Tropical and Subtropical Fruits

Postharvest Physiology, Processing and Packaging

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Muhammad Siddiq
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A John Wiley & Sons, Inc., Publication

Wiley-Blackwell is an imprint of John Wiley & Sons, formed by the merger of Wiley's global Scientific, Technical and Medical business with Blackwell Publishing.

Editorial offices: 2121 State Avenue, Ames, Iowa 50014-8300, USA
The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK
9600 Garsington Road, Oxford, OX4 2DQ, UK

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Library of Congress Cataloging-in-Publication Data

Tropical and subtropical fruits : postharvest physiology, processing and packaging / editor, Muhammad Siddiq ; associate editors, Jasmim Ahmed, Maria Gloria Lobo, Ferhan Ozdali.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-8138-1142-0 (hardcover : alk. paper)
1. Tropical fruit–Processing. I. Siddiq, Muhammad, 1957–
TP440.T76 2012
664′.8046–dc23

2011048258

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

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Set in 9.5/12 pt Times by Aptara® Inc., New Delhi, India

1 2012

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Preface

Tropical and subtropical fruits have gained significant importance in global commerce in recent years, as evidenced by significant growth in their production and consumption since the mid-1990s. Two factors have contributed to this continued growth: (1) increased consumption of fruits and vegetables to promote good health and well-being and (2) the growing popularity of tropical and subtropical fruits among North American and European consumers, which has resulted in increased trade. Tropical and subtropical fruits are a good source of a number of vitamins, minerals, and other natural substances, for example, bioactive phytochemicals, making their demand grow further.

This book is a contemporary collective work that brings together current knowledge and practices in the value chain of tropical and subtropical fruits from "farm-to-fork." This value chain approach to the topic's coverage is the unique feature of this book. An experienced team of more than 60 contributors from North America, South America, Asia, Africa, and Europe has written 31 chapters, divided into five parts. The contributors come from diverse disciplines, including horticulture, postharvest physiology, food science and technology, food biochemistry, food engineering, and packaging technology.

Part I of the book has seven chapters, covering an introduction and overview, postharvest physiology and storage technologies, role of enzymes in fruit quality and processing, phytochemicals, packaging technologies, innovative and novel fruit processing technologies, and quality management of tropical and subtropical fruits. Part II has 11 chapters on tropical fruits (banana, coconut, dates, guava, longan and carambola, lychee, mango, papaya, passion fruit, and pineapple). Part III has four chapters on citrus-group subtropical fruits (grapefruit, lemon and lime, orange, tangerine, mandarin, and clementine), and Part IV covers six chapters on noncitrus subtropical fruits (avocado, figs, kiwifruit, olives and olive oil, pomegranate, watermelon, cantaloupe, and honeydew). The last part, Part V, has three chapters on eight lesser known tropical and subtropical fruits (acerola, cashew apple, cherymoya and pitanga, dragon fruit and durian, and jujube and loquat). Each of these 31 chapters provides an in-depth review of topics covering history, production, consumption trends, varieties and field practices, harvesting and postharvest physiology/storage, commercial processing, application of novel processing techniques, composition and nutritional profiles of raw and processed fruit products, and potential health benefits.

Currently there are a very limited number of books on the tropical and subtropical fruits, with none taking a multidisciplinary approach to covering the topics, as we have attempted in this work. This book is intended as a contemporary source book on tropical and subtropical fruits' postharvest physiology, processing, and packaging for industry, academia, government agencies, libraries, research institutes, laboratories, and other interested professionals.

The editorial team acknowledges many individuals for their support from conception through final development of this book. Foremost is our sincere thanks and gratitude to all authors for their contributions and for bearing with us during the review and finalization process of their chapters. We are grateful to our family members for their understanding and support, enabling us to complete this work.

Muhammad Siddiq
Jasim Ahmed
Maria Gloria Lobo
Ferhan Ozadali

Part I
Overview, Innovative Technologies and Quality Management

1
Introduction and Overview

Adel Kader and Muhammad Siddiq

INTRODUCTION

Although several books on postharvest biology and technology of horticultural perishables, including some of the subtropical and tropical fruits (Table 1.1), have been published during the past 20 years (Seymour et al., 1993; Salunkhe and Kadam, 1995; Shaw et al., 1998; Kader, 2002; Knee, 2002; Chakraverty et al., 2003; Thompson, 2003; Gross et al., 2004; Kays and Paull, 2004; Ben-Yehoshua, 2005; Lamikanra et al., 2005; Wills et al., 2007; Nunes, 2008; Paliyath et al., 2008; Florkowski et al., 2009; Valero and Serrano, 2010), only two focused on tropical and subtropical fruits (Mitra, 1997; Yahia, 2011). Books dealing with specific tropical and subtropical fruits include those on avocado (Whiley et al., 2002), banana and plantain (Robinson and Galan-Sauco, 2010), citrus fruits (Wardowski et al., 2006; Ladaniya, 2008), durian (Ketsa and Subhadrabandhu, 2001), lychee/litchi and longan (Menzel and Waite, 2005), mango (Litz, 2009), olive (Therios, 2008), pineapple (Bartholomew et al., 2002), and pomegranate (Seeram et al., 2006). This book focuses on tropical and subtropical fruit processing and packaging for maintaining quality and safety between harvest and consumption. In this chapter, we provide an overview of current trends in production, consumption, and marketing of tropical and subtropical fruits. Also included is a brief discussion of current trends in postharvest technology research and development and of strategies for reducing postharvest losses of foods of plant origin.

The significance of tropical and subtropical fruits can be seen from the data presented in Table 1.2, which lists these fruits, by rank, in the top 20 commodities produced in a specific world region. It is to be noted that Food and Agriculture Organization (FAO) data on top 20 commodities not only includes all fruits but is composed of all vegetables, field crops, dairy, livestock, and any other specialty crop. Banana, plantain, mango, pineapple, oranges, coconut, olive, and avocado are of commercial importance for many regions of the world. In addition to tropical and subtropical fruits' significance in local economies, in many cases, these fruits are a source of foreign exchange earnings.

