HANDBOOK OF
BANANA PRODUCTION, POSTHARVEST SCIENCE, PROCESSING TECHNOLOGY, AND NUTRITION

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Handbook of Banana Production, Postharvest Science, Processing Technology, and Nutrition

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Preface

Banana is the second major fruit crop produced in the world, with about 1200 varieties of bananas known and classified worldwide. As a major tropical fruit, banana is cultivated in over 130 countries throughout the tropical and subtropical regions on five continents. Global production of the banana has increased by about 150% in the last three decades. The banana market and trade have grown considerably since 1990, with the two major import markets being the United States of America and European Union countries. The year-round availability of banana is attributed to several factors, including the fact that the fruit is grown under diverse climatic conditions, which allows harvesting throughout the year, and improvements in transportation, market access, pre-harvest production practices, and postharvest treatment allows the crop to be shipped long distances relatively free of any pests and diseases.

As a major staple fruit, banana represents the eighth top-starchy source in the world and its per capita consumption is estimated at about 0.5 kg d^{-1} in Latin America and even more than 1 kg d^{-1} in Eastern Africa. Bananas are highly nutritious and a rich source of dietary fiber and a number of vitamins and minerals. In addition to being a major source of carbohydrates for over 500 million inhabitants of tropical countries, the banana is also of major importance as it forms a considerable portion of the annual income for the stakeholders. Along with the increased consumption of this nutrient-rich fruit, the processed banana market has also seen similar growth, especially banana flour as a food ingredient, juice and beverages, and shelf-stable dried products.

This book provides a contemporary source of information that brings together current knowledge and practices in the value-chain of banana production, postharvest handling, value-added processing, and nutrition. This value-chain approach to the topic is the unique feature of this book, with an in-depth coverage on a wide variety of pertinent topics: production and global trade, biology and physiology, pathology and diseases, postharvest handling, packaging technologies, processing and processed products, innovative processing technologies, nutritional profile and health benefits, bioactive and phytochemical compounds, microbiology, and value-added utilization of banana by-products. An experienced team of over 25 contributors from Asia, North America, South America, and the European Union has contributed to this book. These contributors come from a field of diverse disciplines, including agricultural economics, horticulture, crop sciences, plant pathology, food chemistry, food biochemistry, food science and nutrition, food engineering, and molecular epidemiology.

The editors acknowledge many individuals for their support from conception through to the final development of this book. We offer 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. We dedicate this work to the worthy contributions of the numerous researchers and students throughout the world, for their decades of devoted efforts to improve the quality and utilization of fresh bananas and of processed banana products.

East Lansing, March 2020

Muhammad Siddiq
Jasim Ahmed
Maria Gloria Lobo

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Banana Production, Global Trade, Consumption Trends, Postharvest Handling, and Processing

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Introduction

Bananas are produced in more than 130 countries by small-scale and large-scale farmers alike. This fruit plays a very important role in contributing to food security and as a source of export revenue in some economies. The socioeconomic importance of banana production and trade should not be underestimated. About one-fifth of the global banana production is destined for international markets. Between 2008 and 2017, global banana production increased by 15.35%, reaching 113.92 million metric tons (MMT) in 2017. Factors driving the rise in banana production during this period were increases in yield and harvested area. Over the same period, banana exports grew by 26.67%, reaching 23.18 MMT in 2017. The top three banana exporters, Ecuador, Philippines, and Costa Rica, accounted for about 50% of global exports in 2017, while the top three banana importers, the United States, Germany, and Russia accounted for about 35% of the global import trade (FAO 2019a).

Historically, the big multinational companies controlled banana production and trade, but due to a changing business landscape, particularly legal, labor, and environmental issues, these companies now focus more on the transportation and distribution segment of the fruit value chain. This situation led to the growth of national banana companies that have the option to sell the fruit to the big multinational companies or directly to retailers and supermarket chains. As the number of participants on the supply side has increased, the number of participants on the retail side has decreased as result of renewed interest in mergers and acquisitions in the food retail industry. Consequently, there are now more sellers and fewer buyers in the banana market. Unfortunately, this change has not necessarily resulted in better wages and prices in the export growing regions.

