEW) is well recognized as an alternative sanitizer. It has a pH of 5.0–6.5 and contains a high concentration of hypochlorous acid (Zang et al., 2017); it is produced by electrolysis of dilute hydrochloric acid in a chamber without a membrane; and it has become a popular alternative to harsh chemical disinfectants, thanks to its GRAS status and environmentally friendly nature; it was widely used to inactivate or eliminate various foodborne pathogens on foods such as fruits and vegetables (Tango et al., 2017);

SAEW with available chlorine concentrations (ACCs) of 35 and 70 mg/L is used instead of regular production water for soaking pea seeds and spraying the sprouts during seed sprouting. Li et al. (2018a) found that after treatment with SAEW with ACC value of 50 mg/L the number of microorganisms on broccoli sprouts was lower by 1.7 log CFU/g than after tapwater treatment; however, they also found that SAEW adversely affected the morphology of these sprouts. Liang, Wang, Zhao, Han, and Hao (2019) found that treatment with ACC at 10–28 mg/L controlled the growth of natural microbial populations during germination of buckwheat sprouts and decreased *E. coli* 078 and *L. monocytogenes* counts on 8-day-old sprouts by 1.1–2.7 and 1.9–2.5 log CFU/g, respectively. However, too high ACC, at 91.9 mg/L in SAEW, adversely affected the length of those sprouts. Chen et al. (2018) studied the effects of acidic electrolyzed water (AEW) on the microbiological and physicochemical properties of fresh-cut red cabbage and found that the optimal process condition of AEW was ACC at 100 mg/L for 3 min. Under these conditions, most of the native microflora were inactivated, and artificially inoculated *S. typhimurium* DT104 on the red cabbage were reduced by 3.7-log CFU/g, with minimal losses of nutrients and antioxidant activity, and with no requirement for posttreatment decontamination of the wash water.

20.2.13 Combined treatments

Combined treatments involving several compounds or technologies can provide synergistic inhibition or control of microorganism growth and development, without impairing fresh-produce quality. For instance, Park et al. (2018) found that a sequential treatment with ClO_2 gas at 150 ppmv for 1 h and dry heat (80°C) for 5 h caused 4.4- and 4.1-log reduction of *E. coli* O157:H7 and *S. typhimurium*, respectively, in sprouted alfalfa and radish seed production.

Consumption of organic sprouting vegetables has increased dramatically in recent decades because of rising health and safety demands of consumers, and Chen et al. (2019a) found that the sanitizing effects of treating broccoli sprouts with a combination of lactic acid at 2% (v/v) and low-concentration sodium hypochlorite (NaClO) at 4 mg/L inactivated *L. innocua* after 60 s. Furthermore, there were no significant differences in sensory qualities between treatment and control groups; they were all greater than the acceptance limit. Inatsu et al. (2017) found that an NaClO wash at 100 mg/L followed by a second wash with phytic acid or any organic acid at 3 g/L enhanced the sanitation of shredded cabbage and bean sprouts for up to 3 days at 10°C.

Asparagus spears have recently become a popular food among Korean consumers, as indicated by increased domestic consumption (Yoo, Jung, Lee, Choi, & Yun, 2017). However, stored asparagus spears have shown many forms of degradation, such as yellowing, toughness, and soft rot (Yoon et al., 2018). Dipping the spears in hot water at 48°C for 2−4 min combined with MAP were effective in maintaining the asparagus quality while reducing TAB, yeasts, molds, and *E. coli*; however, 8-min dips annulled the beneficial effects of HT (Yoon et al., 2018). Cucumbers have a short postharvest life of less than a week at 10°C, but Maleki, Sedaghat, Woltering, Farhoodi, and Mohebbi (2018) found that coating them with chitosan-limonene in combination with MAP in an atmosphere containing 10% O_2 + 5% CO_2 maintained their quality for 15 days at 10°C. However, this treatment was not desirable under an ambient temperature of 20°C. Waghmare and Annapure (2018) evaluated the effects of irradiation and MAP treatments, alone or in combination, on the quality and shelf life of fresh figs; they found that MAP in (5% O_2 plus 10% CO_2) followed by irradiation doses of 0.5 and 1.0 kGy gave the best improvements in the quality and shelf life of fresh figs up to 15 days at 5°C.

In Brazil, Terao et al. (2018) found that mango treated with HWRB technology at 65°C for 15 s followed by UV-C irradiation at 2.5 kJ/m^2 showed the best control of stem-end rot caused by *Botryosphaeria dothidea* after 18 days of storage.

Purchases of organic food have increased dramatically over recent decades. Zhao, Zhao, Phey, and Yang (2019) evaluated the sanitizing effect of low-concentration AEW containing free available chlorine at 4 mg/L, combined with levulinic acid (LA) at 3% (v/v) on fresh organic lettuce stored for 7 days; the combined sanitizing method showed enhanced bactericidal efficacy against naturally existing microbiota; LA, alone and combined with AEW, effectively reduced surviving inoculated populations of both *E. coli* and *L. innocua* Seeliger on stored lettuce surfaces by 3.5−4.0 log CFU/g, without affecting the lettuce qualities.

In a study conducted by Huang, de Vries, and Chen (2018), a water-assisted UV system (WUV) alone reduced *Salmonella* populations on fresh spinach, lettuce, tomato, blueberry, and carrot by 0.9-, 2.6-, >3.6-, 1.7-, and 2.0-log CFU/g, respectively. For all fresh produce items, WUV combined with peroxyacetic acid (PAA) achieved significantly ($P < .05$) greater *Salmonella* reductions than chlorine wash or PAA wash; the combined treatments kept residual *Salmonella* in wash water below the detection limit of 2 CFU/mL for almost all the replicates. In light of the decontamination efficacy on fresh produce, the ability to disinfect the wash water, and the cost, Huang et al. (2018) recommended chlorine wash for baby spinach, WUV alone for grape tomato, and WUV combined with PAA for iceberg lettuce, blueberry, and baby-cut carrot.

Mukhopadhyay et al. (2019) tested the efficacy of PL at 1−63 J/cm^2 and a 2-min application of a new sanitizer formulation (HEN) comprising hydrogen peroxide (3%), ethylenediaminetetraacetic acid (0.02 mM), and Nisin (20 mg/mL); they also evaluated the synergistic effect of PL and HEN sanitizer (PL-HEN) wash in inactivating *E. coli* O157:H7 on spinach after 13 days of storage at 4°C. The PL-HEN treatment not only significantly reduced spoilage microbial populations but also slowed their growth during storage. Furthermore, the external and internal qualities of the spinach were not significantly affected by this combined treatment. In a different study Huang and Chen (2019) combined two decontamination technologies—PL and UV—with washing, as water-assisted PL (WPL) and WUV and tested the combinations on blueberries, grape tomatoes, and iceberg lettuce shreds. They tested two intensity levels of PL (~0.15 and 0.3 J/cm^2 per pulse; 3 pulses/s) and of UV (~13 and 28 mW/cm^2) for 1 or 2 min. The WPL and WUV treatments reduced *Salmonella* on blueberries, tomatoes, and lettuce shreds by 4.5−5.7, 4.4−5.4, and 1.9−3.1 logs, respectively. For dip-inoculated fresh produce, WPL and WUV treatments reduced *Salmonella* populations on blueberries, tomatoes, and lettuce shreds by 1.8−2.3, 1.9−2.5, and 1.9−2.6 logs, respectively. However, Huang and Chen (2019) concluded that the two systems showed similar decontamination effects on fresh produce, indicating that the UV system could be used to replace the PL system to reduce equipment cost.

Montesinos-Herrero, Moscoso-Ramirez, and Palou (2016) found that 60-s dip treatments with 3% (w/v) sodium benzoate (SB) that was heated above 50°C achieved about 90% reduction of green and blue mold incidence on "Valencia" oranges stored at 20°C and 90% relative humidity for 7 days. This treatment also was effective on "Lanelate" oranges, "Fino" lemons, and "Ortanique" mandarins, but not on "Clemenule" mandarins. Heated solutions that combined SB with low doses (25 or 50 μL/L) of the fungicide IMZ were synergistic and gave much better efficacy than stand-alone treatments. On "Valencia" oranges stored for 8 weeks at 5°C followed by 7 days of shelf life at 20°C, this combination reduced the incidence of green and blue molds by almost 100%. A combined treatment consisting of 60-s dips in 3% potassium sorbate heated to 62°C followed by 48-h exposure at 33°C to air containing CO_2 at 15 kPa or O_2 at 30 kPa was found to be synergistic in very effectively controlling citrus postharvest *Penicillium digitatum* and *Penicillium italicum* after 45 days at

5°C (Montesinos-Herrero & Palou, 2016). Sour rot, caused by *Geotrichum citri-aurantii*, inflicted destructive postharvest loss on citrus in recent years, especially during wet and rainy seasons (Duan, Ouyang, Jing, & Tao, 2016). A combination of the known food preservatives with antifungal activities—sodium dehydroacetate and sodium silicate (Na_2SiO_3) at 3.6 g/L—was synergistic in controlling sour rot in Satsuma mandarin during 8 days of storage at 25°C (Li, Tang, Ouyand, & Tao, 2019). NaOCl at 200 mg/L and the fungicide IMZ at 50 mg/L, both at 50°C for 3 min, was as effective as IMZ at 1000 mg/L and 20°C in controlling *Penicillium* decay in individually film-wrapped lemons stored at 20°C (D'Aquino et al., 2017).

Tango et al. (2017) evaluated sequential combinations of SAEW with chemical and physical treatments such as ultrasonication (US), for bacterial decontamination of fruits. A combination of SAEW with sanitizers comprising calcium oxide and fumaric acid, and mechanical force (US) showed potential for postharvest sanitation processing in the fresh fruit industry.

Karagoz and Demirdoven (2019) showed that coating fresh-cut apples with a film mixture of 0.75% chitosan and with stevia extract (2.5%) significantly reduced the microbial load while preserving apple slices after 3 days at 1°C. Kang and Kang (2019) tested a newly designed combined system that comprised the Spindle and a 222-nm KrCl excilamp (Sp-Ex) against *E. coli* O157:H7, *S. enterica* serovar Typhimurium, and *L. monocytogenes*. They reported that *E. coli* O157:H7 and *S. typhimurium* were reduced below the detection limit of 2.0 log CFU/sample) after 5 and 7 min of treatment on apple and bell-pepper surfaces, respectively, and the amounts of *L. monocytogenes* on apple and bell-pepper surfaces were reduced by 4.26 and 5.48 logs, respectively, after 7 min of treatment. Fruit quality was not impaired by the treatment (Kang & Kang, 2019).

Hwang, Huang, and Wu (2017) inoculated the surfaces of cantaloupe rinds, cucumber peels, grape tomato stem scars, and baby spinach leaves with *Salmonella* or *L. monocytogenes* at 5−6 log CFU/g, submerged them in sodium chlorite solutions at 1.6%−4% for 10 or 30 min, dried them for 20 min, and then soaked them in 6 mM HCl for 10 or 30 min. This sequential treatment caused a reduction of 5.1−5.6 log CFU/g of the inoculated microorganisms.

20.3 Detection

Food safety is a global health concern, and FBD could cause a major health crisis. Therefore detection of foodborne pathogenic microorganisms is an important consideration in ensuring food safety and public health.

Conventional culture-based methods are considered as the "gold standard" for identification of foodborne pathogens. However, these methods require multiple steps, including preenrichment, selective culturing, and isolation on selective media, followed by biochemical and serological confirmatory analysis. These steps are labor intensive and time consuming, so that 4−7 days typically are required to confirm a positive result (Margot, Stephan, O'Mahony, & Iversen, 2013).

Polymerase chain reaction (PCR)-based methods are used in detection of a wide range of pathogens. These methods can detect a single copy of a target DNA sequence and, therefore, can be used to detect a single pathogenic bacterium in food. This technology is promising because it detects the organism by amplifying the target rather than the signal and is, therefore, less prone to producing false positives. A target DNA can be amplified 1-million-fold in less than an hour, with theoretical sensitivities down to a single-target pathogen (Jiang et al., 2018). However, PCR-based diagnostic procedures have several intrinsic shortcomings—such as the requirements for specialized laboratories, complicated equipment, expensive reagents, and trained personnel—which limit their use in resource-poor regions or for point-of-care testing (Martzy et al., 2017). Jiang et al. (2018) considered the real-time fluorescence quantitative PCR method a useful tool for detecting norovirus (NoV) in contaminated foods; it has high sensitivity and specificity. Gao et al. (2019) evaluated NoV contamination in commercially fresh/frozen berry fruits by using a TaqMan-based real-time reverse transcription-PCR assay that yielded very accurate results; their findings showed that NoV contamination was significantly higher in domestic berries than in exported ones, and that NoV was more often detected in fresh than in frozen berries.

de Oliveira, Soccol, and Rogez (2019) developed a method for preventing FBD caused by *Trypanosoma cruzi* in the Amazon region. It uses reverse transcription PCR amplification for messenger RNA-based detection of viable *T. cruzi* in açai and could play a role in examining food samples and thereby ensuring consumer health and reducing this FBD.

Mei et al. (2019) developed a novel visual loop-mediated isothermal amplification method with a lateral-flow dipstick (LFD) that targets the *Salmonella hilA* gene; the method they established is rapid, sensitive, reliable, and easily applied for *Salmonella* diagnosis. A 30-min amplification step followed by 5 min of hybridization at a constant temperature and a 5-min LFD step were sufficient to enable visual detection, and no sophisticated technical personnel or special equipment are required.

Jagadeesan et al. (2019) recently reviewed the use and potential of next-generation sequencing (NGS) in detection of foodborne pathogens. This technology has two predominant uses: (1) determination of the whole genome sequence of a single-cultured pathogen and (2) "metagenomics," in which NGS is applied to a biological sample to generate sequences of multiple microorganisms in the sample (Jagadeesan et al., 2019). These tools can improve understanding of the microbial ecology of food processing lines.

One of the main concerns associated with chlorine-based disinfectants relates to interactions of chlorine with organic matter that generate disinfection by-products (DBPs) that present potential health hazards. At the same time, the reactions that lead to DBP formation consume disinfectants and lower their pathogen-inactivating efficacy, thereby increasing the likelihood of microbial contamination in the food products. To date, the limited reports on DBPs in food mostly address trihalomethanes and haloacetic acids; however, other types of DBPs, including nitrogenous DBPs, nitrosamines, other carbonaceous DBPs, and aldehydes, also may be generated (Fan & Sokorai, 2015; Shen, Norris, Williams, Hagan, & Li, 2016).