TRENDS IN PRODUCTION AND MARKETING

Tropical fruits include acerola, banana, breadfruit, carambola, durian, guava, jackfruit, longan, Mamey sapote, mango, mangosteen, papaya, passion fruit, pineapple, prickly pear, rambutan, sapodilla, soursop, and sweetsop (Table 1.1). A few of these fruits are also grown in subtropical regions. Only four of these fruits, i.e., banana, mango, papaya, and pineapple, are important in international commerce. However, other tropical fruits are becoming more significant in international trade. Most of the tropical fruits are consumed in and/or close to their production areas. The top ten producing countries of tropical fruits are India, the Philippines, China, Indonesia, Bangladesh, Thailand, Brazil, Pakistan, Colombia, and Mexico (FAO, 2011).

Subtropical fruits include avocado, carob, cherimoya, citrus fruits, dates, figs, jujubes, kiwifruit, loquat, lychee, olive, persimmon, and pomegranate. Some of these fruits are also grown in tropical areas. The top ten producing countries of citrus fruits are Brazil, the United States, India,

Tropical and Subtropical Fruits: Postharvest Physiology, Processing and Packaging, First Edition. Edited by Muhammad Siddiq.

Table 1.1. Scientific names of subtropical and tropical fruit.

Common Name	Scientific Name
Acerola (West Indian cherry)	*Malpighia glabra*
Annona fruits	
Cherimoya	*Annona cherimola*
Custard apple	*Annona reticulata*
Atemoya	*Annona atemoya* (*A. cherimola* × *A. squamosa*)
Soursop	*Annona muricata*
Sweetsop, sugar apple	*Annona squamosa*
Avocado	*Persea americana*
Banana	*Musa paradisiaca* var sapientum
Breadfruit	*Atrocarpus altilis, A. communis*
Canistel	*Pouteria campechiana*
Carambola (star fruit)	*Averrhoa carambola*
Carob	*Ceratonia siliqua*
Cashew apple	*Anacardium occidentale*
Citrus fruits	
Grapefruit	*Citrus paradisi*
Kumquat	*Fortunella* spp.
Lemon	*Citrus limon*
Lime	*Citrus aurantifolia*
Mandarin/tangerine	*Citrus reticulata*
Orange	*Citrus sinensis*
Pummelo	*Citrus maxima*
Coconut	*Cocos nucifera*
Date	*Phoenix dactylifera*
Durian	*Durio zibethinus*
Feijoa (pineapple guava)	*Feijoa sellowiana*
Fig	*Ficus carica*
Guava	*Psidium guajava*
Jackfruit	*Atrocarpus heterophyllus*
Jujube, Chinese (Chinese date)	*Zizyphus jujuba*
Jujube, Indian (Ber)	*Zizyphus mauritiana*
Kiwifruit	*Actinidia deliciosa*
Lanson, langsat	*Lansium domesticum*
Longan	*Euphoria longana*
Loquat	*Eriobotrya japonica*
Lychee (litchi)	*Litchi chinensis* or *Nephelium litchi*
Mango	*Mangifera indica*
Mangosteen	*Garcinia mangostana*
Olive	*Olea europea*
Papaya	*Carica papaya*
Passion fruit	*Passiflora edulis*
Pejibaye	*Bactris gasipaes*
Pepino	*Solanum muricatum*
Pineapple	*Ananas comosus*

Table 1.1. (*Continued*)

Common Name	Scientific Name
Pitaya (pitahaya, dragon fruit)	*Hylocereus undatus*
Prickly pear (tuna)	*Opuntia* spp. (including ficus-indica, robusta, etc.)
Plantain	*Musa paradisiaca* var paradisiaca
Pomegranate	*Punica granatum*
Rambutan	*Nephelium lappaceum*
Sapotes	
Mamey sapote	*Calocarpum mannosum*
Sapodilla or chicozapote	*Manilkara zapota*
Black sapote	*Diospyros ebenaster*
Zapote = mammee apple	*Mammea americana*
Spondias (Wi apple)	*Spondias cytherea*
Tamarillo (tree tomato)	*Cyphomandra betacea*
Tamarind	*Tamarindus indica*

Mexico, China, Spain, Iran, Italy, Indonesia, and Egypt (FAO, 2011).

About 50% of the tropical and subtropical fruit production is consumed fresh, and 50% is used in various processed forms (canned, dried, freeze-dried, frozen, juiced). The value of US imports of all fruits exceeded $8.9 billion in 2009–2010 (USDA-ERS, 2010), and the value of US exports of fruits was about $5.9 billion in 2009–2010.

World and regional production of major tropical and subtropical fruits has seen a monumental growth in the last two decades. Discussion on selected fruits follows; for data on most other fruits, the reader is directed to chapters on individual fruits in this book.

Banana

The world production of banana in 2010 was 102.11 million metric tons (MT). The 1990–2010 regional and world banana annual production is shown in Fig. 1.1. From 1990 to 2010, banana production more than doubled, from 46.81 million MT to 102.11 million MT. The Asian region contributed the most to this growth and saw an increase of 220.30%, followed by Oceania, Africa, and the Americas (North, Central, and South), with increases of 106.83%, 67.69%, and 38.16%, respectively. The top ten banana-producing countries in 2010 were India, China, the Philippines, Ecuador, Brazil, Indonesia, Tanzania, Guatemala, Mexico, and Colombia (FAO, 2011).

Pineapple

The world production of pineapple in 2010 was 19.42 million MT. The 1990–2010 regional and world pineapple annual production is shown in Fig. 1.2. From 1990 to 2010, world production increased by 67.61%, from 11.59 million MT; years 2008–2009 saw some decreases in pineapple production. Overall, the Americas (North, Central, and South), Asia, and Africa had significant increases in pineapple production during the last two decades (100.49%, 62.33%, and 29.97%, respectively), whereas production in Europe and Oceania remained fairly flat. Top ten pineapple-producing countries in 2010 were the Philippines, Brazil, Costa Rica, Thailand, China, India, Indonesia, Nigeria, Mexico, and Vietnam (FAO, 2011).