Exports of conventional bananas to developed countries are plateauing, whereas exports of organic bananas to these countries continue to increase. Organic bananas in the US market command a significant premium price; on average, during the period 2013–2017, organic bananas at the US retail level commanded a premium of $0.29/lb over the price paid for conventional bananas (USDA-AMS 2018).

Irregular weather patterns and fungal diseases are usually the main disruptors to the otherwise year-round supply of bananas. The biggest threat to global banana production is

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Fusarium Wilt Tropical Race 4 (TR4), a fungal disease with the potential to disrupt banana production and trade as we know them. This chapter provides an overview of recent trends and developments in world banana production, exports and imports, consumption trends and prices in the US and European Union (EU) markets, and postharvest handling, processing, nutritional profile and health benefits of banana.

Banana Production, Trade, and Consumption

Between 2008 and 2017, global banana production expanded by 15.35%, from 98.76 MMT in 2008 to 113.92 MMT in 2017 (Figure 1.1). Factors driving the gains in production during this period were increases in yield (5.76%) from 19.11 metric tons/hectare (MT/ha) in 2008 to 20.21 MT/ha in 2017, and harvested area (9.09%) from 5.17 million hectares (Mha) in 2008 to 5.64 Mha in 2017. Commercial banana production occurs under very diverse climatic conditions in tropical and subtropical regions worldwide. Asia is the leading banana production region, accounting for 54.18% of the total production in 2017, followed by the Americas and the Caribbean (26.33%), Africa (17.57%), Oceania (1.52%), and the EU (0.40%) (FAO 2019a). Banana fruit plays an important role for household food security, income generation as a cash crop, and as an export revenue source around the world.

Although bananas are grown commercially in more than 130 countries, production is highly concentrated in the top 10 producing countries, accounting for 73.8% of the total production during the period 2015–2017 (Table 1.1). India is by far the largest producer, accounting for 26.8% of the total world production in 2017, followed by China (9.8%) and Indonesia (6.3%). Together, the top three countries accounted for about 43% of the global production. Other important banana producing countries, with their production share,

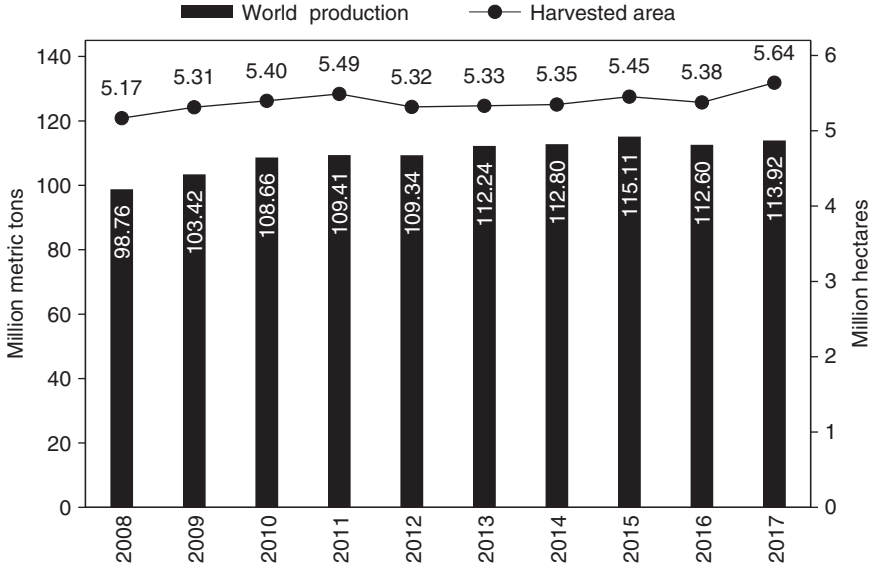

Figure 1.1 Banana total world production and area harvested, 2008–2017. Source: FAO (2019a).