Hyperspectral imaging (HSI) and electronic nose (e-nose) are two emerging techniques that can be applied for rapid, nondestructive, and effective decay detection (Wilson, 2017). Liu et al. (2019) evaluated a technology that combines HSI and e-nose to rapidly detect microbial content and quality attributes of decaying strawberries; the best prediction model was able to predict colony-forming units with 0.925 Rp^2 (root mean square) and a root mean square error of prediction of 0.38 $\log_{10}$ (CFU/g). They concluded that the combination of the two sensing techniques could potentially be implemented to monitor safety and quality of fresh produce (Liu et al., 2019).

20.4 Future perspective

Disinfection of fresh produce and storage facilities is generally a prerequisite for postharvest spoilage control. Food preservation techniques should meet any specific requirements that arise from the nature of the stored produce and its designated use. Such requirements may include prolonged shelf life of perishable products, maintenance of the safety status of individual items by inactivation of pathogenic viruses, bacteria, and spoilage fungi. Additionally, the organoleptic and nutritional properties of the products should not be changed, and the formation of process-induced contaminants should be avoided. Nevertheless, the preservation technique should be inexpensive and convenient to apply and should not elicit concerns among legislators and consumers (Schottroff et al., 2018). Ensuring food safety should be treated with priority because of its significant implications for consumer well-being and commercial success; furthermore, addressing food safety will help to maintain and improve domestic and international trade and thereby boost economic development (Olanya et al., 2019).

Training of food handlers is a key step towards ensuring food safety and it has been widely addressed internationally; however, it is recognized that it is often difficult to quantify the effectiveness of this training, because of the lack of clear evaluation criteria. The government departments responsible for public health should ensure that any necessary educational materials, in the various appropriate formats, are readily available and accessible to the general public as well as to food handlers (Boatemaa et al., 2019). Food retailers and the relevant government departments must find new and effective ways to educate food handlers and consumers on how to protect themselves and others from preventable outbreaks of FBD and from individual infections. Consumers also must act to protect their own health by learning proper ways to handle, store, and cook food (Boatemaa et al., 2019). Mandatory training is necessary because of the rapid proliferation of small and medium-sized restaurants and the consequently increasing need for trained food handlers to staff these establishments. The training not only should focus on theoretical aspects but also should be practical; fostering positive attitudes towards food-safety practices and participation in an established food-safety culture. The support and positive reinforcement and motivation imparted to food handlers by supervisors, managers, and trainers are extremely important to the success of food safety training (Al-Kandari, Al-Abdeen, & Sidhu, 2019).

Industrial relevance—the washing step of fresh-produce processing lines is critical. The dosage of disinfectants needs to be adequately optimized to avoid microbial contamination without accumulating DBPs. Critical parameters that influence the efficacy of water disinfection and the occurrence of DBPs in fresh-produce processing lines were identified under commercial conditions: monitoring and control of pH were shown to be critical in optimizing the concentration of the most active form of chlorine in the water.

Migliori, Salvati, Di Cesare, Scalzo, and Parisi (2017) reported on the need for improved investigation of preharvest uses of natural antimicrobial products. Development of more efficacious decontamination treatments, alone or in combination with other treatments, should focus on currently used and newly introduced chemicals and techniques that would preserve external and internal quality parameters, as well as nutritional, organoleptic, and esthetic attributes of fresh or fresh-cut products. Moreover, it is important to remember that microbial contamination from fields or other sources can become established on the surfaces of tools and equipment and thereby, directly or indirectly, contaminate produce that touches contaminated surfaces. Furthermore, the invasion of products by organisms that subsequently localize into the inner parts, interactions between the microbial cells and food-contacting surfaces, and development of biofilms could impair the antimicrobial activity of the currently used approaches (Yoon & Lee, 2019). Therefore "a low tech" practice of regularly cleaning and sanitizing the surfaces of tools and equipment that contact produce—whether in small or large quantities—must become a key element of food safety standards (Newman et al., 2017), because Tatsika, Karamanoli, Karayanni, and Genitsaris (2019) reported that the usually applied domestic washing methods proved to be inefficient in removing such contamination.

There is no disinfectant that is absolutely better than all others. The capability to control spoilage development in fresh produce or processed products after harvest and during prolonged storage depends on many factors, including the nature of the fresh produce, whether we are dealing with organic or conventional agriculture, storage duration, characteristics of the postharvest facilities, possible integration of the disinfection operations with other technologies, and the capabilities of the operating staff (Feliziani et al., 2016). The newest technologies qualify under all these categories, in addition to being nontoxic to humans, and to preserving the nutritional value and organoleptic quality of fresh and fresh-cut produce (Table 20.1).

TABLE 20.1 Summary of the most important phytosanitary treatments for fresh and fresh-cut fruits and vegetables.

Source of decontamination/ technology	Produce/ product	Microorganism/other materials	Treatment (washed, unless otherwise mentioned)	References
Chlorine and derivatives	Carrot	*Escherichia coli*, *Pseudomonas*	50 mg/L	Dharmarha et al. (2019)
	Lettuce and cabbage	Aerobic bacteria	20–25 mg/L	Tudela et al. (2019)
	Onion	Aerobic bacteria		Tudela et al. (2019)
	Tomato	Pesticides	2 mg/L for 5 min	Heshmati and Nazemi (2017)
Hydrogen peroxide	Lettuce	*E. coli*, *Salmonella*, *Listeria*	10%	Back et al. (2014)
	Disinfecting rooms (mist)	*Listeria*	5%	Moretro et al. (2019)
Ozone	Spinach leaves (gaseous)	*E. coli*	1.5 g/L for 30 min	Yesil et al. (2017)

(*Continued*)

TABLE 20.1 (Continued)

Source of decontamination/ technology	Produce/ product	Microorganism/other materials	Treatment (washed, unless otherwise mentioned)	References
	Fuji apple	*Listeria*	50–87 ppb	Sheng et al. (2018)
	Tomato	*Salmonella*	6.85 ppm for 2–4 h	Wang et al. (2019)
	Fruits and vegetables	Herbicide/fungicide	5 ppm (gas)	Heshmati and Nazemi (2017)
Organic acids	Sweet cherry—acetic acid (vapor)	Bacteria and molds	3 mg/L	Hassenberg et al. (2018)
	Cherry tomato—sodium benzoate	*E. coli*, *Salmonella*, *Listeria*	3000 ppm	Chen et al. (2019b)
	Strawberry—peracetic acid	*Listeria*	40–80 ppm for 2 min	Nicolau-Lapena et al. (2019)
Chlorine dioxide	Spinach, tomato	*E. coli*, *Salmonella*, *Listeria*	0.05–0.08 mg/L for 20–30 min	Park and Kang (2018)
	Tomato, carrot	*E. coli*, *Salmonella*, *Listeria*	0.15 mg for 5 h	Bridges et al. (2018)
MAP	Grapes, soybean sprouts, lotus roots	*E. coli*, yeast/mold	1005 CO_2 (active MAP)	Hyun and Lee (2018)
Essential oil	Fresh cilantro	Mold	Carvacrol:peppermint (vapor at 8 mg/L)	López-Gómez et al. (2019)
Cold plasma	Berry fruits, fresh cut lettuce, baby kale	*E. coli*, *Salmonella*	5–30 min exposure	Bovi et al. (2019); Dong and Yang (2019); Shah et al. (2019)
UV-C	Fresh pistachio	Total counts	UV-C at 2.1 kJ/m^2 packed in PET	Hosseini et al. (2019)
	Strawberry	Coliforms and yeasts	UV-C for 7.5 min	Oviedo et al. (2018)
	Pineapple		UV-C at 39.6 kJ/m^2 for 30 min	Sari et al. (2016)
PL	Blueberry	*Salmonella*	9 J/cm^2	Cao et al. (2017)
	Meat, fruits, vegetables	*Salmonella*, *Listeria*, *Bacillus*, and *E. coli*	0.05–3.0 J/cm^2	Holck et al. (2018)
Heat treatments	Fresh-cut guava	Coliforms counts, lactic acid bacteria	50°C for 10 and 30 min (dips)	Poubol et al. (2018)

(*Continued*)

TABLE 20.1 (Continued)

Source of decontamination/ technology	Produce/ product	Microorganism/other materials	Treatment (washed, unless otherwise mentioned)	References
	Acorn squash	Total fungi	54°C—15 s (HWRB)	Chalupowicz et al. (2018)
	Calçots (floral stem)	Aerobic mesophilic bacteria	55°C—1 min (dips)	Zudaire et al. (2018)
	Apple	Natural microflora	55°C—0.5–2 min (dips)	Kabelitz and Hassenberg (2018)
	Fresh-cut cantaloupe	*Salmonella*	76.1°C—3 min (dips)	Alicea et al. (2018)
	Lotus root	Total counts	40°C–60°C—30 min (dips)	Li et al. (2018b)
	Peas, spinach, broccoli, potatoes, and carrots	*Listeria*, *Salmonella*	85°C–87.8°C—0.5 min96.7°C—1 min (steam)	Ceylan et al. (2017)
	Cherry tomato, orange	*E. coli*, *Salmonella*, *Listeria*	200°C—3 or 20 s (superheated steam)	Ban and Kang (2018)
	Apple	*Botrytis cinerea*, *Penicillium expansum*, and *Colletotrichum gloeosporioides*	38°C—4 d + *Pichia guilliermondii*	Zhao and Yin (2018)
Irradiation	Strawberry	*E. coli*	1 kGy	Shayanfar et al. (2017)
	Fruit berries	*Norovirus* and *Adenovirus*	4 kGy	Pimenta et al. (2019)
	Cherry tomato	*E. coli*, *Salmonella*, *Listeria*	3.6 kGy (E-beam)	Madureira et al. (2019)
	Grapefruit	Overall quality	1 kGy	Ramakrishnan et al. (2019)
Electrolyzed water	Broccoli sprouts	Total counts	50 mg/L	Li et al. (2018a)
	Buckwheat sprouts	*Listeria*	10–28 mg/L	Liang et al. (2019)
	Fresh-cut red cabbage	*Salmonella*	100 mg/l—3 min	Chen et al. (2018)
Combined treatments	Sprouts	*E. coli*, *Salmonella*	ClO_2 (gas) + dry heat (80°C)	Park et al. (2018)
	Sprouts, shredded fresh-cut	*Listeria*	NaClO + organic acids	Chen et al. (2019b); Inatsu et al. (2017)

(*Continued*)

TABLE 20.1 (Continued)

Source of decontamination/technology	Produce/product	Microorganism/other materials	Treatment (washed, unless otherwise mentioned)	References
	Asparagus	Aerobic bacteria, yeast, mold	48°C—2–4 min + MAP	Yoon et al. (2018)
	Fig	Total counts	Irradiation + MAP	Waghmare and Annapure (2018)
	Mango	*Botryosphaeria*	65°C—15 s (HWRB) + UV-C	Terao et al. (2018)
	Fruits and vegetables	*Salmonella*	WUV + Peroxyacetic acid	Huang et al. (2018)
	Fruits, vegetables, and fresh-cut	*Salmonella*	PL + WUV	Huang and Chen (2019)
	Citrus fruits	*Penicillium*	Hot (50°C) sodium benzoate (3%) for 1 min + fungicide	Montesinos-Herrero et al. (2016)
	Fresh fruits	Total counts	Acidic electrolyzed water + calcium oxide + fumaric acid + ultrasonication	Tango et al. (2017)
	Apple and pepper	*E. coli*, *Salmonella*, *Listeria*	Spindle + 222 nm KrCl excilamp for 5–7 min	Karagoz and Demirdoven (2019)
	Fruits and vegetables	*Salmonella*, *Listeria*	Sequential treatment of 1.6%–4% NaClO for 10–30 min and then 6 mM hydrogen chloride for 10–30 min	Hwang et al. (2017)

HWRB, Hot water rinsing and brushing; *MAP*, modified atmosphere packaging; *PET*, polyethylene terephthalate; *PL*, pulsed light; *UV*, ultra violet; *WUV*, water-assisted UV.

References

Ali, A., Yeoh, W. K., Forney, C., & Siddiqui, M. W. (2018). Advances in postharvest technologies to extend the storage life of minimally processed fruits and vegetables. *Critical Reviews in Food Science and Nutrition*, *58*, 2632–2649.

Alicea, C., Annous, B. A., Mendez, D. P., Burke, A., & Orellana, L. E. (2018). Evaluation of hot water, gaseous chlorine dioxide, and chlorine treatments in combination with an edible coating for enhancing safety, quality, and shelf life of fresh-cut cantaloupes. *Journal of Food Protection*, *81*, 534–541.

Al-Kandari, D., Al-Abdeen, J., & Sidhu, J. (2019). Food safety knowledge, attitudes and practices of food handlers in restaurants in Kuwait. *Food Control*, *103*, 103–110.

Alsawmahi, O. N., Al-Juhaimi, F. Y., Alhamdan, A. M., Ghafoor, K., Mohamed Ahmed, I. A., Hassan, B. H., . . . Adiamo, O. Q. (2018). Enzyme activity, sugar composition, microbial growth and texture of fresh Barhi dates as affected by modified atmosphere packaging. *Journal of Food Science and Technology*, *55*, 4492–4504.

Astill, G., Minor, T., & Thornsbury, S. (2019). Changes in U.S. produce grower food safety practices from 1999 to 2016. *Food Control*, *104*, 326–332.

Atidegla, S. C., Huat, J., Agbossou, E. K., Saint-Macary, H., & Kakai, R. G. (2016). Vegetable contamination by the fecal bacteria of poultry manure: Case study of gardening sites in Southern Benin. *International Journal of Food Science*, *2016*, 1–8.

Back, K. H., Ha, J. W., & Kang, D. H. (2014). Effect of hydrogen peroxide vapor treatment for inactivating *Salmonella typhimurium*, *Escherichia coli* O157:H7 and *Listeria monocytogenes* on organic fresh lettuce. *Food Control*, *44*, 78–85.

Ban, G. H., & Kang, D. H. (2018). Inactivation of *Escherichia coli* O157:H7, *Salmonella typhimurium*, and *Listeria monocytogenes* on cherry tomatoes and oranges by superheated steam. *Food Research International*, *112*, 38–47.

Bhilwadikar, T., Pounraj, S., Manivannan, S., Rastogi, N. M., & Negi, P. S. (2019). Decontamination of microorganisms and pesticides from fresh fruits and vegetables: A comprehensive review from common household processes to modern techniques. *Comprehensive Reviews in Food Science and Food Safety*, *18*, 1003–1038.

Boatemaa, S., Barney, M., Drimie, S., Harper, J., Korsten, L., & Pereira, L. (2019). Awakening from the listeriosis crisis: Food safety challenges, practices and governance in the food retail sector in South Africa. *Food Control*, *104*, 333–342.

Bourke, P., Ziuzina, D., Han, L., Cullen, P. J., & Gilmore, B. F. (2017). Microbiological interactions with cold plasma. *Journal of Applied Microbiology*, *123*, 308–324.