Papaya

The papaya world production was 11.20 million MT in 2010. Figure 1.3 shows regional and world papaya annual production data from 1990 to 2010; the total production increased by 243.21% (from 3.26 million MT). Asia and the Americas (North, Central, and South) had significant increases at 399.41% and 226.51%, respectively; during the same period, Africa saw an increase of 52.44% in papaya production. The top ten papaya-producing countries were India, Brazil, Nigeria, Indonesia, Mexico, Columbia, Ethiopia, Congo, Thailand, and Guatemala (FAO, 2011).

Mango, mangosteen, and guava

The mango production data is not reported separately by the FAO; it includes mangosteen and guava, too. For these fruits, there was an increase of 126.77%, from 17.05 million MT in 1990 to 38.67 million MT in 2010 (Fig. 1.4). During the last two decades, Africa, Asia, and the Americas (North, Central, and South) saw increases of 139.83%, 132.40%,

Table 1.2. Regional significance of tropical and subtropical fruits: Fruits in the top 20 commodities produced.[1]

Region	Tropical and Subtropical Fruits in Top 20 Commodities Produced
Africa	
Eastern Africa	Plantain (5), banana (6), mango (17)
Middle Africa	Plantain (3), banana (4), palm Oil (15), mango (18)
Northern Africa	Olive (6), date (11), orange (13)
Southern Africa	Orange (11)
Western Africa	Citrus, minor (7), plantain (9), palm oil (18)
Americas	
North America	Orange (16)
Central America	Banana (5), mango, mangosteen, guava (10), orange (12), avocado (14), lemon and lime (16), pineapple (17)
Caribbean	Mango, mangosteen, guava (5), banana (7), plantain (10), avocado (13), orange (16)
South America	Banana (8), orange (11)
Asia	
Central Asia	Watermelon (20)
Eastern Asia	Watermelon (17)
Southern Asia	Mango, mangosteen, guava (6), banana (8)
South-Eastern Asia	Palm Oil (2), banana (7), coconut (9), mango, mangosteen, guava (10), palm kernel (15), pineapple (20)
Western Asia	Olives (7), date (12)
Europe	
Eastern Europe	—
Northern Europe	—
Southern Europe	Olive (1), orange (12), tangerine, mandarin, clementine (19)
Western Europe	—
Oceania	
Australia and New Zealand	Kiwifruit (13), Orange (20)
Melanesia	Banana (3), palm oil (5), coconut (6), palm kernel (18)
Micronesia	Coconut (1), banana (3), watermelons (14), plantain (20)
Polynesia	Coconut (1), banana (3), mango, mangosteen, guava (11), pineapple (12)

[1]Numbers in parentheses are commodity ranks for respective regions.
Source: Adapted from FAO (2011).

and 88.86%, respectively. The top ten mango, mangosteen, and guava producing countries were India, China, Thailand, Pakistan, Mexico, Indonesia, Brazil, Bangladesh, and the Philippines (FAO, 2011).

Citrus group

The citrus group includes oranges, grapefruit, lemon and lime, and tangerine. The 2010 world production of citrus fruits was 112.01 million MT (Fig. 1.5), which represented an increase of 52.26% from 73.57 million MT in 1990. Asia and Africa saw major increases in total production at 125.43% and 70.08%, respectively. In the Americas (North, Central, and South), after a growth of 41.72% from 1999 to 2000, production decreased 13.58% from 2000 to 2010. The production of citrus group fruits in Europe remained fairly unchanged during the last two decades. On an individual fruit basis, oranges, grapefruit, lemon and lime, and tangerine had increases of 39.84%, 70.70%, 96.38%, and 69.99%,

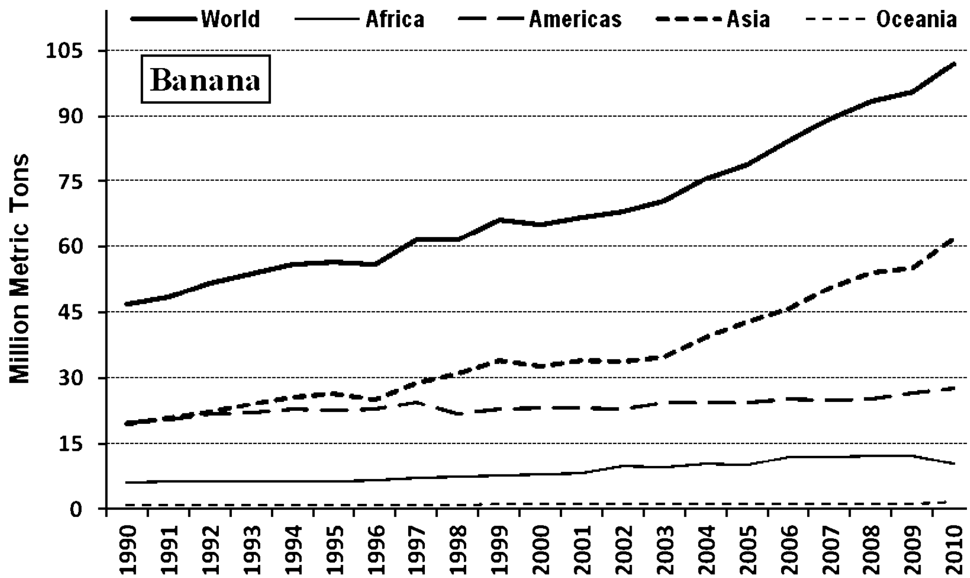

Figure 1.1. Regional and world banana production, 1990–2010 (not shown: Europe, with <1% of world total) (source: FAO, 2011).

respectively. The top ten producers of citrus group fruits were China, the United States, Brazil, Mexico, India, Spain, Argentina, Turkey, Iran, and Italy (FAO, 2011).