Table 1.1 World's 10 major banana producers by quantity, 2008–2017 (million metric tons).

Country[1]	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	% Share, 2015–2017
India	26.2	26.5	29.8	28.5	26.5	27.6	29.7	29.2	29.1	30.5	26.0
China	7.8	8.8	9.6	10.4	11.6	12.1	11.8	12.5	13.1	11.2	10.8
Indonesia	6	6.4	5.8	6.1	6.2	6.3	6.9	9.5	7	7.2	6.9
Brazil	7	6.8	7	7.3	6.9	6.9	7	6.8	6.8	6.7	5.9
Ecuador	6.7	7.6	7.9	7.4	7	6	6.8	7.2	6.5	6.4	5.8
Philippines	8.7	9	9.1	9.2	9.2	8.6	5.7	5.8	5.8	6.0	5.2
Angola	1.7	2	2	2.6	3	3.1	3.5	3.6	3.9	4.3	3.5
Guatemala	2.3	2.7	2.6	2.9	3	3.3	3.4	3.8	3.8	3.9	3.4
Colombia	2	2	2	2	3.5	3.8	3.3	3.7	3.7	3.8	3.3
Tanzania	2.4	3	3.2	3.1	2.5	2.7	3.2	3.6	3.6	3.5	3.1
Top-10, total	*70.8*	*74.8*	*79*	*79.5*	*79.4*	*80.4*	*81.3*	*85.7*	*83.3*	83.3	73.9
Others, total	28.0	28.6	29.7	29.9	29.9	31.8	31.5	29.4	29.3	30.6	26.1
World, total	*98.8*	*103.4*	*108.7*	*109.4*	*109.3*	*112.2*	*112.8*	*115.1*	*112.6*	*113.9*	*100.0*

[1]Ranked by 2017 production.
Source: FAO (2019a).

include Brazil (5.9%), Ecuador (5.5%), the Philippines (5.3%), Angola (3.8%), Guatemala (3.4%), Colombia (3.3%), and Tanzania (3.1%) (FAO 2019a).

Disease continues to be the biggest threat to banana production, particularly Black Sigatoka and Fusarium Wilt (TR4). The economic impact of Black Sigatoka is significant for producers due to the cost of protection measures, such as regular fungicide applications, which may increase production costs by 25% or more (FAO 2013). The disease that constitutes the biggest threat to banana production is Fusarium Wilt (TR4), which has the potential to infect most banana varieties, including the widely cultivated Cavendish cultivar, and eliminate all banana plantations worldwide. It has already infested plantations in South East Asia, Pakistan, Jordan, Mozambique, and Australia. There is no viable and fully effective treatment; the only preventive measure is quarantine because the fungus spores may remain latent in the soil for decades (FAO 2019b). Only the cisgenic Cavendish-type banana with a gene taken from a wild banana has remained free of the disease so far, with additional research needed (Wageningen University 2017).

The bulk of banana production is cultivated under conventional practices; despite premium prices in international markets, global organic banana production remains low. In terms of area, in 2012, land under organic banana reached 78,831 ha, or 1.5% of the global area harvested. Since 2012, organic banana area has decreased by 35%, reaching 58,407 ha in 2016 (FiBL 2018). One reason for this drop in area could be disease outbreak; for instance, organic banana growers in Guatemala and Honduras have lost their share of the US organic banana market since 2014 due to the need for fungicides to control Black Sigatoka (Fresh Plaza 2016).

In terms of market structure, the supply side of the banana market has changed noticeably from when it once was an oligopoly, where a few vertically integrated multinational companies controlled the trade. For instance, the top five multinational banana companies, Chiquita, Del Monte, Dole, Fyffes, and Noboa, went from controlling 65.3% of the global banana exports in 1980 to 44.4% by 2013 (FAO 2014). Several factors are responsible for the observable structural change; chief among them was the conscious decision on the part of the traditional multinational companies to reduce their level of risk exposure by moving from primary production to focusing their attention more on the transportation and distribution aspects of the value chain. This decision opened the door for the rise in the number of national companies better placed to minimize some of the production risks and to guarantee supply. Due to the way they operate, national companies sell the fruit to the big multinational companies or directly to supermarket chains and food retailers.