Bovi, G. G., Frohling, A., Pathak, N., Vladramidis, V. P., & Schluter, O. (2019). Safety control of whole berries by cold atmospheric pressure plasma processing: A review. *Journal of Food Protection*, *82*, 1233–1243.

Bridges, D. F., Rane, B., & Wu, V. C. H. (2018). The effectiveness of closed-circulation gaseous chlorine dioxide or ozone treatment against bacterial pathogens on produce. *Food Control*, *91*, 262–267.

Cao, X., Huang, R., & Chen, H. (2017). Evaluation of pulsed light treatments on inactivation of Salmonella on blueberries and its impact on shelf-life and quality attributes. *International Journal of Food Microbiology*, *260*, 17–26.

Ceylan, E., McMahon, W., & Garren, D. M. (2017). Thermal inactivation of *Listeria monocytogenes* and *Salmonella* during water and steam blanching of vegetables. *Journal of Food Protection*, *80*, 1550–1556.

Chalupowicz, D., Alkalai-Tuvia, S., Zaaroor-Presman, M., & Fallik, E. (2018). The potential use of hot water rinsing and brushing technology to extend storability and shelf life of sweet acorn squash (*Cucurbita pepo* L.). *Horticulturae*, *4*(19). Available from https://doi.org/10.3390/horticulturae4030019.

Chen, X., Xue, S. J., Shi, J., Kostrzynska, M., Tang, J. S., Guevremont, E., . . . Mondor, M. (2018). Red cabbage washing with acidic electrolysed water: Effects on microbial quality and physicochemical properties. *Food Quality and Safety*, *2*, 229–237.

Chen, L., Zhang, H., Liu, Q., Pang, X., Zhao, X., & Yang, H. (2019a). Sanitizing efficacy of lactic acid combined with low-concentration sodium hypochlorite on *Listeria innocua* in organic broccoli sprouts. *International Journal of Food Microbiology*, *295*, 41–48.

Chen, H., Zhang, Y., & Zhong, Q. (2019b). Potential of acidified sodium benzoate as an alternative wash solution of cherry tomatoes: Changes of quality, background microbes, and inoculated pathogens during storage at 4 and 21°C post-washing. *Food Microbiology*, *82*, 111–118.

Cook, N., Knight, A., & Richards, G. P. (2016). Persistence and elimination of human norovirus in food and on food contact surfaces: A critical review. *Journal of Food Protection*, *79*, 1273–1294.

D'Aquino, S., Dai, S., Deng, Z., Gentile, A., Angioni, A., De Pau, L., & Palma, A. (2017). A sequential treatment with sodium hypochlorite and a reduced dose of imazalil heated at 50°C effectively control decay of individually film-wrapped lemons stored at 20°C. *Postharvest Biology and Technology*, *124*, 75–84.

de Oliveira, A. C., Soccol, V. T., & Rogez, H. (2019). Disinfection, heat treatment and quality control by RT-PCR. *International Journal of Food Microbiology*, *301*, 34–40.

de Souza, L. P., Faroni, L. R. D. A., Heleno, F. F., Pinto, F. G., de Queiroz, M. E. L. R., & Prates, L. H. F. (2018). Ozone treatment for pesticide removal from carrots: Optimization by response surface methodology. *Food Chemistry*, *243*, 435–441.

Decol, L. T., Casarin, L. S., Hessel, C. T., Batista, A. C. F., Allende, A., & Tondo, E. C. (2017). Microbial quality of irrigation water used in leafy green production in Southern Brazil and its relationship with produce safety. *Food Microbiology*, *65*, 105–113.

den Besten, H. M. W., Wells-Bennik, M. H. J., & Zwietering, M. H. Z. (2018). Natural diversity in heat resistance of bacteria and bacterial spores: Impact on food safety and quality. *Annual Review of Food Science and Technology*, *9*, 383–410.

Dharmarha, V., Pulido, N., Boyer, R. R., Pruden, A., Strawn, L. K., & Ponder, M. A. (2019). Effect of post-harvest interventions on surficial carrot bacterial community dynamics, pathogen survival, and antibiotic resistance. *International Journal of Food Microbiology*, *291*, 25–34.

Diao, E., Li, X., Zhang, Z., Ma, W., Ji, N., & Dong, H. (2015). Ultraviolet irradiation detoxification of aflatoxins. *Trends in Food Science and Technology*, *42*, 64–69.

Diep, B., Moulin, J., Bastic-Schmid, V., Putallaz, T., Gimonet, J., Valles, A. D., & Klijn, A. (2019). Validation protocol for commercial sterility testing methods. *Food Control*, *103*, 1–8.

Dong, X. Y., & Yang, Y. L. (2019). A novel approach to enhance blueberry quality during storage using cold plasma at atmospheric air pressure. *Food and Bioprocess Technology*, *12*, 1409–1421.

Donglu, F., Wenjian, Y., Kimatu, B. M., Mariga, A. M., Liyan, Z., Xinxin, A., & Qiuhui, H. (2016). Effect of nanocomposite-based packaging on storage stability of mushrooms (*Flammulina velutipes*). *Innovative Food Science and Emerging Technologies*, *33*, 489–497.

Duan, X. F., Ouyang, Q. L., Jing, G. X., & Tao, N. G. (2016). Effect of sodium dehydroacetate on the development of sour rot on Satsuma mandarin. *Food Control*, *65*, 8–13.

Fan, X., & Sokorai, K. J. (2015). Formation of trichloromethane in chlorinated water and fresh-cut produce and as a result of reaction with citric acid. *Postharvest Biology and Technology*, *109*, 65–72.

Feliziani, E., Lichter, A., Smilanick, J. L., & Ippolito, A. (2016). Disinfecting agents for controlling fruit and vegetable diseases after harvest. *Postharvest Biology and Technology*, *122*, 53–59.

Formica-Oliveira, A. C., Martínez-Hernández, G. B., Díaz-López, V., Artés, F., & Artés-Hernández, F. (2017). Effects of UV-B and UV-C combination on phenolic compounds biosynthesis in fresh-cut carrots. *Postharvest Biology and Technology*, *127*, 99–104.

Gabric, D., Barba, F., Roohinejad, S., Gharibzahedi, S. T. M., Radojcin, M., Putnik, P., & Kovačević, D. B. (2018). Pulsed electric fields as an alternative to thermal processing for preservation of nutritive and physicochemical properties of beverages: A review. *Journal of Food Process Engineering*, *41*. Available from https://doi.org/10.1111/jfpe.12638.

Gabriel, A. A., Tongco, A. M. P., & Barnes, A. A., Jr. (2017). Utility of UV-C radiation as anti-salmonella decontamination treatment for desiccated coconut flakes. *Food Control*, *71*, 117–123.

Gao, X., Wang, Z., Wang, Y., Liu, Z., Guan, X., Ma, Y., ... Xu, Y. (2019). Surveillance of norovirus contamination in commercial fresh/frozen berries from Heilongjiang Province, China, using a TaqMan real-time RT-PCR assay. *Food Microbiology*, *82*, 119–126.

Garrido, Y., Marin, A., Tudela, J. A., Allende, A., & Gil, M. I. (2019). Chlorate uptake during washing is influenced by product type and cut piece size, as well as washing time and wash water content. *Postharvest Biology and Technology*, *151*, 45–52.

Garvey, M., & Rowan, N. J. (2019). Pulsed UV as a potential surface sanitizer in food production processes to ensure consumer safety. *Current Opinion in Food Science*, *26*, 65–70.

Gomez, B., Munekata, P. E. S., Gavahian, M., Barba, F. J., Marti-Quijal, F. J., Bolumar, T., Campagnol, P. C. B., Tomasevic, I., & Lorenzo, J. M. (2019). Application of pulsed electric fields in meat and fish processing industries: An overview. *Food Research International*, *123*, 95–105.

Guerreiro, D., Madureira, J., Silva, T., Melo, R., Santos, P. M. P., Ferreira, A., & Cabo Verde, S. (2016). Post-harvest treatment of cherry tomatoes by gamma radiation: Microbial and physicochemical parameters evaluation. *Innovative Food Science and Emerging Technologies*, *36*, 1–9.

Hassenberg, K., Schuhmann, F., Ulrichs, C., Herppich, W. B., & Huyskens-Keil, S. (2018). Effects of acetic acid vapour on the microbial status of 'Merchant' and 'Oktavia' sweet cherries (*Prunus avium* L.). *Food Control*, *90*, 422–428.

Heshmati, A., & Nazemi, F. (2017). Dichlorvos (DDVP) residue removal from tomato by washing with tap and ozone water, a commercial detergent solution and ultrasonic cleaner. *Food Science and Technology, Campinas*, *38*, 441–446.

Holck, A. L., Liland, K. H., Dromtorp, S. M., Carlehog, M., & McLeod, A. (2018). Comparison of UV-C and pulsed UV light treatments for reduction of *Salmonella*, *Listeria monocytogenes*, and Enterohemorrhagic *Escherichia coli* on eggs. *Journal of Food Protection*, *81*, 6–16.

Hosseini, F. S., Akhavan, H. R., Maghsoudi, H., Hajumohammadi-Farimani, R., & Balvardi, M. (2019). Effects of rotational UV-C irradiation system and packaging on shelf life of fresh pistachio. *Journal of the Science of Food and Agriculture*, *99*, 5229–5238.

Huang, R., & Chen, H. (2019). Comparison of water-assisted decontamination systems of pulsed light and ultraviolet for *Salmonella* inactivation on blueberry, tomato, and lettuce. *Journal of Food Science*, *84*, 1145–1150.

Huang, R., de Vries, D., & Chen, H. (2018). Strategies to enhance fresh produce decontamination using combined treatments of ultraviolet, washing and disinfectants. *International Journal of Food Microbiology*, *283*, 37–44.

Hwang, C. A., Huang, L., & Wu, V. C. H. (2017). In situ generation of chlorine dioxide for surface decontamination of produce. *Journal of Food Protection*, *80*, 567–572.

Hyun, J. E., & Lee, S. Y. (2018). Effect of modified atmosphere packaging on preserving various types of fresh produce. *Journal of Food Safety*, *38*. Available from https://doi.org/10.1111/jfs.12376.

Inatsu, Y., Weerakkody, K., Bari, M. L., Hosotani, Y., Nakamura, N., & Kawasaki, S. (2017). The efficacy of combined (NaClO and organic acids) washing treatments in controlling *Escherichia coli* O157: H7, Listeria monocytogenes and spoilage bacteria on shredded cabbage and bean sprout. *LWT – Food Science and Technology*, *85*, 1–8.

Jagadeesan, B., Gerner-Smidt, P., Allard, M. W., Leuillet, S., Winkler, A., Xiao, Y., ... Grant, K. (2019). The use of next generation sequencing for improving food safety: Translation into practice. *Food Microbiology*, *79*, 96–115.

Jiang, T., Han, C., Seamus, F., Li, N., Wang, J., Zhang, H., ... Li, F. (2018). Norovirus contamination in retail oysters from Beijing and Qingdao, China. *Food Control*, *86*, 415–419.

Jiang, Y., Sokorai, K., Pyrgiotakis, G., Demokritou, P., Li, X., Mukhopadhyay, S., ... Fan, X. (2017). Cold plasma-activated hydrogen peroxide aerosol inactivates *Escherichia coli* O157:H7, *Salmonella typhimurium*, and *Listeria innocua* and maintains quality of grape tomato, spinach and cantaloupe. *International Journal of Food Microbiology*, *249*, 53–60.

Jung, Y. J., Jang, H., & Matthews, K. R. (2014). Effect of the food production chain from farm practices to vegetable processing on outbreak incidence. *Microbial Biotechnology*, *7*, 517–527.

Kabelitz, T., & Hassenberg, K. (2018). Control of apple surface microflora for fresh-cut produce by post-harvest hot-water treatment. *LWT – Food Science and Technology*, *98*, 492–499.

Kabelitz, T., Schmidt, B., Herppich, W. B., & Hassenberg, K. (2019). Effects of hot water dipping on apple heat transfer and postharvest fruit quality. *LWT – Food Science and Technology*, *108*, 416–420.

Kang, J. W., & Kang, D. H. (2019). Decontamination effect of the spindle and 222-nanometer krypton-chlorine excimer lamp combination against pathogens on apples (*Malus domestica* Borkh.) and bell peppers (*Capsicum annuum* L.). *Applied Environmental Microbiology*, *85*, e00006–e00019. Available from https://doi.org/10.1128/AEM.00006-19.

Karagoz, S., & Demirdoven, A. (2019). Effect of chitosan coatings with and without *Stevia rebaudiana* and modified atmosphere packaging on quality of cold stored fresh-cut apples. *LWT – Food Science and Technology*, *108*, 332–337.

Kingsley, D. H., Perez-Perez, R. E., Niemira, B. A., & Fan, X. (2018). Evaluation of gaseous chlorine dioxide for the inactivation of Tulane virus on blueberries. *International Journal of Food Microbiology*, *273*, 28–32.

Kurpas, M., & Wieczorek, K. (2018). Ready-to-eat meat products as a source of *Listeria monocytogenes*. *Journal of Veterinary Research*, *62*, 49–55.

Le Toquin, E., Faure, S., Orange, N., & Gas, F. (2018). New biocide foam containing hydrogen peroxide for the decontamination of vertical surface contaminated with *Bacillus thuringiensis* spores. *Frontiers in Microbiology*, *27*. Available from https://doi.org/10.3389/fmicb.2018.02295.

Li, L., Hao, J., Song, S., Nirasawa, S., Jiang, Z., & Liu, H. (2018a). Effect of slightly acidic electrolyzed water on bioactive compounds and morphology of broccoli sprouts. *Food Research International*, *105*, 102–109.

Li, S., Li, X., He, X., Liu, Z., Yi, Y., Wang, H., & Lamikanra, O. (2018b). Effect of mild heat treatment on shelf life of fresh lotus root. *LWT – Food Science and Technology*, *90*, 83–89.

Li, L., Tang, X., Ouyand, Q., & Tao, N. (2019). Combination of sodium dehydroacetate and sodium silicate reduces sour rot of citrus fruit. *Postharvest Biology and Technology*, *151*, 19–25.

Liang, D., Wang, Q. F., Zhao, D. D., Han, X., & Hao, J. X. (2019). Systematic, application of slightly acidic electrolyzed water (SAEW) for natural microbial reduction of buckwheat sprouts. *LWT – Food Science and Technology*, *108*, 14–20.

Liu, Q., Sun, K., Zhao, N., Yang, J., Zhang, Y., Ma, C., ... Tu, K. (2019). Information fusion of hyperspectral imaging and electronic nose for evaluation of fungal contamination in strawberries during decay. *Postharvest Biology and Technology*, *153*, 152–160.