TRENDS IN CONSUMPTION

The food availability data represent the supply of food available for consumption in the United States. For a given year, the supply of each commodity is the sum of production, imports, and beginning inventories, and from this amount, the US Department of Agriculture's (USDA's) Economic Research Service (ERS) subtracts out exports, farm and industrial uses, and ending stocks. The USDA collects data on these components directly from producers and distributors using techniques that vary by commodity. These data are not

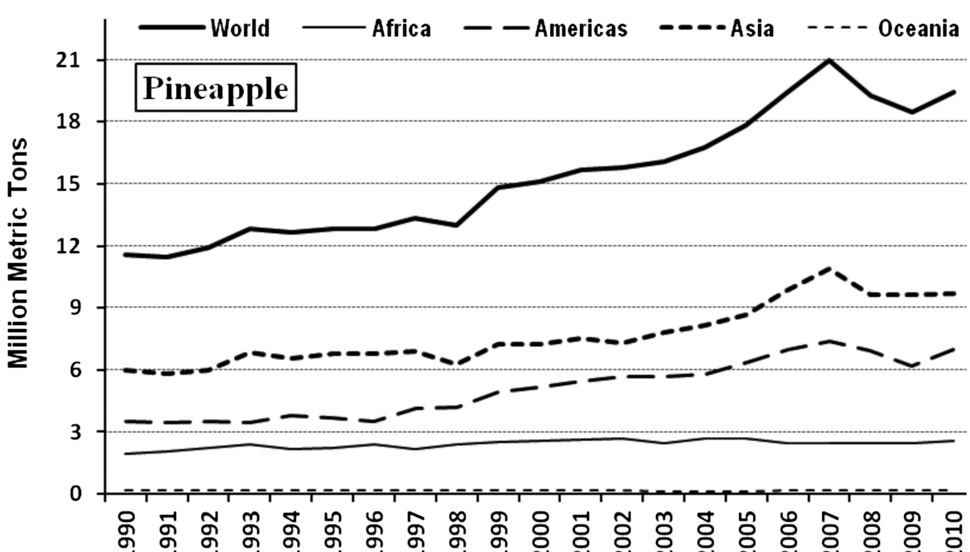

Figure 1.2. Regional and world pineapple production, 1990–2010 (not shown: Europe, with <1% of world total) (source: FAO, 2011).

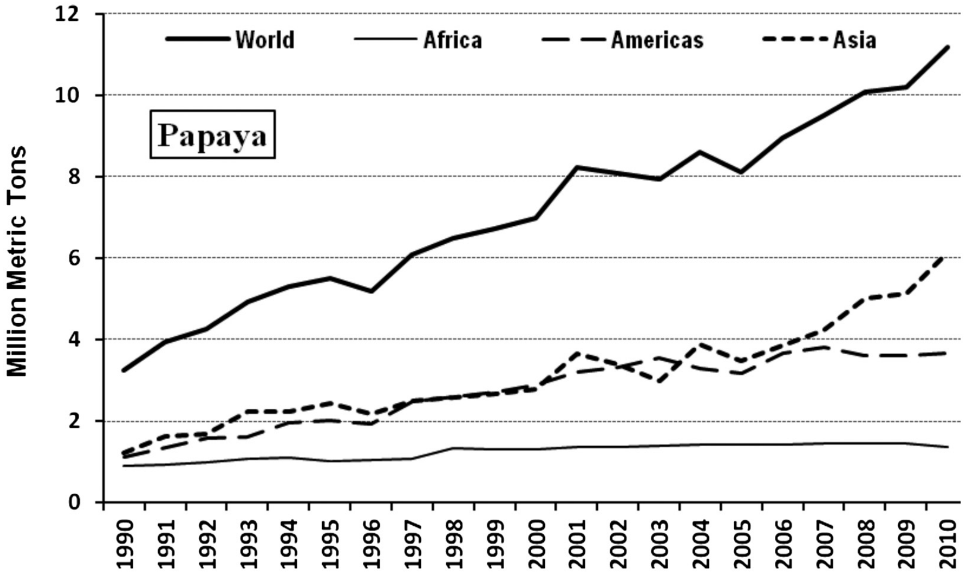

Figure 1.3. Regional and world papaya production, 1990–2010 (not shown: Europe and Oceania, with <1% of world total) (source: FAO, 2011).

collected from individual consumers, and thus provide an independent basis for examining food consumption trends. Per capita estimates are calculated by dividing the total annual availability for a commodity by the US population for that year. ERS manages and disseminates the food availability data within a data system posted on the ERS website (http://www.ers.usda.gov/Data/FoodConsumption/). In recent years, ERS began adjusting per capita fruit consumption estimates on the basis of postharvest loss estimates, which averaged 11.4% at the retail level for fresh fruit in 2006 (Buzby et al., 2009). The US per capita fruit consumption estimates (per year) in 2008 were 122.6 lbs

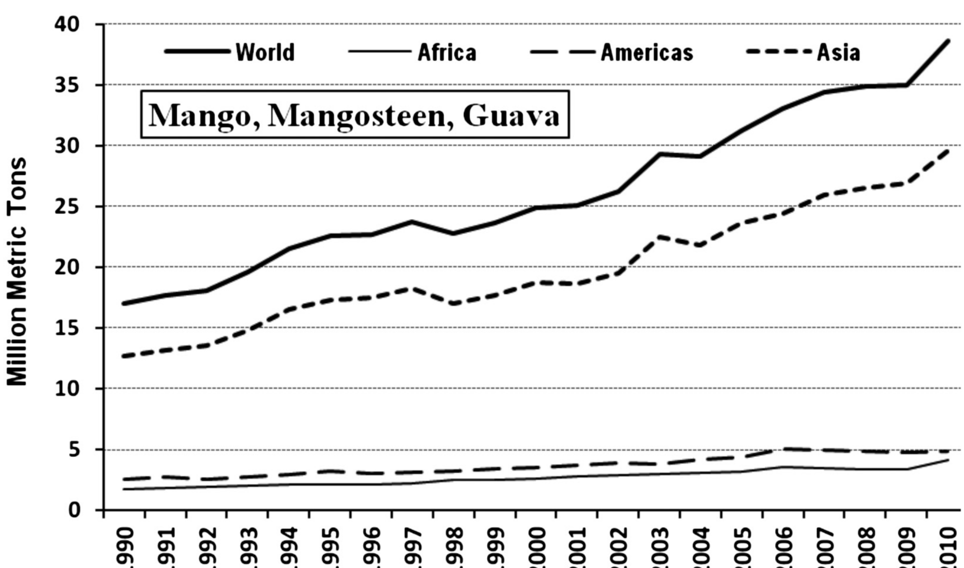

Figure 1.4. Regional and world mango, mangosteen, and guava production, 1990–2010 (not shown: Europe and Oceania, with <1% of world total) (source: FAO, 2011).