As result of a changing business landscape, the big multinational banana companies have undergone significant changes. Once publicly traded companies, three of the biggest multinational banana companies have become private. Dole was privatized in 2013 in a transaction valued at $1.2 billion (Reuters 2013). By the end of 2014, Cutrale-Safra had acquired Chiquita in a transaction estimated at $1.3 billion (Reuters 2014). In December 2016, Sumitomo acquired Fyffes in a transaction valued at €751 million (Reuters 2016). Privatization will allow these companies a more efficient use of their resources to focus on competitive pressures as they plan for their long-term viability.

While there has been an increase in the number of participants on the supply side of the banana market, the number of participants on the retail side, especially in the developed world, has decreased due to renewed interest in mergers and acquisitions in the food retail industry. As a result, market power in the banana market has shifted from the suppliers to major supermarket chains and food retailers, which now have more supply choices. Retailers may buy the fruit from small wholesalers or directly from producers, bypassing the traditional intermediaries. However, it remains uncertain how this change may have a positive impact on wages and prices in the export growing regions. Fairtrade bananas represent one successful effort to improve not just prices and wages in the growing regions. In 2016, certified banana producers received €28.50 million from the Fairtrade premium, an increase of 5% compared with the previous year. The premium received went for payments to small producers and hired labor organizations, and investments in services and infrastructure (Fairtrade 2018).

Global Trade Exports and Imports

A considerable share of the total banana production goes to the export market, with about one-fifth of the global production sold in the international markets. In 2017, 20.35% of the global banana production (valued at $11.49 billion) went to the international markets. On average, about 18% of the total banana production was exported during the period 2008–2017 and exports showed a significant increase (26.7%) from 18.30 MMT in 2008 to 23.18 MMT in 2017. Exports value increased by 49.9%, from $7.67 billion in 2007 to $11.49 billion in 2016 (FAO 2019a). The top 10 banana exporters control more than 80% of

Table 1.2 World's 10 major fresh banana-exporting countries, 2008–2017 (million metric tons).

Country[1]	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	% Share, 2015–2017
Ecuador	5.3	5.7	5.2	5.8	5.2	5.4	5.7	6.1	6	6.4	29.1
Costa Rica	2.1	1.7	1.9	1.9	1.9	1.9	2.2	2	2.4	2.5	10.9
Guatemala	1.4	1.5	1.4	1.5	1.9	2	2.1	2.2	2.1	2.3	10.4
Colombia	1.7	1.8	1.7	1.8	1.7	1.5	1.7	1.6	1.8	1.9	8.3
Philippines	2.2	1.7	1.6	2	2.6	3.3	3.1	1.2	1.4	2.7	8.3
Belgium	1.3	1.2	1.2	1.3	1.2	1.2	1.3	1.1	1.1	1.3	5.4
Honduras	0.6	0.5	0.5	0.5	0.6	0.7	0.6	0.7	0.7	0.6	3.2
USA	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.6	0.6	0.6	2.8
Netherlands	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.7	2.6
Mexico	0.1	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.6	2.2
Top-10, total	*15.3*	*14.9*	*14.3*	*15.7*	*16.1*	*17.2*	*18.0*	*16.4*	*17.1*	*19.6*	*83.2*
Others, total	3.0	3.3	3.2	3.1	3.0	2.9	3.7	3.3	3.7	3.6	16.8
World, total	*18.3*	*18.2*	*17.5*	*18.7*	*19.1*	*20.1*	*21.7*	*19.7*	*20.8*	23.2	*100.0*

[1] Ranked by 2017 exporters.
Source: FAO (2019a).

the total exports (Table 1.2). Interestingly, none of the top three producers (India, China, and Indonesia) plays a major role in the international banana market. As was the case with production, banana exports are highly concentrated, with the top three exporters accounting for about 50% of the global exports of the fruit during the period 2015–2017. Ecuador is the leading exporter, accounting for 29.1% of the exports during the same period, followed by Costa Rica (10.9%) and Guatemala (10.4%).