López-Gómez, A., Ros-Chumillas, M., Antolinos, V., Buendía-Moreno, L., Navarro-Segura, L., Sánchez-Martínez, M. J., ... Soto-Jover, S. (2019). Fresh culinary herbs decontamination with essential oil vapours applied under vacuum conditions. *Postharvest Biology and Technology*, *156*. Available from https://doi.org/10.1016/j.postharvbio.2019.110942.

Lozowicka, B., & Jankowska, M. (2016). Comparison of the effects of water and thermal processing on pesticide removal in selected fruit and vegetables. *Journal of Elementology*, *21*, 99–111.

Lung, H. M., Cheng, Y. C., Chang, Y. H., Huang, H. W., Yang, B. B., & Wang, C. Y. (2015). Microbial decontamination of food by electron beam irradiation. *Trends in Food Science and Technology*, *44*, 66−78.

Madureira, J., Severion, A., Cojocaru, M., Garofalide, S., Santons, P. M. P., Carolino, M. M., . . . Cabo Verde, S. (2019). E-beam treatment to guarantee the safety and quality of cherry tomatoes. *Innovative Food Science and Emerging Technologies*, *55*, 57−65.

Maffei, D. F., Moreira, D. A., Silva, M. B. R., Faria, D. B., Saldana, E., Ishimura, I., . . . Franco, B. D. G. M. (2019). Assessing the relationship between organic farming practices and microbiological characteristics of organic lettuce varieties (*Lactuca sativa* L.) grown in Sao Paulo, Brazil. *Journal of Applied Microbiology*, *127*, 237−247.

Maleki, G., Sedaghat, N., Woltering, E. J., Farhoodi, M., & Mohebbi, M. (2018). Chitosan-limonene coating in combination with modified atmosphere packaging preserve postharvest quality of cucumber during storage. *Journal of Food Measurement and Characterization*, *12*, 1610−1621.

Mannozzi, C., Fauster, T., Haas, K., Tylewicz, U., Romani, S., Dalla Rosa, M., & Jaeger, H. (2018). Role of thermal and electric field effects during the pre-treatment of fruit and vegetable mash by pulsed electric fields (PEF) and ohmic heating (OH). *Innovative Food Science and Emerging Technologies*, *48*, 131−137.

Margot, H., Stephan, R., O'Mahony, E., & Iversen, C. (2013). Comparison of rapid cultural methods for the detection of *Salmonella* species. *International Journal of Food Microbiology*, *163*, 47−50.

Martzy, R., Kolm, C., Brunner, K., Mach, R. L., Krska, R., Sinkovec, H., . . . Reischer, G. H. (2017). A loop-mediated isothermal amplification (LAMP) assay for the rapid detection of *Enterococcus* spp. in water. *Water Research*, *122*, 62−69.

Mei, X., Zhai, X., Lei, C., Ye, X., Kang, Z., Wu, X., . . . Wang, H. (2019). Development and application of a visual loop-mediated isothermal amplification combined with lateral flow dipstick (LAMP-LFD) method for rapid detection of *Salmonella* strains in food samples. *Food Control*, *104*, 9−19.

Migliori, C. A., Salvati, L., Di Cesare, L. F., Scalzo, R. L., & Parisi, M. (2017). Effects of preharvest applications of natural antimicrobial products on tomato fruit decay and quality during long-term storage. *Scientia Horticulturae*, *222*, 193−202.

Minor, T., Lasher, A., Klontz, K., Brown, B., Nardinelli, C., & Zorn, D. (2015). The per case and total annual costs of foodborne illness in the United States. *Risk Analysis*, *35*, 1125−1139.

Montesinos-Herrero, C., & Palou, L. (2016). Synergism between potassium sorbate dips and brief exposure to high CO_2 or O_2 at curing temperature for the control of citrus postharvest green and blue molds. *Crop Protection*, *81*, 43−46.

Montesinos-Herrero, C., Moscoso-Ramirez, P. A., & Palou, L. (2016). Evaluation of sodium benzoate and other food additives for the control of citrus postharvest green and blue molds. *Postharvest Biology and Technology*, *115*, 72−80.

Moretro, T., Fanebust, H., Fagerlund, A., & Langsrud, S. (2019). Whole room disinfection with hydrogen peroxide mist to control *Listeria monocytogenes* in food industry related environments. *International Journal of Food Microbiology*, *292*, 118−125.

Mphahlele, R. R., Fawole, O. A., & Opara, U. L. (2016). Influence of packaging system and long-term storage on physiological attributes, biochemical quality, volatile composition and antioxidant properties of pomegranate fruit. *Scientia Horticulturae*, *211*, 140−151.

Mukhopadhyay, S., Sokorai, K., Ukuku, D. O., Fan, X., Olanya, M., & Juneja, V. (2019). Effects of pulsed light and sanitizer wash combination on inactivation of *Escherichia coli* O157:H7, microbial loads and apparent quality of spinach leaves. *Food Microbiology*, *82*, 127−134.

Murray, K., Moyer, P., Wu, F., Goyette, J. B., & Warriner, K. (2018). Inactivation of *Listeria monocytogenes* on and within apples destined for caramel apple production by using sequential forced air ozone gas followed by a continuous advanced oxidative process treatment. *Journal of Food Protection*, *81*, 357−364.

Murray, K., Wu, F., Shi, J., Xue, S. J., & Warriner, K. (2017). Challenges in the microbiological food safety of fresh produce: Limitations of post-harvest washing and the need for alternative interventions. *Food Quality and Safety*, *2017*(1), 289−301.

Nam, H. A., Ramakrishnan, S. R., & Kwon, J. H. (2019). Effects of electron-beam irradiation on the quality characteristics of mandarin oranges (*Citrus unshiu* (Swingle) Marcov) during storage. *Food Chemistry*, *286*, 338−345.

Nasef, I. N. (2018). Short hot water as safe treatment induces chilling tolerance and antioxidant enzymes, prevents decay and maintains quality of cold-stored cucumbers. *Postharvest Biology and Technology*, *138*, 1−10.

Newman, K. L., Bartz, F. E., Johnston, L., Moe, C. L., Jaykus, L. A., & Leon, J. S. (2017). Microbial load of fresh produce and paired equipment surfaces in packing facilities near the U.S. and Mexico border. *Journal of Food Protection*, *80*, 582−589.

Nicolau-Lapena, I., Abadias, M., Bobo, G., Aguilo-Aguayo, I., Lafarga, T., & Vinas, I. (2019). Strawberry sanitization by peracetic acid washing and its effect on fruit quality. *Food Microbiology*, *83*, 159−166.

Olanya, O. M., Hoshide, A. K., Ijabadeniyi Ukuku, D. O., Mukhopadhyay, S., Niemira, B. A., & Ayeni, O. M. (2019). Cost estimation of listeriosis (*Listeria monocytogenes*) occurrence in South Africa in 2017 and its food safety implication. *Food Control*, *102*, 231−239.

Oliveira, M., Abadias, M., Usall, J., Torres, R., Teixido, N., & Vinas, I. (2015). Application of modified atmosphere packaging as a safety approach to fresh-cut fruits and vegetables − A review. *Trends in Food Science and Technology*, *46*, 13−26.

Oviedo, G. A. L., Navarro, M. C., & ltamiranda, J. A. (2018). Study of photoreactivation in microbiological crops obtained from microbial loading of the surface of strawberries subbed to different doses of short-wave UV-C ultraviolet light. *Revista Colombiana de Investigaciones Agroindustriales*, *5*, 32−40.

Pandey, A. K., Kumar, P., Singh, P., Tripathi, N. N., & Bajpai, V. K. (2017). Essential oils: Sources of antimicrobials and food preservatives. *Frontiers in Microbiology*, *7*, 2161. Available from https://doi.org/10.3389/fmicb.2016.02161.

Park, S. H., & Kang, D. H. (2018). Effect of temperature on chlorine dioxide inactivation of *Escherichia coli* O157:H7, *Salmonella typhimurium*, and *Listeria monocytogenes* on spinach, tomatoes, stainless steel, and glass surfaces. *International Journal of Food Microbiology*, *275*, 39−45.

Park, S. H., Ahn, J. B., & Kang, D. H. (2018). Inactivation of foodborne pathogens on alfalfa and radish seeds by sequential treatment with chlorine dioxide gas and dry heat. *Food Control*, *85*, 253−258.

Pignata, C., D'Angelo, D., Fea, E., & Gilli, G. (2017). A review on microbiological decontamination of fresh produce with nonthermal plasma. *Journal of Applied Microbiology*, *122*, 1438−1455.

Pimenta, A. I., Margaca, F. M. A., & Verde, S. C. (2019). Virucidal activity of gamma radiation on strawberries and raspberries. *International Journal of Food Microbiology*, *304*, 89−96.

Pinela, J., Barreira, J. C. M., Barros, L., Verde, S. C., Antonio, A. L., Oliveira, M. B. P. P., ... Ferreira, I. C. F. R. (2016). Modified atmosphere packaging and post-packaging irradiation of *Rumex induratus* leaves: A comparative study of postharvest quality changes. *Journal of Food Science and Technology*, *53*, 2943−2956.

Poubol, J., Techavuthiporn, C., & Kanlayanarat, S. (2018). Guava fruit treated with hot water on microbiological quality of fresh-cut 'Kimju' and 'Pan Srithong' guava. *International Food Research Journal*, *25*, 903−907.

Ramakrishnan, S. R., Jo, Y., Nam, H. A., Gu, S. Y., Baek, M. E., & Kwon, J. H. (2019). Implications of low-dose e-beam irradiation as a phytosanitary treatment on physicochemical and sensory qualities of grapefruit and lemons during postharvest cold storage. *Scientia Horticulturae*, *245*, 1−6.

Rowen, N. J. (2019). Pulsed light as an emerging technology to cause disruption for food and adjacent industries − Quo vadis? *Trends in Food Science and Technology*, *88*, 316−332.

Sant'Ana, A. S., Silva, F. F. P., Maffei, D. F., & Franco, B. D. G. M. (2014). Fruits and vegetables: Introduction. In C. A. Batt, & M. L. Tortorello (Eds.), *Encyclopedia of food microbiology* (2nd ed., pp. 972−982). Amsterdam: Academic Press.

Sarangapani, C., Patange, A., Bourke, P., Keener, K., & Cullen, P. J. (2018). Recent advances in the application of cold plasma technology in foods. *Annual Review of Food Science and Technology*, *9*, 609−629.

Sari, L. K., Setha, S., & Naradison, M. (2016). Effect of UV-C irradiation on postharvest quality of 'Phulae' pineapple. *Scientia Horticulturae*, *213*, 314−320.

Schnabel, U., Andrasch, M., Stachowiak, J., Weit, C., Weihe, T., Schmidt, C., ... Ehlbeck, J. (2019). Sanitation of fresh-cut endive lettuce by plasma processed tap water (PPtW) − Up-scaling to industrial level. *Innovative Food Science and Emerging Technologies*, *53*, 45−55.

Schottroff, F., Frohling, A., Zunabovic-Pichler, M., Krottenthaler, A., Schluter, O., & Jager, H. (2018). Sublethal injury and viable but nonculturable (VBNC) state in microorganisms during preservation of food and biological materials by non-thermal processes. *Frontiers in Microbiology*, *9*, 2773. Available from https://doi.org/10.3389/fmicb.2018.02773.

Shah, U., Ranieri, P., Zhou, Y., Schauer, C. L., Miller, V., Fridman, G., & Sekhon, J. K. (2019). Effects of cold plasma treatments on spot-inoculated *Escherichia coli* O157:H7 and quality of baby kale (*Brassica oleracea*) leaves. *Innovative Food Science and Emerging Technologies*, *57*, 102104.

Shahbaz, H. M., Akram, K., Ahn, J. J., & Kwon, J. H. (2016). Worldwide status of fresh fruits irradiation and concerns about quality, safety, and consumers acceptance. *Critical Reviews in Food Science and Nutrition*, *56*, 1790−1807.

Shayanfar, S., Mena, K. D., & Pillai, S. D. (2017). Quantifying the reduction in potential infection risks from non-O157 Shiga toxin-producing *Escherichia coli* in strawberries by low dose electron beam processing. *Food Control*, *72*, 324−327.

Shen, C., Norris, P., Williams, O., Hagan, S., & Li, K. W. (2016). Generation of chlorine by-products in simulated wash water. *Food Chemistry*, *190*, 97−102.

Sheng, L., Hanrahan, I., Sun, X., Taylor, M. H., Mendoza, M., & Zhu, M. J. (2018). Survival of *Listeria innocua* on Fuji apples under commercial cold storage with or without low dose continuous ozone gaseous. *Food Microbiology*, *76*, 21−28.

Sivakumar, D., & Fallik, E. (2013). Influence of heat treatments on quality retention of fresh and fresh-cut produce. *Food Review International*, *29*, 294−320.

Sun, X., Baldwin, E., & Bai, J. (2019). Applications of gaseous chlorine dioxide on postharvest handling and storage of fruits and vegetables − A review. *Food Control*, *95*, 18−26.

Tang, D., Lin, Q., Lin, J., Wang, D., Liu, C., Wu, W., . . . Chen, K. (2017). Effects of combined heat and preservative treatment on storability of Ponkan fruit (*Citrus reticulata* Blanco cv. Ponkan) during postharvest storage. *Journal of Food Quality*, *17*, 1−7.

Tango, C. N., Khan, I., Kounkeu, P. F. N., Momna, R., Hussain, M. S., & Oh, D. H. (2017). Slightly acidic electrolyzed water combined with chemical and physical treatments to decontaminate bacteria on fresh fruits. *Food Microbiology*, *76*, 97−105.

Tatsika, S., Karamanoli, K., Karayanni, H., & Genitsaris, S. (2019). Metagenomic characterization of bacterial communities on ready-to-eat vegetables and effects of household washing on their diversity and composition. *Pathogens*, *8*, 37. Available from https://doi.org/10.3390/pathogens8010037.

Terao, D., de Lima Nechet, K., Toyoko Shiraishi Frighetto, R., de Almeida Anjos, V. D., Benato, E. A., & de Almeida Halfeld-Vieira, B. (2018). Physical postharvest treatments in the control of stem-end rot of mango. *Journal of Phytopathology*, *166*, 581−589.

Tokala, V. Y., Singh, Z., & Payne, A. D. (2018). Postharvest uses of ozone application in fresh horticultural produce. *Postharvest Biology Nanotechnology*, 129−170. Available from https://doi.org/10.1002/9781119289470.ch6.

Tudela, J. A., Lopez-Galvez, F., Allende, A., Hernandez, N., Andujar, S., Marin, A., . . . Gil, M. I. (2019). Operational limits of sodium hypochlorite for different fresh produce wash water based on microbial inactivation and disinfection by-products (DBPs). *Food Control*, *104*, 300−307.