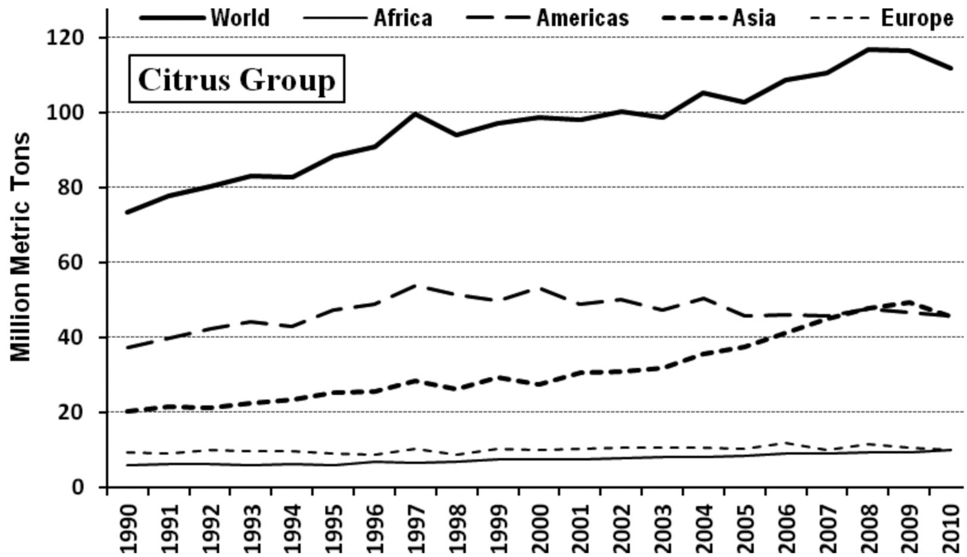

Figure 1.5. Regional and world citrus group fruit production, 1990–2010 (not shown: Oceania, with <1% of world total) (source: FAO, 2011).

total fruits (including about 54 lbs fresh + 52 lbs juice + 11 lbs canned + 3 lbs frozen + 2 lbs dried). The total included 37.1 lbs citrus fruits (including about 30.4 lbs oranges + 2.4 lbs grapefruits + 1.6 lbs limes + 1.5 lbs lemons + 1.2 lbs tangerines) plus 85.5 lbs noncitrus fruits (including 10.1 lbs bananas, 5.4 lbs pineapples, 0.8 lb mangos, 0.8 lb olives, and 0.2 lb papayas). Despite all the efforts of the various governmental and industry organizations to encourage increased consumption of fruits, the average fruit consumption in the United States is still much below recommendations of at least two servings (200 g) per day.

CURRENT POSTHARVEST TECHNOLOGY, RESEARCH AND DEVELOPMENT TRENDS

Current trends that are expected to continue in the future include globalization of produce marketing, consolidation or formation of alliances among producers and marketers from various production areas, consolidation of retail marketing organizations, and increased demand for year round supply of many produce items with better flavor. Other trends include shifting toward more sustainable production and marketing systems, increased demand for organic produce and locally produced foods, use of processing and packaging technologies that preserve flavor and nutritional quality of produce, and increased efforts to assure safety of food products.

Maintaining the cold chain and the modified atmosphere chain, when needed, are very important to preserving quality and safety of intact and fresh-cut fruits throughout their distribution systems and to globalization of produce marketing. Other postharvest technologies, such as the use of the anti-ethylene action gas (1-methylcyclopropene), surface coatings, postharvest fungicides, heat treatments, ionizing radiation, ozone, ethylene scrubbers, and modified atmosphere packaging, are supplements to the most important technologies that are focused on maintenance of optimal ranges of temperature and relative humidity (Kader, 2003). A major challenge in postharvest handling of tropical and subtropical fruits is their susceptibility to chilling injury if exposed to temperatures below 5°–12°C (depending on the species), which limits their postharvest life.

Research aimed at identifying maturity and quality indices for a broad range of fruits has resulted in development of many nondestructive methods of quality evaluation (Abbott et al., 1997; Knee, 2002). Near-infrared (NIR) spectrophotometry is used commercially to differentiate some fruits according to their sugar content. Fruit bounce firmness measurement and acoustic impulse transmission technologies are used to separate fruits, such as avocados and mangoes, based on their firmness. Development of nondestructive quality evaluation technologies continues to be a very active R&D area (Florkowski et al., 2009).

Research on how to maintain quality and safety of fresh-cut fruits increased greatly during the past 20 years in response to commercial development of value-added, ready-to-eat products. Strategies for delaying browning and softening of wounded plant tissues and for maintaining their safety by minimizing microbial growth have been developed (Lamikanra, 2002; Sapers et al., 2006; Fan et al., 2009; Martin-Belloso and Soliva-Fortuny, 2010), but more research is needed to enable extension of postcutting life based on flavor and nutritional quality. Minimal processing technologies (such as treatments with high pressure, UV radiation, and/or mild heat) and use of nanotechnology in food preservation and packaging are active R&D areas (Barrett et al., 2004).