Countries in Central America, more specifically Guatemala, Ecuador, and Costa Rica, have significantly increased their participation in the international markets, with their exports growing by 64.3, 20.8, and 19.1%, respectively, during the period 2008–2017. One of the reasons behind the noticeable increase in exports is the close proximity to the US market, which is an advantage in terms of lower transportation costs and transit times. Interestingly, Belgium and the United States are included in the top 10 exporters; however, it is important to clarify that they are re-exporters, with Belgium shipping the fruit to the EU market and the United States shipping the fruit to the Canadian market (FAO 2019a).

Banana import value has grown at an average annual rate of about 3.0%, from $11.74 billion in 2008 to $14.93 billion in 2017. Table 1.3 lists the top 10 banana importing countries, with world total import volume increasing by 26.1%, from 17.6 MMT in 2008 to 22.2 MMT in 2017. The United States is the leading banana importer, accounting for over 22.3% of the total imports during the period 2015–2017, followed by Germany (6.7%), Russia (6.6%), Belgium (6.2%), and the UK (5.3%). Together, these five countries accounted for about 47% of the imports during the period 2015–2017 (FAO 2019a).

Table 1.3 World's 10 major importing countries, 2008–2017 (million metric tons).

Country[1]	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	% Share, 2015–2017
USA	4	3.6	4.1	4.1	4.4	4.5	4.6	4.6	4.6	4.8	22.3
Germany	1.4	1.4	1.2	1.3	1.2	1.3	1.4	1.4	1.4	1.4	6.7
Russia	1	1	1.1	1.3	1.3	1.3	1.3	1.2	1.4	1.5	6.6
Belgium	1.5	1.3	1.4	1.3	1.3	1.3	1.3	1.2	1.3	1.4	6.2
UK	1	0.9	1	1	1	1.1	1.1	1.1	1.1	1.1	5.3
China	0.4	0.5	0.7	0.8	0.6	0.5	1.1	1.1	0.9	1.0	4.8
Japan	1.1	1.3	1.1	1.1	1.1	1	0.9	1	1	1.0	4.7
Netherlands	0.2	0.2	0.2	0.3	0.4	0.4	0.5	0.7	0.8	0.9	3.8
Italy	0.7	0.7	0.7	0.7	0.6	0.7	0.7	0.7	0.7	0.8	3.4
France	0.6	0.5	0.5	0.6	0.5	0.6	0.6	0.6	0.6	0.7	3.0
Top-10, total	*11.9*	*11.4*	*12.0*	*12.5*	*12.4*	*12.7*	*13.5*	*13.6*	*13.8*	*14.7*	*66.8*
Others, total	5.7	5.8	5.9	6.2	5.9	7.0	6.7	6.8	6.5	7.5	33.2
World, total	*17.6*	*17.2*	*17.9*	*18.7*	*18.3*	*19.7*	*20.1*	*20.4*	*20.3*	*22.2*	*100.0*

[1]Ranked by 2017 importers.
Source: FAO (2019a).

US Production, Imports, and Consumption

US Production

Because of climatic requirements, most of the continental United States is not suitable for banana production; limited commercial production takes place only in Hawaii and Florida. In Hawaii, the top banana (Cavendish cultivar) producing state, the industry is contracting. The area harvested peaked at 445 ha in 2008, before declining to 242 ha in 2017. That same year, production was estimated at 3,024 MT (metric tons) valued at $6.02 million (USDA-NASS 2018). Yield has also trended downward, from 17.73 MT/ha in 2008 to 15.84 MT/ha in 2017, which is considerably less than the yield obtained in other commercial growing areas such as Costa Rica (59.48 MT/ha) or Ecuador (39.75 MT/ha) (FAO 2019a).