Tzortzakis, N., Chrysargyris, A., Sivakumar, D., & Loulakakis, K. (2016). Vapour or dipping applications of methyl jasmonate, vinegar and sage oil for pepper fruit sanitation towards grey mould. *Postharvest Biology and Technology*, *18*, 120−127.

US FDA. (2018). CFR − Code of federal regulations title 21. Code of Federal Regulations, US.

Usall, J., Ippolito, A., Sisquella, M., & Neri, F. (2016). Physical treatments to control postharvest diseases of fresh fruits and vegetables. *Postharvest Biology and Technology*, *122*, 30−40.

Van Haute, S., Tryland, I., Veys, A., & Sampers, I. (2015). Wash water disinfection of a full-scale leafy vegetables washing process with hydrogen peroxide and the use of a commercial metal ion mixture to improve disinfection efficiency. *Food Control*, *50*, 173−183.

Wadamori, Y., Gooneratne, R., & Hussain, M. A. (2017). Outbreaks and factors influencing microbiological contamination of fresh produce. *Journal of the Science and Food and Agriculture*, *97*, 1396−1403.

Waghmare, R. B., & Annapure, U. S. (2018). Integrated effect of radiation processing and modified atmosphere packaging (MAP) on shelf life of fresh fig. *Journal of Food Science and Technology*, *55*, 1993−2002.

Wang, L., Fan, X., Sokorai, K., & Sites, J. (2019). Quality deterioration of grape tomato fruit during storage after treatments with gaseous ozone at conditions that significantly reduced populations of *Salmonella* on stem scar and smooth surface. *Food Control*, *103*, 9−20.

WHO. (2018). Listeriosis-South Africa. Retrieved June 18, 2018, from http://www.who.int/csr/don/28-march-2018-listeriosis-south-africa/en/.

Wilson, A. D. (2017). Electronic-nose devices − Potential for noninvasive early disease-detection applications. *Annals of clinical case reports*, 2, article 1401 (1−3).

Xylia, P., Chrysargyris, A., Botsaris, G., & Tzortzakis, N. (2018). Mint and pomegranate extracts/oils as antibacterial agents against *Escherichia coli* O157:H7 and *Listeria monocytogenes* on shredded carrots. *Journal of Food Safety*, *38*, 12423. Available from https://doi.org/10.1111/jfs.12423.

Xylia, P., Clark, A., Chrysargyris, A., & Romanazzi, G. (2019). Quality and safety attributes on shredded carrots by using *Origanum majorana* and ascorbic acid. *Postharvest Biology and Technology*, *155*, 120–129.

Yeni, F., Yavas, S., Alpas, H., & Soyer, Y. (2016). Most common foodborne pathogens and mycotoxins on fresh produce: A review of recent outbreaks. *Critical Review of Food Science*, *56*, 1532–1544.

Yesil, M., Kasler, D. R., Huang, E., & Yousef, A. E. (2017). Efficacy of gaseous ozone application during vacuum cooling against *Escherichia coli* O157:H7 on spinach leaves as influenced by bacterium population size. *Journal of Food Protection*, *80*, 1066–1071.

Yoo, N. H., Jung, S. K., Lee, C. A., Choi, D. G., & Yun, S. J. (2017). Post-harvest LED and UV-B irradiation enhance antioxidant properties of asparagus spears. *Korean Journal of Horticultural Science and Technology*, *35*, 188–198.

Yoon, J. H., & Lee, S. Y. (2019). Review: Comparison of the effectiveness of decontaminating strategies for fresh fruits and vegetables and related limitations. *Critical Reviews in Food Science and Nutrition*, *58*, 3189–3208.

Yoon, H. S., Choi, I. L., Heo, J. Y., Kim, J. Y., Han, S. J., & Kang, H. M. (2018). Influence of hot water immersion and MAP pre-treatments on sterilization and asparagus spear qualities during cold storage. *Horticultural Science and Technology*, *36*, 756–765.

Yuan, W. Q., Teo, C. H. M., & Yuk, H. G. (2019). Combined antibacterial activities of essential oil compounds against *Escherichia coli* O157:H7 and their applications potential on fresh-cut lettuce. *Food Control*, *96*, 112–118.

Zang, Y. T., Li, B. M., Shi, Z. X., Sheng, X. W., Wu, H. X., & Shu, D. Q. (2017). Inactivation efficiency of slightly acidic electrolyzed water against microbes on facility surfaces in a disinfection channel. *International Journal of Agricultural and Biological Engineering*, *10*, 23–30.

Zanin, L. M., da Cunha, D. T., de Rosso, V. V., Carpiles, V. D., & Stedefeldt, E. (2017). Knowledge, attitudes and practices of food handlers in food safety: An integrative review. *Food Research International*, *100*, 53–62.

Zhao, Y., & Yin, J. (2018). Effects of *Pichia guilliermondii* and hot air treatment on the postharvest preservation of Red Fuji apple quality attributes. *Journal of Food Protection*, *81*, 186–194.

Zhao, L., Zhao, M. Y., Phey, C. P., & Yang, H. (2019). Efficacy of low concentration acidic electrolysed water and levulinic acid combination on fresh organic lettuce (*Lactuca sativa* Var. Crispa L.) and its antimicrobial mechanism. *Food Control*, *101*, 241–250.

Ziuzina, D., Han, L., Cullen, P. J., & Bourke, P. (2015). Cold plasma inactivation of internalised bacteria and biofilms for *Salmonella enterica* serovar Typhimurium, *Listeria monocytogenes* and *Escherichia coli*. *International Journal of Food Microbiology*, *210*, 53–61.

Zudaire, L., Vinas, I., Abadias, M., Simo, J., & Aguilo-Aguayo, I. (2018). Efficacy of chlorine, peroxyacetic acid and mild-heat treatment on the reduction of natural microflora and maintenance of quality of fresh-cut calçots (*Allium cepa* L.). *LWT – Food Science and Technology*, *95*, 339–345.

This page intentionally left blank

CHAPTER

21

Measuring consumer acceptability of fruits and vegetables

Bernhard Brückner

Leibniz-Institute of Vegetable and Ornamental Crops, Großbeeren, Germany

Abbreviations

CATA	check-all that applies
HUT	home use tests

21.1 Introduction

The view on fruit and vegetable quality has changed. What had started as the view beyond the produce itself a few decades ago has become mainstream today. The agricultural production chain is more integrated across all stakeholders now, and the consumer has gained a central role: produce quality cannot be defined without information from and about the consumer. But in the last 15 years, the consumer with his/her hedonic judgment is not seen to be the end of the chain (or the starting point in a reverse view) but is itself subject to various influences and actors. These may be situational, emotional, ethical, or political convictions, physiological status, and social context. This opened a new realm of quality-related integration and interdisciplinary research.

In the past, each member of a value chain of fresh produce focused on attaining acceptance by the following actor within the chain. In practice, it largely required maintenance of quality standards (see Chapters 2, 5, and 6). The rationale was to have defined criteria, which could facilitate communication during ordering, shipment, or distribution and, to some extent, allow comparison of different product shipments.

Thus the quality of fresh horticultural produce was usually evaluated against standards for grading. These standards included product attributes that can be readily determined, and are related to color, appearance, and absence of defects (see also Chapter 3: Postharvest Regulation and Quality Standards on Fresh Produce). In the past, breeders

Postharvest Handling
DOI: https://doi.org/10.1016/B978-0-12-822845-6.00021-X

successfully developed cultivars with improved yields and attributes laid down in the specifications (see also Chapter 7: Fresh-Cut Produce Quality: Implications for Postharvest, and Chapter 9: Postharvest Quality Properties of Potential Tropical Fruits Related to Their Unique Structural Characters). Besides yield and grades, other targets were the hardiness and resistance of the plants, uniformity, extension of the season, and, in some cases, shelf life or suitability for processing.

Consumers were thought to be satisfied with the grades, season extension, and varied choices at prices they could afford. However, this proved not to be the whole truth. Much more is needed for being successful with regard to consumers (Köster & Mojet, 2016; see also Chapters 19–21). For instance, in the 1990s, German consumers were dissatisfied with the poor flavor intensity of fresh tomatoes originating from the Netherlands. Subsequently, Dutch tomatoes experienced a sustained decline in sales of 30% in Germany (Behr & Illert, 2002). Due to efforts to improve the flavor through breeding, variety selection, cultural and postharvest techniques, and consumer surveying, the Netherlands is again the largest exporter of fresh tomatoes in Europe (European Commission 2021). Much of the attractiveness to consumers of products of this origin was lost during those years, because of the characteristics of the fruit which were perceived through the senses of consumers.

Flavor intensity is part of the consumption experience and thus perceivable only after purchase. Other important drivers of acceptability among consumers include intrinsic attributes, such as appearance, color, odor, and texture. These can be more readily perceived and help in the search for attractive products before the final selection and purchase. Both, quality assessed from experience and quality criteria used during the search can be evaluated by consumers directly by comparing their expectations with the information received from their sensorial perceptions (Grunert, 2005). Innovation in the food sector often relies on additional information (technical and emotional) provided with the product to assist consumer evaluation (Grunert, 2017).

21.2 Experience and credence attributes

It is argued, that the quality of a product is assessed by consumers very rarely using direct sensory impressions only (Costell, Tarrega, & Bayarri, 2010; Fernqvist, 2019). And of course, there are other factors that cannot be ascertained even by experienced consumers. Most health-related properties and their effect on the human body cannot directly be experienced, felt, or validated by a consumer. The quality of the production process—increasingly important and well-recognized by many consumers—is, in most cases, undetectable in opposite to intrinsic properties. Not only are consumers unable to detect differences between the use and nonuse of genetically modified techniques (see also Chapter 9: Postharvest Quality Properties of Potential Tropical Fruits Related to Their Unique Structural Characters), regard or disregard for social or environmental standards, or whether the produce is conventionally or organically grown, even sophisticated instrumentation can hardly authenticate organically grown produce. Results of studies with consumers on the ability to distinguish organic and conventional produce with their senses are not consistent (Banasiak et al., 2004; Bordeleau, Myers-Smith, Midak, & Szeremeta, 2002; Maggio, De Pascale, Paradiso, & Barbieri, 2013).

Those nonsensory attributes are important to many consumers, but they are unable to experience them and must rely on other sources (see also Chapter 19: Compositional Determinants of Fruit and Vegetable Quality and Nutritional Value). Consumers, therefore, use cues that they recognize at and around the product and infer credence attributes from these (Vermeir and Roose, 2020). All properties that can be observed may serve this purpose, for example, appearance, color, size, visible structure, firmness to the touch and increasingly packaging, and the information on it (Köster, 2009; Samant & Seo, 2020; Thomson, 2008). They may also be communicated at a retail outlet, or through press or social media. In the case of fruit and vegetables, the place of origin is an important cue for inferring quality. This cue can be so strong that it surpasses actual sensory perception, for instance, experimentally shown in the case of nationally or organically produced tomatoes rated over imported ones, although all three have been in this experiment the same, but differently labeled (Fernquist & Ekelund, 2013). Important cues can also be brands or product concepts, although these are more often associated with processed products.

Not only prior to, but also after purchase, credence attributes will be effective and may still influence the perceived quality of the product, but they may fade with time. Especially in the case of repeated purchase and consumption, personal experience becomes more important than the indirectly assessed credence qualities. This gradual loss of quality dimensions may become a disadvantage, especially for products where a high proportion of extrinsic, credence quality is involved (e.g., functional foods).

The producer only partly controls the perception of credence attributes, as well as the perception of experience attributes. Situational variables change during transport, storage, preparation, and consumption. Learning how to handle produce can result in consistency or improve the experience of quality and, therefore, information on maturity (see also Chapters 4, 5, 15, and 16), storage conditions, and preparation methods is helpful to consumers.

A comprehensive discussion of the influences on consumer acceptability can be found in the book by Meiselman (2007), Chapter 1, Postharvest Systems—Some Introductory Thoughts, of which contains a review of many models of food acceptance, with different emphases within the three classes of variables of eating research:

- food variables: palatability, appearance, and flavor,
- people variables: responsiveness to food cues, restrained eating, expectations human focused, human-product linked, and
- environmental variables: physical, social context, and economic factors.

The contextual, situational, environmental, and social influences on food acceptability are much more integrated now in the view of food quality. More recently, Cardello and Meiselman reviewed the research on various kinds of context effects on food acceptability and choice (Meiselman, 2019; Varela & Ares, 2018).

21.3 Acceptability and acceptance

The classical definition of acceptance (Amerine, Pangborn, & Roessler, 1965) reflects the two opposite scenarios:

- "Actual utilization (purchase or eating)" by consumers. From a practical, economic perspective consumption frequency, food choice, purchase interest, and consumed quantity are most important. Positive affective response to a product is required, but numerous other factors can reduce the correlation to actual use: inappropriate situation, image, ethical/health concerns, satiety, price, availability (Grunert, 2005; Lange, Issanchou, & Combris, 2000; Tuorila, 2007).
- "Experience or feature of experience, characterized by a positive attitude toward the food." The second refers to an experience, gained directly from the sensory interaction between consumer and product, is the basis and will lead to an individual, scalable intent to consume or buy, thus defining acceptability.

When consumers are considered as individuals (and thus between-individual variance is avoided), the influence of product attributes triggers acceptability (see also Chapter 19: Compositional Determinants of Fruit and Vegetable Quality and Nutritional Value) in a certain situational environment. Similar consumers can be grouped into consumers segments, still presuming given situational context.

Measuring acceptability needs awareness of contextual, situational, environmental, and social influences beside the affective product–consumer interplay. Experimental setup can take those factors into account but inevitably relies on asking "whether the consumer likes a presented product, prefers it over another product or finds the product acceptable based on its sensory characteristics" (Lawless & Heymann, 2010).

21.4 Qualitative tests

Qualitative tests often measure the subjective responses of a consumer to the sensory properties of a product. Consumers talk about their feelings in a small group setting or interview (Guerrero & Xicola, 2018; Meilgaard, Civille, & Carr, 2016). The initial response to a new concept, the general acceptance of a prototype, or information on other obvious problems is obtained and allows for project readjustment. Because of the personal interaction, the consumer's terminology can be studied and consumer-oriented terms can be learned for use in questionnaires and advertisements. Another advantage is to learn about reasons for and practices of consumer behavior regarding product use, which could facilitate handling, etc. For fruit and vegetables, this is not only limited to innovation in package convenience, but also to new origin, mix, size, and properties of the produce for use in cooking.

Usually, an interviewer or moderator with skills in group dynamics, probing techniques, summarizing and reporting meets a group of 10–12 persons (focus group). Group members are selected on the basis of product usage and socio-demographics, and they participate in two or three sessions, each for 1–2 h. The subject of interest is presented, and the discussion facilitates obtaining as much information as possible. If the group meets on a regular basis, for instance, to use a product at home between sessions, it is called a focus panel. If additional (or sensitive) information is sought from each individual, one-to-one consumer interviews are appropriate. Such interviews may be conducted at the interviewer's site or in consumer's homes. In some cases, observation of the consumer's product preparation etc. yields very different information from the consumer's verbal statements (Meilgaard et al., 2016).