Nutritional and flavor quality of fruits

Fresh fruits play a very significant role in human nutrition, especially as sources of vitamins (vitamin C, vitamin A, vitamin B_6, thiamine, niacin), minerals, and dietary fiber (Vicente et al., 2009). Other constituents that may lower risk of cancer and other diseases include flavornoids, carotenoids, polyphenols, and other phytonutrients (Tomas-Barberan and Gil, 2008). Postharvest losses in nutritional quality, particularly vitamin C content, can be substantial and are enhanced by physical damage, extended storage duration, high temperatures, low relative humidity, and chilling injury of chilling-sensitive fruits. The effects of processing methods on nutritional quality of fruits are presented in reviews by Rickman et al. (2007a, 2007b). Further research by human nutrition and health researchers in collaboration with postharvest horticulturists and food scientists is needed to better understand the bioavailability and value of phytochemicals in fruits to human health. Much greater efforts are needed to inform consumers, especially children, about the health benefits of eating fruits.

Flavor attributes and associated constituents include sweetness (sugars), sourness or acidity (acids), astringency (tannins), aroma (odor-active volatile compounds), off flavors (acetaldehyde, ethanol, and/or ethyl acetate above certain concentrations that depend on the fruit's sugar content), and off odors (sulfurous compounds above certain concentrations).

Providing better flavored fruits is likely to increase their consumption, which would be good for the producers and handlers (making more money or at least staying in business) as well as for the consumers (increased consumption of healthy foods). To achieve this goal, producers and processors need to implement the following action plan (Kader, 2008):

1. Replace poor flavor cultivars with good flavor cultivars from among those that already exist and/or by selecting new cultivars with superior flavor and good textural quality.
2. Identify optimal cultural practices that maximize flavor quality, such as optimizing crop load and avoiding excess nitrogen and water, which along with low calcium shorten the postharvest life of fruits due to increased susceptibility to physical damage, physiological disorders, and decay.
3. Encourage producers to harvest fruits at partially ripe to fully ripe stages by developing handling methods that protect the fruits from physical damage.
4. Identify optimal postharvest handling conditions (time, temperature, relative humidity, atmospheric composition) that maintain flavor quality of fruits and their value added products.
5. Develop ready-to-eat, value-added products with good flavor.
6. Optimize the maturity/ripeness stage in relation to flavor quality at the time of processing and select processing methods to retain good flavor of the processed fruit products.

Management of temperature and relative humidity

Providing the optimal ranges of temperature and relative humidity (RH) is the most important tool for maintaining quality and safety of intact and fresh-cut fruits (Gross et al., 2004; Kader, 2002). There is a continuing trend toward increased precision in temperature and RH management to provide the optimum environment for fresh produce during cooling, storage, and transport. Precision temperature management tools, including radio-frequency identification (RFID) tags and time–temperature monitors, are becoming more common in produce handling. Several manufacturers have developed self-contained temperature and RH monitors and recorders, which are small and can be packed in a box with the product. Data are read by connecting these units to a personal computer with the appropriate software provided by the manufacturer. Infrared thermometers are used to measure surface temperature of products from a distance in various locations within storage facilities. Electronic thermometers (with very thin, strong probes for fast response) are used for measuring product temperature during cooling, storage, and transport operations. Recent surveys indicate the need for continued improvements in temperature maintenance throughout the produce handling systems.

Modified and controlled atmospheres

Continued research on technologies to reduce water loss included the use of polymeric films (Ben-Yehoshua, 2005) and surface coatings (Baldwin, 1994; Amarante and Banks, 2001). The use of polymeric films for packaging produce and their application in modified atmosphere packaging (MAP) systems at the pallet, shipping containers (plastic liners), and consumer package levels continues to increase (Kader et al., 1989; Beaudry, 2000; Watkins, 2000). MAP (usually to maintain 2–4% O_2 and 8–12% CO_2) is widely used in extending the shelf life of fresh-cut fruit products. The use of absorbers of ethylene, carbon dioxide, oxygen, and/or water vapor as part of MAP is increasing. Although much research has been done on the use of surface coatings to modify the internal atmosphere within the commodity, commercial applications are still very limited due to the variability of the fruit's gas diffusion characteristics and the stability and thickness of the coating.

Several refinements in controlled atmosphere (CA) storage technology have been made in recent years (Yahia, 2009). These include the creation of nitrogen on demand by separation from compressed air using molecular sieve beds or membrane systems, use of low (0.7–1.5%) O_2 concentrations that can be accurately monitored and controlled, rapid establishment of CA, ethylene-free CA, programmed (or sequential) CA (such as storage in 1% O_2 for 2–6 weeks, followed by storage in 2–3% O_2 for the remainder of the storage period), and dynamic CA, where levels of O_2 and CO_2 are modified as needed based on monitoring some attributes or produce quality such as ethanol concentration and chlorophyll fluorescence. Despite the extensive research and development efforts of hypobaric storage (Burg, 2004), its commercial use is very limited.

The use of CA in refrigerated marine containers continues to benefit from technological and scientific developments. CA transport is used to continue the CA chain for some fruits (such as kiwifruits) that had been stored in CA since harvest. CA transport of bananas permits their harvest at a more fully mature stage, resulting in higher yield. CA transport of avocados facilitates the use of a lower temperature (5°C) than if shipped in air because CA ameliorates chilling injury symptoms. CA combined with precision temperature management may allow nonchemical insect control in some commodities (Mitcham, 2003) for markets that have restrictions against pests endemic to exporting countries and for markets that prefer organic produce.

At the commercial level, CA is most widely applied during the storage and/or transport of avocados, bananas, kiwifruits, mangos, persimmons, pomegranates, and nuts and dried fruits. Continued technological developments in the future to provide CA during transport and storage at reasonable cost (positive benefit/cost ratio) are essential to expanding its application on fresh tropical and subtropical fruits.