21.5 Quantitative tests

There are two approaches to quantitative consumer acceptability testing: tests that rely on choice or on rating. Relative preference is determined using the first method.

21.5.1 Testing preference

Preference, classically used for testing in the food industry, can be defined in three ways (Amerine et al., 1965):

1. expression of a higher degree of preference;
2. choice of one object over others; and
3. basis of choice, psychological continuum of affectivity (pleasantness/unpleasantness).

However, preference tests are usually designed to measure the appeal of one food or food product over another (Stone, Bleibaum, & Thomas, 2020). The panelists receive two coded samples (usually simultaneously), and their task is to answer the question: "which sample do you prefer or like better?" (Meilgaard et al., 2016). The task is rather intuitive and can be performed easily even by semi- or illiterate consumers (Coetzee & Taylor, 1996).

It is usually recommended that the consumer must choose one product over the other (Stone, Bleibaum, & Thomas, 2012). Such a choice helps the interpretation (because tests rely on a binominal distribution) and enables the use of all answers. If a preference decision is not given, the researcher has to decide either to ignore or to split those answers 50:50, or to split them in proportion to other answers. Another possibility for large consumer numbers (>100) is to calculate confidence intervals based on a multinominal distribution. With nonoverlapping confidence intervals of respondents expressing a preference, and a small number of no preference answers, the significance level can be identified. Details of relevant procedures can be found in the literature (Lawless & Heymann, 2010; Moskowitz, Beckley, & Resurreccion, 2012b; Meilgaard et al., 2016).

Special cases of preference testing are repeated pair-wise preference tests and sequential preference ranking of a series of samples. The aim of both methods is to obtain information on the relative preference for an array of products. It is again an intuitive task for consumers to rank products according to their preference for visual, tactile, and pronounced taste or flavor perception, but complex multiflavor or taste samples can become stressful. A sequence of increased acceptability can be calculated not only from ranking, but also from the results of repeated pair-wise comparisons. In both cases, received data are ordinal and thus the absolute degree of liking and the relative distance of successive samples cannot be quantified. The reported liking is only relative between the samples and inherent to the presented set of samples.

Preference tests are less frequently used than measuring acceptability with fruit and vegetables. This is probably because the typical case is not comparing one cultivar, cultivation technique, or maturity stage to another (see also Chapter 5: Models for Improving Fresh Produce Chains, and Chapter 7: Fresh-Cut Produce Quality: Implications for Postharvest), but comparing a range of influences on the resulting quality. In very few cases, only a single property may be changed, but physiological processes lead to a multitude of altered texture, taste, aroma or flavor attributes. To be able to explain differences in acceptability, therefore a larger data set that gives quantitative information on acceptability is necessary. There are cases where, for example, the cooking method (Torres de Castro, de Lacerda, Rodrigues de Alencar, & Assunção Botelho, 2020), use of a chemical or distinct postharvest alternatives have a positive or negative effect on preference. Here preference testing is most efficient (Harker, Amos, White, Petley, & Wohlers, 2008).

21.5.2 Testing acceptability

The vocabulary of researchers on food quality is still not unified, as it had been advocated earlier (Shewfelt & Brückner, 2000). Consumer tests are labeled "acceptance tests" when testing hedonic rating alone, taking other factors into account, or include some measure of actual purchase. In this chapter, tests are referred to acceptability tests, realizing that other than pure affective ratings influence purchase and consumption. Acceptability tests, as described here, provide information on the emotional relation between the consumer and the product, which is the basis for subsequent behavior (Tuorila, 2007).

In these acceptability tests, panelists work as a measuring instrument not to measure products, but to quantify their own affective reaction evoked by the sample. Different from preference testing, acceptability tests can be performed using only one sample, but usually 10 or 12 samples are tested. The samples are coded with a three- to four-digit number and are usually presented one after the other (monadic). The sequence of samples differs from panelist to panelist, because the constant position as an earlier or later presented sample will bias the results. The possible number of samples depends, as well as the type of samples and the composition of the panel, on the number and type of questions posed.

The central question is "how much do you like the product?" or "how acceptable is the product?" (Meilgaard et al., 2016). However, detailed information on the acceptability of several attributes is often required and can be included in the protocol. Additional questions ask consumers how much they like the appearance, aroma, flavor, texture or aftertaste, or even more specific attributes such as color, sweetness, or crunchiness. Answers allow responses as to whether, for example, the sweetness is not liked because the product is too sweet or not sweet enough. Therefore just-about-right questions are used where respondents have to rate whether the level of the sensory attribute is "too low," "just right," or "too high."

Although the rating is also done on a hedonic scale, it forces panelists to form a fairly analytical judgment that may influence results (Popper, Rosenstock, Schraidt, & Kroll, 2004). The hedonic response can be affected or even modified during analytical approaches through the selection of specific sensory terms used (Prescott, Lee, & Kim, 2011) and has been recommended (Stone et al., 2012).

More and more recent research shows that sensory terms in questions to consumers (Delarue, Lawlor, & Rogeaux, 2015) are possible without risking detrimental bias. One example is check-all that applies (CATA) questionnaires (Ares & Jaeger, 2015). All sensory terms can be checked, if they play a role for the liking of the product. CATA tests proved to be easy to answer by consumers and the hedonic results seemed unbiased. Those were obtained in a separate task (Ares & Varela, 2017). Jaeger et al. (2020) found the rating of sensory terms on a scale (applicability, not intensity) influence the hedonic results of the same products more, than just checking terms, but, on the other hand, even the selection of terms itself is critical. Negative connotations may lead to more negative hedonic results, than a more positive set of terms.

Panelists for acceptability tests are chosen to represent a target population. They are users of the product in question but should be naive users, not professionals in food issues. A discussion of the use of employees for in-company product testing can be found in Lawless and Heymann (2010). Other requirements are demographic characteristics, such as age or gender distribution, again with respect to the target population. In contrast, analytical testers are selected after successfully passing standardized tests for olfactory, taste, and color sensibilities, as well as memory, verbal abilities, and creativity. They do not need to be members of a target population (Lawless & Heymann, 2010; Stone et al., 2020).

21.6 Scales

Information regarding scales is obtained from assigned words, numbers, or scale positions marked by a panelist. There has been much discussion about the best scale (Cardello & Jaeger, 2010; Gamba et al., 2020; Moskowitz, Beckley, & Resurreccion, 2012b). Important issues are the number and type of statements, the relative difference between single statements or a more-or-less unstructured line scale. Very often a nine-point hedonic scale is used. It consists of four, presumably equally spaced, categories for liking, a neutral point, and four corresponding categories for disliking (e.g., dislike extremely, dislike very much, dislike moderately, dislike slightly, neither like nor dislike, like slightly, like moderately, like very much, and like extremely).

This scale has been suggested by Peryam and Pilgrim (1957) and has been validated and successfully used (Stone et al., 2020). It contains no additional information on possible consequences of the degree of liking or disliking as, for instance, is found in the food action rating scale suggested by Schutz (1965). For testing children, alternative scales have been developed which use fewer points and displace verbal statements with facial symbols for different degrees of liking (Chen, Resurreccion, & Paguio, 1996; Laureati & Pagliarini, 2018; Popper & Kroll, 2003). Data derived from the scales are ordinal, but results from unstructured line scales may be regarded as quantitative numerically, especially in tests that use many panelists.

21.7 Extracting information

Acceptability data are usually obtained from observations of consumer behavior (with all the interference of environmental factors) or the reporting of panelists transferring their perceptions into words or numbers. To come even closer to the processes of sensation and perception, physiologists study the explanations on how signals from food molecules are processed and transduced from receptor cells to the brain (Drayna, 2005; Margolskee, 2004; Puputti, Aisala, Hoppu, & Sandell, 2018; Wise & Breslin, 2013).

Progress and availability of computing capacities stimulated analytical approaches to measure consumer behavior using eye-tracking, facial expression analysis (Ares & Varela, 2018). An emerging field of new insights into the processing of signals in the brain is offered by functional magnetic resonance imaging. The activity of brain areas in response to food (thinking of, smelling or eating) can be depicted and located, and assigned to those areas responsible for activity or emotions. The nature of this research is very fundamental and mostly qualitative but may help to explain the complex phenomena of perception, integration, and hedonic consequences in the future (Niedziela & Ambroze, 2020; Rolls, 2012; Rudenga & Small, 2013; Sescousse, Redoute, & Dreher, 2010; Ares & Vidal, 2021).

21.8 Test sites

A sensory laboratory offers the best control over the preparation and handling of samples, as well as the control of environmental factors during the sessions. Light can be used to mask, for example, sample color differences or, most often, standardized light spectra can be utilized. Data entry can easily be computerized. Panelists work in screened booths, protected from the influence of their surroundings, which could possibly draw attention away from the sample testing. A disadvantage is that the situation differs from normal product use at home. The amount of food may be smaller in the unfamiliar laboratory situation than during an in-home use, and the time for which the consumer is exposed to the product is shorter in the laboratory, where the focus is strongly on working through the testing sequence. Therefore the repeated presentation of the same product may be used to investigate acceptability changes with time, which can decrease for some products when satiety begins. A detailed discussion of the advantages and disadvantages can be found in Köster (2009), Meiselman (2008), Moskowitz, Beckley, and Resurreccion (2012c), and Stone et al. (2020).

Other often-used test sites are central locations, such as shopping centers or similar publicly accessible locations. The advantage of these is the large number of subjects who can be selected and approached. The disadvantage is the limited control of the test conditions, sample preparation, and handling. For fruit and vegetable testing, with limited preparation effort, it can be a feasible alternative. For improved testing facilities, mobile sensory/chemical units or even virtual reality or immersive environment have been used (Moskowitz et al., 2012b; Porcherot et al., 2018; Lichters, Moslein, Sarstedt, & Scharf, 2021).

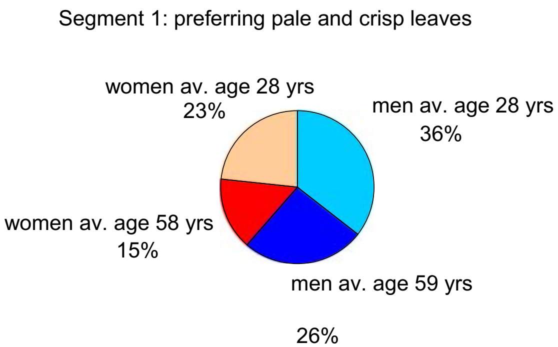
Even more closely resembling actual consumption situations are home use tests (HUT), with the advantage of a natural, unbiased setting. Under these conditions, information on the performance of products during preparation can also be collected by completion of a questionnaire. Testing of complex foods, whole meals, and products with a high proportion of extrinsic or credence attributes takes advantage of the familiar social context (Stone et al., 2020), but the researcher loses much of the control of the testing procedure. Fruit and vegetables have seldom been tested using HUT.

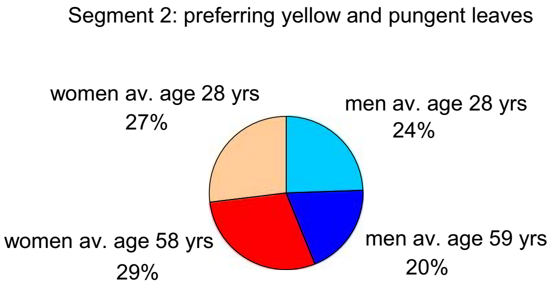
21.9 Consumer segments

As a good sensory practice for acceptability tests, a group of around 30 panelists is viewed as a minimum group size for testing (Mammasse & Schlich, 2014; Meilgaard et al., 2016; Moskowitz, 1997). If separation into different groups of the population is intended, for example, income groups, or urban versus rural, a larger group is recommended (Meiselman, 2013). A large number of panelists is necessary because consumers are individuals and differ from each other in what they regard as acceptable. The variability among consumers has long been recognized (Pangborn, 1981) and many attempts have been tried to relate it to sociodemographic background, but this has usually failed (Moskowitz, Beckley, & Resurreccion, 2012a). The differences between single consumers can be even greater than the differences detected between consumers from different European countries, as shown in the case of coffee (Moskowitz et al., 2012a). Other efforts are directed to specific populations like children, the elderly or low-income groups (Ares & Varela, 2018).

Addressing a target population also means analyzing consumer panelists' data for underlying preference segments, but this has not been applied as a standard in the area of fruit and vegetable studies. Early studies using segments (Rozenbaum, 1989) showed differences in the sweetness preferences for grapefruit by consumers; sweet, hard apples, or juicy, acidic apples were preferred by different consumer segments (Daillant-Spinnler, MacFie, Beyts, & Hedderley, 1996); similar segments were identified for peaches and mangoes (Malundo, 1996); preferences for levels of sugars and acids differed in table grapes (Crisosto & Crisosto, 2002); and kiwifruit consumers were segmented into those who liked a new yellow-fleshed, sweet, and fruity flavored cultivar or those preferring the familiar green-fleshed and sweet-tart tasting kiwifruit (Jaeger, Rossiter, Wismer, & Harker, 2003). Despite a general liking for juicy, sweet pears, "ideal" color and shape differed among consumers (Jaeger, Lund, Lau, & Harker, 2003). Tomato consumer segments were identified (Bruckner, 2000; Causse et al., 2010; Pagliarini, Monteleone, & Ratti, 2001) on the basis of the preference for red color and sweetness, acidity and texture, with at least two groups preferring fruit at different stages of ripening.

Acceptability testing of existing and new cabbage breeds resulted in overall liking rates ranging from 68% to 71% on a line scale (unpublished data). Differences were partly significant, but small. Data standardization and cluster analysis led to three different consumer segments. Segment 1 consumers (41%) preferred pale and crisp cabbage leaves, Segment 3 consumers (26%) more intensive yellow color and pungent taste. The acceptability value range between the cabbage breeds was higher within the segments and gender and age distribution may encourage marketing into targeted product lines.





Segmentation of consumers is performed not only on the basis of taste preferences (including or not the actual consumption contexts), but also on the basis of attitudes, motives, or convictions (Jurkenbeck, Spiller, & Meyerding, 2019; Verain, Sijtsema, Taufik, Raaijmakers, & Reinders, 2020), social influence (Robinson & Higgs, 2012), or curiosity (Costa, Silva, & Oliveira, 2020; Schifferstein, Wehrle, & Carbon, 2019).

There are also examples where produce details, such as cultivar, presence of a label, price, and presentation (in several tray types or loose), were varied to optimize acceptability by segments of domestic and international markets. This research was done using conjoint analysis. Rather than measuring the acceptability of the product features alone, the contributory values of the features within this complex mix were determined through systematic variation (Almli & Naes, 2018; Moskowitz, 2005). One possibility is to separate panelists into subgroups based on the preference for selected attributes of one or a few products (MacFie & Thomson, 1988), or on the pattern of preferences for the whole set of products, using cluster analysis (Moskowitz et al., 2012a). To level out individual differences in scale usage, usually the ratings of one subject are standardized (i.e., set to zero, standard deviation set to one), and a cluster analysis of the data will identify similar subjects, based on the way they scored for liking of the products or product attributes (if attribute liking was one of the questions). Another alternative is the possibility of internal and external preference mapping (Greenhoff & MacFie, 1994; Naes, Brockhoff, & Tomic, 2010). In both methods, individuals are identified on the basis of their preferences only (internal preference mapping) or combined with nonpreference data (external preference mapping). Overviews of consumer acceptability data analysis have been published recently (Meilgaard et al., 2016).

21.10 The necessity for acceptability testing

Four primary areas for the need to conduct acceptability tests were defined by Meilgaard et al. (2016):

- product maintenance;
- product improvement/optimization;
- development of new products;
- assessment of market potential.

One of the major reasons for recommending the implementation of consumer acceptability tests is the fact that many newly launched products fail in the marketplace if they are not properly tested (Dijksterhuis, 2016; Köster & Mojet, 2018; MacFie, 2007). At first glance, a new product launch seems to be atypical for the fresh fruit and vegetable sector, but new varieties of exotic fruit and vegetables, new sizes, mixtures, or convenience properties (e.g., fresh-cut fruit, premixed salads) are being developed (see also Chapter 8: Multiomics Approaches for the Improvements of Postharvest Systems, and Chapter 20: Mitigating Contamination of Fresh and Fresh-Cut Produce). Consumer needs are changing over time, influenced by demographic, socioeconomic, and cultural change, reflected in trends such as an increased average age, smaller household size, ecological consciousness, body optimization and sports nutrition, individualization, and reduced willingness (and necessity) to spend time and effort in preparing food.

Retail chains now compete globally and have to attract increasingly sophisticated consumers. New fruit and vegetable products often require advanced technology to maintain or sometimes even improve quality during storage, transport (see also Chapter 13: Sorting for Defects) and processing, such as the use of chemicals to affect ripening; storage and shipment techniques like ultralow oxygen or dynamic controlled atmosphere; modified atmosphere packaging or new packaging materials; processing (e.g., for fresh-cut; see also Chapter 8: Multiomics Approaches for the Improvements of Postharvest Systems); high-pressure treatments; or additives for microbial control (see also Chapter 20). Besides prolonging shelf life, all of these technologies can affect attributes relevant to acceptability. It can be very difficult, if not impossible to measure those changes instrumentally, as we have seen in experiments with peeled asparagus, where unsuitable packaging led to reduced consumer acceptability because of weak off-odors (Brueckner, 2004).

New challenges for acceptability testing will arise from the regional or global dimensions of fruit and vegetable sourcing. Acceptability testing, sometimes used to identify regional or traditional product characteristics, will increasingly be used to pave the way for global produce distribution (Egolf, Hartmann, & Siegrist, 2019; Koppel, Chambers, Vazquez-Araujo, Carbonell-Barrachina, & Suwonsichon, 2014). Scale usage and vocabulary will need to be further developed to enable cross-cultural use.

The focus of acceptability testing will continuously broaden from the product itself to the product with its package and information (Menichelli et al., 2013) as well as functional and emotional dimensions (King, Meiselman, & Carr, 2013; Köster, 2009). As emotions play a role in the food context, so does wellness. Health benefits of fruit and vegetables can be specified by analysis, but wellness is experienced by the individual consumer. However, methods of measurement need to be developed (Boelsma, Brink, Stafleu, & Hendricks, 2010).

An interesting point is raised by Meiselman (2013). Research on consumer acceptability and choices usually concentrates on a single-product/acceptability interface. But many products are purchased and consumed together in a meal or in a preset sequence following a habit or ritual. More and more research includes now variables of the consumption environment and its relation to taste perception (Cardello & Meiselman, 2018).

Much of these new developments in the perspective of studying fruit and vegetable quality in terms of the consumer seem to divert the focus from the product, the object of this book, to the social and cultural environment of consumers. But within the systems approach, we have seen, that "...the key to increasing the amount of an item consumed and the economic value of the item lies in understanding consumer desires" (see also Chapter 11: Plant to Plate—Achieving Effective Traceability in the Digital Age, and Chapter 19: Compositional Determinants of Fruit and Vegetable Quality and Nutritional Value).

Feedback from consumers throughout each chain is required at each business link to provide value to ensure the flow of money needed to sustain each business link, all the way to and including the consumer.

References

Almli, V. L., & Naes, T. (2018). Conjoint analysis in sensory and consumer science: Principles, applications, and future perspectives. In G. Ares, & P. Varela (Eds.), *Methods in consumer research* (Vol. 1). Woodhead Publishing, Series in Food Science, Technology and Nutrition.

Amerine, M. A., Pangborn, R. M., & Roessler, E. B. (1965). *Principles of sensory evaluation of food*. New York: Academic Press.

Ares, G., & Vidal, L. (2021). Commentary on "The future of consumer neuroscience in food research" by Niedziela and Ambroze. *Food Quality and Preference*, *92*, 104176.

Ares, S. R., & Jaeger, S. R. (2015). Check-all-that-apply (CATA) questions with consumers in practice: Experimental considerations and impact on outcome. In J. Delarue, J. B. Lawlor, & M. Rogeaux (Eds.), *Rapid sensory profiling techniques. Applications in new product development and consumer research* (pp. 227−245). Woodhead Publishing, Series in Food Science, Technology and Nutrition.

Ares, G., & Varela, P. (2017). Trained vs. consumer panels for analytical testing: Fueling a long lasting debate in the field. *Food Quality and Preference*, *61*, 79−86.

Ares, G., & Varela, P. (2018). Methods in consumer research. *Alternative approaches and special applications* (Vol. 2). Woodhead Publishing, Series in Food Science, Technology and Nutrition.

Banasiak, U., Becker, B., Beer, H., Bergthaller, W., Betschke, T., Boess, C., et al. (2004). *Landwirtschaftsverlag GmbH, Munster Hiltrup. Schriftenreihe des Ministeriums für Verbraucherschutz, Ernährung und Landwirtschaft*. Reihe A: Angewandte Wissenschaft.

Behr, H. C., & Illert, S. (2002). *ZMP-Bilanz Gemüse, Zentrale Markt- und Preisberichtstelle für Erzeugnisse der Land-, Forst- und Ernährungswirtschaft GmbH, Bonn, 1995−2002*.

Boelsma, E., Brink, E. J., Stafleu, A., & Hendricks, H. J. J. (2010). Measures of postprandial wellness after single intake of two protein-carbohydrate meals. *Appetite*, *54*, 456−464.

Bordeleau, G., Myers-Smith, I., Midak, M., & Szeremeta, A. (2002). *Food quality: A comparison of organic and conventional fruits and vegetables*. København, Denmark: Ecological Agriculture Den Kongelige Veterinær- og Landbohøjskole. Research Report.

Bruckner, B. (2000). Acceptability of tomatoes defined by sensory attributes and consumer segments. In W. J. Florkowski, R. L. Shewfelt, & S. E. Prussia (Eds.), *Integrated view of fruit and vegetable quality* (pp. 229−240). Lancaster, PA: Technomic Publishing.

Brueckner, B. (2004). Welche Verpackungsmaterialien bei ungeschältem und geschältem Spargel? *Spargel & Erdbeerprofi*, *6*(2), 16−17.

Cardello, A. V., & Jaeger, S. R. (2010). Hedonic measurement for product development: New methods for direct and indirect scaling. In S. R. Jaeger, & H. MacFie (Eds.), *Consumer driven innovation in food and personal care products* (pp. 135−174). Woodhead Publishing Series in Food Science, Technology and Nutrition.

Cardello, A. V., & Meiselman, H. L. (2018). Contextual influences on consumer responses to food products. In G. Ares, & P. Varela (Eds.), *Methods in consumer research* (Vol. 1). Woodhead Publishing, Series in Food Science, Technology and Nutrition.

Causse, M., Friguet, C., Coriet, C., Lepicier, M., Navez, P., Lee, M., … Grandillo, S. (2010). Consumer preferences for fresh tomato at the European scale: A common segmentation on taste and firmness. *Journal of Food Science*, *75*(9), 531−541.

Chen, A. W., Resurreccion, A. V. A., & Paguio, L. P. (1996). Age appropriate hedonic scales to measure food preferences of young children. *Journal of Sensory Studies*, *11*, 141−163.

Coetzee, H., & Taylor, J. R. N. (1996). The use and adaptation of the paired-comparison method in the sensory evaluation of hamburger-type patties by illiterate/semi-literate consumers. *Food Quality and Preference*, *7*, 81−85.

Costa, A., Silva, C., & Oliveira, A. (2020). Food neophobia and its association with food preferences and dietary intake of adults. *Nutrition and Dietetics*, *77*(5), 542−549.

Costell, E., Tarrega, A., & Bayarri, S. (2010). Food acceptance: The role of consumer perception and attitudes. *Chemosensory Perception*, *3*(1), 42–50.

Crisosto, C. H., & Crisosto, G. M. (2002). Understanding American and Chinese consumer acceptance of "Redglobe" table grapes. *Postharvest Biology and Technology*, *24*, 155–162.

Daillant-Spinnler, B., MacFie, H. J. H., Beyts, P. K., & Hedderley, D. (1996). Relationships between perceived sensory properties and major preference directions of 12 varieties of apples from the southern hemisphere. *Food Quality and Preference*, *7*, 113–126.

Delarue, J., Lawlor, J. B., & Rogeaux, M. (2015). *Rapid sensory profiling techniques. Applications in new product development and consumer research* (pp. 227–245). Woodhead Publishing, Series in Food Science, Technology and Nutrition.

Dijksterhuis, G. (2016). New product failure: Five potential sources discussed. *Trends in Food Science & Technology*, *50*, 243–248.

Drayna, D. (2005). Human taste genetics. *Annual Review of Genomics and Human Genetics*, *6*, 217–235.

Egolf, A., Hartmann, C., & Siegrist, M. (2019). When evolution works against the future: Disgust's contributions to the acceptance of new food technologies. *Risk Analysis*, *39*, 1546–1559. Available from https://doi.org/10.1111/risa.13279.

European Commission (2021). The tomato market in the EU: Vol. 3a: Trade for fresh products. Working Document AGRI.G2 - F&V - 2021. Available from: https://ec.europa.eu/info/sites/default/files/food-farming-fisheries/farming/documents/tomatoes-trade_en.pdf (accessed 29.10.21).

Fernquist, F., & Ekelund, L. (2013). Consumer attitudes towards origin and organic – The role of credence labels on consumer's liking of tomatoes. *European Journal of Horticultural Science*, *78*(4), 184–190.

Fernqvist, F. (2019). Credence. In H. L. Meiselman (Ed.), *The effects of environment on product design and evaluation* (1st ed.). Woodhead Publishing, Elsevier, Context.

Gamba, M. M., Lima, T., Della Lucia, S. M., Vidigal, M. C. T. R., Simiqueli, A. A., & Minim, V. P. R. (2020). Performance of different scales in the hedonic threshold methodology. *Journal of Sensory Studies*, *35*(5), e12592.

Greenhoff, K., & MacFie, H. J. H. (1994). Preference mapping in practice. In H. J. H. MacFie, & D. M. H. Thomson (Eds.), *Measurement of food preferences* (pp. 137–166). Glasgow: Chapman & Hall.

Grunert, K. G. (2005). Consumer behaviour with regard to food innovations: Quality perception and decision making. In W. M. F. Jongen, & M. T. G. Meulenberg (Eds.), *Innovation in agri-food systems* (pp. 57–85). Wageningen: Wageningen Academic Publishers.

Grunert, K. G. (2017). *Consumer trends and new product opportunities in the food sector*. Wageningen: Wageningen Academic Publishers.

Guerrero, L., & Xicola, J. (2018). New approaches to focus groups. In H. L. Meiselman (Ed.), *The effects of environment on product design and evaluation* (1st ed.). Woodhead Publishing, Elsevier, Context.

Harker, F. R., Amos, R. L., White, A., Petley, M. B., & Wohlers, M. (2008). Flavor differences in heterogeneous foods can be detected using repeated measures of consumer preferences. *Journal of Sensory Studies*, *23*, 52–64.

Jaeger, S. R., Lund, C. M., Lau, K., & Harker, F. R. (2003). In search of the "ideal" pear (*Pyrus* spp.): Results of a multidisciplinary exploration. *Journal of Food Science*, *68*, 1108–1117.

Jaeger, S. R., Rossiter, K. L., Wismer, W. V., & Harker, F. R. (2003). Consumer-driven product development in the kiwifruit industry. *Food Quality and Preference*, *14*, 187–198.

Jaeger, S. R., Jin, D., Christina, M., Roigard, C. M., Le Blond, M., & Ares, G. (2020). Risk of hedonic bias in sensory co-elicitations: Comparison of CATA questions and applicability ratings. *Journal of Sensory Studies*, *35*(5). Available from https://doi.org/10.1111/joss.12601.

Jurkenbeck, K., Spiller, A., & Meyerding, S. G. H. (2019). Tomato attributes and consumer preferences – A consumer segmentation approach. *British Food Journal*, *122*(1), 328–344.

King, S. C., Meiselman, H. L., & Carr, T. (2013). Measuring emotions associated with foods: Important elements of questionnaire and test design. *Food Quality and Preference*, *28*(2), 8–16.

Koppel, K., Chambers, E., Vazquez-Araujo, L., Carbonell-Barrachina, A. A., & Suwonsichon, S. (2014). Cross-country comparison of pomegranate juice acceptance in Estonia, Spain, Thailand, and United States. *Food Quality and Preference*, *31*(1), 116–123.

Köster, E. P. (2009). Diversity in the determinants of food choice: A psychological perspective. *Food Quality and Preference*, *20*(2), 70–82.

Köster, E. P., & Mojet, J. (2016). Familiarity, monotony, or variety: The role of flavor complexity in food intake. In P. Etiévant, E. Guichard, C. Salles, & A. Voilley (Eds.), *Flavor: From food to behaviors, wellbeing and health* (pp. 277–291). Woodhead Publishing, Series in Food Science, Technology and Nutrition.

Köster, E., & Mojet, J. (2018). Complexity of consumer perception: Thoughts on pre-product launch research. In (1st ed.). H. L. Meiselman (Ed.), *The effects of environment on product design and evaluation* (Vol. 1). Woodhead Publishing, Elsevier.