Reducing undesirable effects of ethylene

The promotion of ripening and senescence in harvested fruits by ethylene ($>$0.1 ppm) results in acceleration of deterioration and reduced postharvest life. Ethylene induces abscission of fruits, softening of fruits, and several physiological disorders (Abeles et al., 1992; Reid, 1995). Ethylene may increase decay development of some fruits by accelerating their senescence and softening, and by inhibiting the formation of antifungal compounds in the host tissue. In some cases, ethylene may stimulate growth of fungi such as *Penicillium italicum* on oranges (Sommer, 1989).

Low temperatures, controlled or modified atmospheres (Kader, 1986a), and ethylene avoidance and/or scrubbing techniques are used to reduce ethylene damage. The discovery of the ethylene action inhibitor 1-methylcyclopropene (1-MCP) in the early 1990s (Sisler and Blankenship, 1996) was a major breakthrough. In July 2002, 1-MCP (under the trade name "SmartFresh") at concentrations up to 1 ppm was approved by the US Environmental Protection Agency for use on apples, apricots, avocados, kiwifruit, mangoes, nectarines, papayas, peaches, pears, persimmons, plums, and tomatoes. The first commercial application has been on apples to retard their softening and scald development and extend their postharvest life during air and CA storage. As more research is completed, the use of 1-MCP is being extended to several other commodities (Blankenship and Dole, 2003; Sozzi and Beaudry, 2007; Watkins, 2008).

Postharvest pathology

Currently used treatments for decay control include (1) heat treatments (Lurie, 1998; Paull and Chen, 2000), such as dipping mangoes for 5 min in 50°C water to reduce subsequent development of anthracnose; (2) use of safer postharvest fungicides, such as Fenhexamid and Fludioxonil; (3) use of biological control agents (Wilson and Wisniewski, 1989; Droby et al., 2009), such as "bio-Save" (*Pseudomonas syringae*) and "Aspire" (*Candida olephila*) alone or in combination with fungicides at lower concentrations on citrus fruits; (4) use of growth regulators, such as gibberellic acid or 2,4-D to delay senescence of citrus fruits; (5) use of 15–20% CO_2 in air or 5% O_2 on figs and pomegranates; and (6) use of SO_2 fumigation (100 ppm for 1 hour) on longans and lychees.

Integrated pest management (IPM) approaches are increasingly being used for control of decay-causing pathogens and insects that are of quarantine importance on some subtropical and tropical fruits. Maintaining the health of the fruit (by minimizing physical damage and providing optimal ranges of temperature and RH) is an essential component of Postharvest IPM. Also, using cultivars with resistance to certain diseases is a very important tool of IPM.

Postharvest entomology

A large number of insects can be carried by fresh fruits during postharvest handling. Many of these insect species, especially the fruit flies of the family Tephritidae (e.g., Mediterranean fruit fly, Oriental fruit fly, Mexican fruit fly, Caribbean fruit fly), can seriously disrupt trade among countries. Continuing globalization of marketing fresh produce will be facilitated by use of acceptable disinfestation treatments. Selection of the best treatment for each commodity will depend upon the comparative cost and the efficacy of that treatment against the insects of concern with the least potential for damaging the host (Paull and Armstrong, 1994; Sharp and Hallman, 1994; Heather and Hallman, 2008). Much of the research during the past 20 years has been focused on finding alternatives to methyl bromide fumigation.

Currently approved quarantine treatments include certification of insect-free areas, use of chemicals (e.g., methyl bromide, phosphine, hydrogen cyanide), cold treatments, heat treatments, irradiation, and some combinations of these treatments, such as methyl bromide fumigation followed by cold treatment. The potential for additional treatments, such as new fumigants (carbonyl sulfide, methyl iodide, sulfuryl fluoride), insecticidal atmospheres ($<$0.5% O_2 and/or 40–60% CO_2) alone on or in combination with heat treatments, and ultraviolet radiation, is being investigated (Neven, 2010). Each of these treatments is usable on a limited number of fruits but causes phytotoxic effects on others.

Most insects are sterilized when subjected to irradiation doses ranging between 50 and 750 Gy. The actual dosage required varies in accordance with the species and its stage of development. An irradiation dose of 250 Gy has been approved for certain fresh commodities, such as lychee, mango, and papaya, by US quarantine authorities in light of its efficacy in preventing the reproduction of tropical fruit flies. Most fresh fruits will tolerate irradiation dose of 250 Gy with minimal detrimental effects on quality. At doses above 250 Gy and up to 1,000 Gy (the maximum allowed as of 2010), damage can be sustained by some fruits (Kader, 1986b). Detrimental effects on fresh fruits may include loss of green color (yellowing), tissue discoloration, and uneven ripening (Kader, 1986b; Bruhn et al., 2009).

FOOD SAFETY AND SECURITY (DEFENSE)

Over the past 15 years, food safety has become and continues to be the primary concern of the fresh produce industry and regulatory agencies (Sapers et al., 2006; Fan et al., 2009). The US Food and Drug Administration (FDA) published in October 1998 a *Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables*. This guide is based on the general principle that prevention of microbial contamination of fresh produce is favored over reliance on corrective actions once contamination has occurred. A manual for trainers, titled *Improving the Safety and Quality of Fresh Fruits and Vegetables*, was published by the FDA in November 2002 to provide uniform, broad-based scientific and practical information on the safe production, handling, storage, and transport of fresh produce. Also, commodity-specific food safety manuals have been developed and are being used.

The emphasis of current research on produce safety is on developing reliable and quick detection methods for human pathogens, improved efficacy of water disinfection methods, and developing methods for reducing microbial load on intact and fresh-cut fruits. Other aspects of produce safety include assuring that the residues of pesticides are within the legal limits and handling conditions that may lead to contamination with mycotoxins are avoided.

On March 19, 2003, the FDA released food security (defense) guidance documents for food producers, processors, and transporters. These documents are intended to help operators of food handling facilities identify preventive measures to minimize the security risks to their products.