Lange, C., Issanchou, S., & Combris, P. (2000). Expected vs experienced quality: Trade-off with price. *Food Quality and Preference*, *11*(4), 289–297.

Laureati, M., & Pagliarini, E. (2018). New developments in sensory and consumer research with children. In G. Ares, & P. Varela (Eds.), *Methods in consumer research* (Vol. 2). Woodhead Publishing, Series in Food Science, Technology and Nutrition.

Lawless, H. T., & Heymann, H. (2010). Acceptance testing. In H. T. Lawless, & H. Heymann (Eds.), *Sensory evaluation of food – Principles and practices* (2nd ed., pp. 335–349). Springer.

Lichters, M., Moslein, R., Sarstedt, M., & Scharf, A. (2021). Segmenting consumers based on sensory acceptance tests in sensory labs, immersive environments, and natural consumption settings. *Food Quality and Preference*, *89*, 104138.

MacFie, H. J. H. (2007). *Consumer-led food product development*. Cambridge: Woodhead Publishing.

MacFie, H. J. H., & Thomson, D. M. H. (1988). Preference mapping and multidimensional scaling. In J. R. Pigott (Ed.), *Sensory analysis of foods*. New York: Elsevier.

Maggio, A., De Pascale, S., Paradiso, R., & Barbieri, G. (2013). Quality and nutritional value of vegetables from organic and conventional farming. *Scientia Horticulturae*, *164*(17), 532–539.

Malundo, T. M. M. (1996). *Application of the quality enhancement (QE) approach to mango (Mangifera indica L.) flavour research* (thesis/dissertation). Athens, GA: University of Georgia.

Mammasse, M., & Schlich, P. (2014). Adequate number of consumers in a liking test. Insights from resampling in seven studies. *Food Quality and Preference*, *31*(1), 124–128.

Margolskee, R. F. (2004). *Insights into taste transduction and coding from molecular, biochemical, and transgenic studies* (p. 44) Washington, DC: American Chemical Society.

Meilgaard, M. C., Civille, G. V., & Carr, B. T. (2016). *Sensory evaluation techniques* (6th ed.). Boca Raton, FL: CRC Press, Taylor & Francis Group, Internet resource.

Meiselman, H. L. (2007). Integrating consumer responses to food products. In H. J. H. MacFie (Ed.), *Consumer led food product development* (pp. 3–33). Cambridge: Woodhead Publishing.

Meiselman, H. L. (2008). Experiencing products within a physical and social context. In H. N. J. Schifferstein, & P. Hekkert (Eds.), *Product experience* (pp. 559–580). Oxford: Elsevier.

Meiselman, H. L. (2013). The future in sensory/consumer research: Evolving to a better science. *Food Quality and Preference*, *27*, 208–214.

Meiselman, H. L. (2019). *Context*. *The effects of environment on product design and evaluation* (1st ed.). Woodhead Publishing, Elsevier.

Menichelli, E., Olson, V. N., Meyer, C., & Naes, T. (2013). Combining extrinsic and intrinsic information in consumer acceptance studies. *Food Quality and Preference*, *23*(2), 148–159.

Moskowitz, H. R. (1997). Base size in product testing: A psychophysical viewpoint and analysis. *Food Quality and Preference*, *8*, 24–255.

Moskowitz, H. R. (2005). Systematic variation of concept elements and the conjoint analysis approach. In H. R. Moskowitz, S. Porretta, & M. Silcher (Eds.), *Concept research in food product design and development* (pp. 77–104). Ames, IA: Blackwell Publishing.

Moskowitz, H. R., Beckley, J. H., & Resurreccion, A. V. A. (2012a). High level product assessment. In H. R. Moskowitz, J. H. Beckley, & A. V. A. Resurreccion (Eds.), *Sensory and consumer research in food product design and development* (pp. 167–207). Ames, IA: Blackwell Publishing.

Moskowitz, H. R., Beckley, J. H., & Resurreccion, A. V. A. (2012b). What types of sensory tests do sensory researchers do to measure sensory response to the product? In H. R. Moskowitz, J. H. Beckley, & A. V. A. Resurreccion (Eds.), *Sensory and consumer research in food product design and development* (pp. 229–283). Ames, IA: Blackwell Publishing.

Moskowitz, H. R., Beckley, J. H., & Resurreccion, A. V. A. (2012c). *Sensory and consumer research in food product design and development*. Ames, IA: Blackwell Publishing.

Naes, T., Brockhoff, P. B., & Tomic, O. (2010). Preference mapping for understanding relations between sensory product attributes and consumer acceptance. *Statistics for sensory and consumer science* (pp. 127–153). Chichester, UK: Wiley Publishing, ch. 9.

Niedziela, M., & Ambroze, K. (2020). The future of consumer neuroscience in food research. *Food Quality and Preference*, *92*. Available from https://doi.org/10.1016/j.foodqual.2020.104124.

Pagliarini, E., Monteleone, E., & Ratti, S. (2001). Sensory profile of eight tomato cultivars (*Lycopersicon esculentum*) and its relationship to consumer preference. *Italian Journal of Food Science*, *13*, 285–296.

Pangborn, R. (1981). Individuality in responses to sensory stimuli. In J. Solms, & R. L. Hall (Eds.), *Criteria of food acceptance* (pp. 177–217). Zurich: Forster Verlag AG.

Peryam, D. R., & Pilgrim, F. J. (1957). Advanced taste test method. *Food Technology*, *11*, 9–14.

Popper, R., & Kroll, J. J. (2003). Conducting sensory research with children. *Food Technology*, *57*(5), 60–65.

Popper, R., Rosenstock, W., Schraidt, M., & Kroll, B. J. (2004). The effect of attribute questions on overall liking ratings. *Food Quality and Preference*, *15*, 853–858.

Porcherot, C., Delplanque, S., Gaudreau, N., Ischer, M., De Marles, A., & Cayeux, I. (2018). Immersive techniques and virtual reality. In G. Ares, & P. Varela (Eds.), *Methods in consumer research* (Vol. 2). Woodhead Publishing, Series in Food Science, Technology and Nutrition.

Prescott, J., Lee, S. M., & Kim, K. (2011). Analytic approaches to evaluation modify hedonic responses. *Food Quality and Preference*, *22*, 391–393.

Puputti, S., Aisala, H., Hoppu, U., & Sandell, M. (2018). Multidimensional measurement of individual differences in taste perception. *Food Quality and Preference*, *65*, 10–17. Available from https://doi.org/10.1016/j.foodqual.2017.12.006.

Robinson, E., & Higgs, S. (2012). Liking food less: The impact of social influence on food liking evaluations in female students. *PLoS One*, *7*(11), e48858. Available from https://doi.org/10.1371/journal.pone.0048858.

Rolls, E. T. (2012). Taste, olfactory and food texture reward processing in the brain and the control of appetite. *Proceedings of the Nutrition Society*, *71*(4), 488–501.

Rozenbaum, J. (1989). Consumer acceptance of a new brand of selected sweeter grapefruits. Citriculture. In: *Proceedings of the sixth international citrus congress, Middle East* (Vol. 4: Economics, marketing and commercial trends; processing, pp. 1645–1650), March 6–11, 1988, Tel Aviv, Israel.

Rudenga, K. J., & Small, D. M. (2013). Ventromedial prefrontal cortex response to concentrated sucrose reflects liking rather than sweet quality coding. *Chemical Senses*, *38*(7), 585–594.

Samant, S. S., & Seo, H. S. (2020). Influences of sensory attribute intensity, emotional responses, and non-sensory factors on purchase intent toward mixed-vegetable juice products under informed tasting condition. *Food Research International*, *132*, 109095.

Schifferstein, H. N. J., Wehrle, T., & Carbon, C. C. (2019). Consumer expectations for vegetables with typical and atypical colors: The case of carrots. *Food Quality and Preference*, *72*, 98–108.

Schutz, H. G. (1965). A food action rating scale for measuring food acceptance. *Journal of Food Science*, *30*, 365–374.

Sescousse, G., Redoute, J., & Dreher, J. C. (2010). The architecture of reward value coding in the human orbitofrontal cortex. *Journal of Neuroscience*, *30*(39), 13095–13104.

Shewfelt, R. L., & Brückner, B. (2000). *Fruit & vegetable quality. An integrated view*. Lancaster, PA: Technomic Publishing.

Stone, H., Bleibaum, R. N., & Thomas, H. A. (2012). *Sensory evaluation practices* (4th ed.). San Diego: Academic Press.

Stone, H., Bleibaum, R. N., & Thomas, H. A. (2020). *Sensory evaluation practices* (5th ed.). Academic Press, Elsevier.

Thomson, D. (2008). Liking isn't enough!. In: *Third European conference on sensory and consumer research. A sense of innovation*, Hamburg, Germany.

Torres de Castro, N., de Lacerda, L., Rodrigues de Alencar, E., & Assunção Botelho, R. B. (2020). Is there a best technique to cook vegetables? – A study about physical and sensory aspects to stimulate their consumption. *International Journal of Gastronomy and Food Science*, *21*. Available from https://doi.org/10.1016/j.ijgfs.2020.100218.

Tuorila, H. (2007). Sensory perception as a basis of food acceptance and consumption. In H. J. H. MacFie (Ed.), *Consumer-led food product development* (pp. 34–65). Woodhead Publishing.

Varela, P., & Ares, G. (2018). Recent advances in consumer science. In (1st ed.). H. L. Meiselman (Ed.), *The effects of environment on product design and evaluation* (Vol. 1). Woodhead Publishing, Elsevier, Context.

Verain, M. C. D., Sijtsema, S. J., Taufik, D., Raaijmakers, I., & Reinders, M. J. (2020). Motive-based consumer segments and their fruit and vegetable consumption in several contexts. *Food Research International*, *127*. Available from https://doi.org/10.1016/j.foodres.2019.108731.

Vermeir, I., & Roose, G. (2020). Visual design cues impacting food choice: A review and future research agenda. *Foods*, *9*(10), 1495.

Wise, P. M., & Breslin, P. A. (2013). Individual differences in sour and salt sensitivity detection and quality thresholds for citric acid and sodium chloride. *Chemical Senses*, *38*(4), 333–342.

Epilogue

Wojciech J. Florkowski, Nigel H. Banks, Robert L. Shewfelt and Stanley E. Prussia

Consumers demonstrate their preferences in fresh fruits and vegetables by what they eat. These preferences are shaped by many factors. They continually evolve in response to expectations that originate from multiple interacting sources. Postharvest systems are responsive, complex systems. They deliver outcomes that are easier to understand than they are to predict. The fourth edition of this book is a further attempt to link the interdisciplinary nature of postharvest research and market realities to eating fresh fruits and vegetables.

Among the consumption motives is the mounting scientific evidence of broad benefits of eating fresh produce. Growth in fresh produce consumption is unevenly distributed across countries. This uneven consumption shapes domestic and international shipping of fresh produce that has experienced an unprecedented growth in recent decades. Asians are the largest consumers of vegetables, specifically in Pacific Asian countries. Those societies will continue to drive the consumption of fruits and vegetables in the foreseeable future.

Fads come and go as they reflect consumer short-term choices. Shifts in these short-term choices induce various fruit and vegetable sectors to expand or contract. Long-term trends evolve from these continual adjustments in fresh produce supply systems.

Breeding is a primary driver of the dynamics of consumer choices. New cultivars provide a broad platform for postharvest systems to deliver fresh produce that is tasty, accessible, convenient, safe, and competitively priced. With postharvest work, in contrast, a single disciplinary focus can address a selected narrow issue, but it does not capture the multidimensional nature of postharvest handling. As a result, it cannot maximize the benefits. Consistent with the systems approach, postharvest research is most relevant and powerful when it is an interdisciplinary endeavor.

The academic nature of research leads the reward path at public universities through narrow, disciplinary assessments. That path clashes with the uncertainty associated with the reality of raising, harvesting, sorting, grading, shipping, transporting, storing, marketing, and retailing fresh fruits and vegetables. Multiple actions and ownership transfers occur over time and space. These create natural barriers to information exchange that is needed to continually improve value chains for fresh fruits and vegetables in delivering the optimal eating quality to consumers. The latter depends increasingly on the speed of information exchange necessary to enhance the flexibility of responses throughout the value chain. A compounding issue is access to the latest research results. This is challenged by the speed of publication due to the peer-review process, the type of publication, and the language of the publication. The relative slowness of public postharvest research has encouraged the entry of the private research entities.

Waste and loss of fresh fruits and vegetables is larger than that of other food groups. This reflects the lability of quality in fresh produce. Fresh fruits and vegetables are living organisms that continue to respire, senesce, and die during postharvest handling. Efficiencies and effectiveness of postharvest handling have greatly improved since the publication of the first edition of this book, reducing premarket losses. Much of the waste results from consumer behavior and is the combination of the purchase, handling, storing, and the decision when to eat before it spoils. Those aspects of consumer choice and lifestyle have been beyond the scope of the current volume. Adopting a broader systemic view, perhaps this will provide useful complementary content for a future edition.

Responsive value chains adjust to consumer choices. They also communicate to consumers the wholesomeness of what is already available. This multidirectional communication becomes increasingly sophisticated as a system builds. Consumers become more diversified in their purchasing power. Participants increasingly adopt a broader, whole system outlook. They are seeking the win—win—win that develops as collectively they home toward a high quality, low waste with minimal negative impacts on remote societies and the planet. This is the offer intrinsic to adopting the systems approach to postharvest handling.

Index

Note: Page numbers followed by "*f*" and "*t*" refer to figures and tables, respectively.

F

G

Q

R

T

W

X

Y

Z

Fourth Edition

Postharvest Handling

A Systems Approach

This newly revised fourth edition of *Postharvest Handling* brings new and updated chapters with new knowledge and applications from postharvest research. The revised edition brings back the aspects of preharvest conditions and their effects on postharvest quality and features new chapters on the increasingly important role of transportation and logistics. It emphasizes consumers and systems thinking for postharvest chains for fresh produce.

This book also explores current challenges—including oversupply, waste, food safety, lack of resources, sustainability—and best practices for systems to thrive in spite of these challenges. This unique resource provides an overview of postharvest systems and their role in food value chains and offers essential tools to monitor and control the handling process.

Written by a team of experts in Postharvest Systems and Handling, this book continues to be the most practical and up-to-date resource for postharvest physiologists and technologists across the disciplines of agricultural economics, agricultural engineering, food science, and horticulture along with businesses handling fresh or minimally processed products.

- Thoroughly revised and updated fourth edition
- Features new chapters on transportation and logistics, modeling chains, and systems thinking for postharvest value chains
- Focuses on recent postharvest, management, and systems research

ELSEVIER

ACADEMIC PRESS
An imprint of Elsevier
elsevier.com/books-and-journals

ISBN 978-0-12-822845-6
9 780128 228456