POTENTIAL OF BIOTECHNOLOGY TO IMPROVE QUALITY AND POSTHARVEST SHELF LIFE OF FRUITS

There are many opportunities to develop genotypes that have lower respiration and ethylene production rates, less sensitivity to ethylene, slower softening rates, improved flavor quality, enhanced nutritional quality (vitamins, minerals, dietary fiber, and phytonutrients including carotenoids and polyphenols), reduced browning potential, decreased susceptibility to chilling injury, and increased resistance to postharvest decay-causing pathogens.

Biotechnology is a tool that can be utilized, in an interdisciplinary approach, to address some of the concerns about quality attributes and the biological causes of deterioration of harvested produce (Kader, 2003; Pech et al., 2005). Three approaches are being utilized to extend postharvest life and maintain quality: selecting for slower ripening lines, modification of ethylene responses, or reducing softening rate. For example, papaya varieties having slow ripening characteristics have been selected, delayed ripening by the down-regulation of ethylene synthesis enzymes, ACC synthase (ACS) and ACC oxidase (ACO), is being tested for banana and papaya, and the modification of fruit softening related enzymes is being examined (Paull and Chen, 2004).

In some cases the goals may be contradictory, such as lowering phenolic content and activities of phenylalanine ammonialyase and /or polyphenoloxidase to reduce browning potential versus increasing polyphenols as antioxidants with positive effects on human health. Another example is reducing ethylene production versus increasing flavor volatiles production in fruits. Overall, priority should be given to attaining and maintaining good flavor and nutritional quality to meet consumer demands. Extension of postharvest life should be based on flavor and texture rather than appearance only. Introducing resistance to physiological disorders and/or decay-causing pathogens will reduce the use of postharvest fungicides and other chemicals by the produce industry. Changes in surface structure of some commodities can help in reducing microbial contamination. It is not likely that biotechnology-based changes in fresh fruits will lessen the importance of careful and expedited handling, proper temperature and RH maintenance, and effective sanitation procedures the throughout the postharvest handling system.

POSTHARVEST LOSSES

Postharvest losses vary greatly among commodities and production areas and seasons. In the United States, the losses of fresh fruits and vegetables are estimated to range from 2% to 23%, depending on the commodity, with an overall average of about 12% losses between production and consumption sites (Table 1.3). Estimates of postharvest losses in developing countries are generally much higher than those in the US and can be up to 50% in some fresh fruits.

Kader (2005) estimated that worldwide, about one-third of all fruits and vegetables produced are never consumed by humans. The general difference between developed and developing countries is that more of the losses occur between production and retail sites in developing than in developed countries. It is not economical or practical to aim for 0% losses, but an acceptable loss level for each commodity production area and season combination can be identified on the basis of cost-benefit analysis (return on investment evaluations).

The basic requirements for maintaining quality and safety of fruits between harvest and consumption sites are the same in developing and developed countries. However, the extent of adoption of the specific harvesting and postharvest handling technologies varies greatly among countries and within each country, depending on scale of operation, intended markets, and the return on investment (cost/benefit ratio) of each technology (Kader, 2010). Although labor costs are lower in developing countries, labor training, productivity, and management are generally better in developed countries. Availability and efficient use of the cold chain is much more evident in developed countries than in developing countries. Unreliability of the power supply, lack of proper maintenance, and inefficiency of

Table 1.3. Estimated postharvest losses (%) of fresh produce in developed and developing countries.

	Developed Countries		Developing Countries	
Location	Range	Mean	Range	Mean
From production to retail site	2–23	12	5–50	22
At retail, food service, and consumer sites	5–30	20	2–20	10
Cumulative total	7–53	32	7–70	32

Postharvest losses in selected countries: India (40–50%), Indonesia (20–50%), Iran (35–45%), Philippines (27–42%), Sri Lanka (16–41%), Thailand (17–35%), and Vietnam (20–25%)

Source: Adapted from Kader (2005); Rolle (2006).

utilization of cold storage and refrigerated transport facilities are among the reasons for failure of the cold chain in developing countries. Cost of providing the cold chain per ton of produce depends on energy costs plus utilization efficiency of the facilities throughout the year. There is a great variation among and within countries in the extent of compliance with quality standards and food safety regulations, which is associated with the extent of participation in the global marketing of fresh fruits. Successful exporters of fresh fruits from developing countries must follow the required quality standards and safety regulations, such as avoiding microbial contamination, and requirements for traceability of the importing companies and/or countries.

Strategies for improving handling of fruits in developing countries include: (1) application of current knowledge to improve the handling systems of horticultural perishables and assure their quality and safety; (2) removing the socioeconomic constraints, such as inadequacies of infrastructure, poor marketing systems, and weak research and development capacity; and (3) overcoming the limitations of small-scale operations by encouraging consolidation and vertical integration among producers and marketers of each commodity or group of commodities (Kader, 2010).

CONCLUDING REMARKS

The postharvest handling systems for fresh fruits begin with harvesting and involve preparation for fresh market or for processing (e.g., freezing, canning, drying), cooling, transportation, storage, and/or handling at destination (wholesale and retail marketing). In all of these steps, proper procedures for providing the optimum ranges of temperature and RH are essential for maintaining produce quality and safety and for minimizing postharvest losses between production and consumption sites. Energy requirements for the various handling steps vary by commodity and its intended use, but in all cases, there are opportunities for improving efficiency and reducing the amount of energy used.

Modified and controlled atmospheres treatment with 1-methylcy-clopropene, exclusion and scrubbing of ethylene from transport and storage environments, treatment with postharvest fungicides, and other technologies can be useful supplements to proper temperature and humidity management for extending the postharvest life of horticultural perishables. More research is needed to estimate the return on investment in each of these technologies.

There is a continuing need to develop insect control procedures that are effective against the insects of concern and cause no damage to the host commodity to facilitate international distribution of fresh subtropical and tropical fruits.

Effective implementation of food safety assurance procedures, such as good agricultural practices (GAP) and hazard analysis critical control points (HACCP), will continue to be very critical to successful marketing of fresh produce.

There is a wealth of information about all aspects of postharvest technology available on the Internet. A list of the most useful websites is included as part of the "References" section.

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