Florida banana production occurs mainly in Miami-Dade County, which has a subtropical climate considered marginal for commercial banana production. Popular cultivars for this area include Thai-banana "Hawaiano," "Goldfinger," and "Monalisa" (Crane and Balerdi 2016). Florida banana production takes place on about 450 ha (USDA-NASS 2012). Because of the low production volumes, there is no official data on Florida's banana production, yield, and farm gate value.

US Imports

In 2017, total US fresh banana imports were valued at $2.1 billion; conventional bananas, comprising the bulk of imports, were valued at $1.87 billion, while organic banana imports

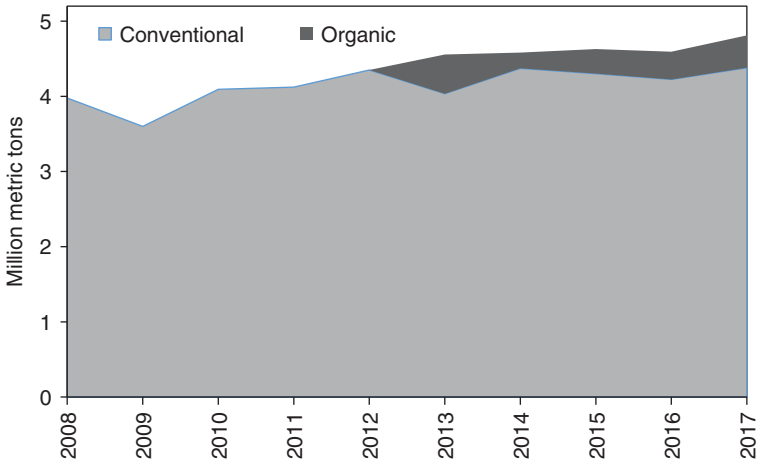

Figure 1.2 US conventional and organic banana imports, 2008–2017. Source: USDA-FAS (2018).

were valued at $232 million. US fresh banana imports have grown at an annual rate of about 2.4%, from 3.97 MMT in 2008 to 4.81 MMT in 2017 (Figure 1.2). The growth in imports since 2012 has been minimal, with organic banana imports having modest growth and conventional banana imports reaching a plateau (USDA-FAS 2018). Guatemala is by far the dominant supplier of conventional bananas to the US market, with a market share of 41.8% during the period 2015–2017, followed by Costa Rica (18.5%) and Honduras (13.7%). Together, these three countries account for 74% of US banana imports. Other important conventional banana suppliers to the US market and their import share are Ecuador (13.5%), Mexico (6.5%), and Colombia (5.1%).

US organic banana imports have not followed a consistent upward trend, fluctuating between 0.52 MMT in 2013 and 0.43 MMT in 2017. This is primarily due to the loss of organic certification by growers in Guatemala and Honduras from the use of fungicides to control Black Sigatoka (Fresh Plaza 2016). Ecuador is the main supplier of organic bananas to the US market, accounting for about half of the total supply of the fruit during the period 2015–2017, followed by Peru (17.25%) and Colombia (15.57%). These three countries supplied over 80% of the total organic banana imports during 2015–2017 (USDA-FAS 2018).

Table 1.4 illustrates import prices for selected exporters of conventional and organic bananas during the period 2013–2017 in US dollars per kilogram (kg). Over this period, the average import price of conventional bananas ranged from a low of $0.48/kg in 2013 to a high of $0.52/kg in 2017, while import prices of organic bananas ranged from a low of $0.61/kg in 2013 to a high of $0.68/kg in 2015. Honduras is the lowest-cost supplier of both conventional and organic bananas to the US market.

US Consumption

Figure 1.3 illustrates US per capita consumption of selected fruits for the period 2008–2017. Fresh banana consumption has increased at an annual rate of 1.36%, while orange consumption has decreased by 7.72%, and apple consumption has remained unchanged

Table 1.4 Average annual conventional and organic banana import prices from selected suppliers, 2013–2017 (US $/kg).

Partner country	2013		2014		2015		2016		2017	
	Conv.	Org.	Conv.	Org.	Conv.	Org.	Conv.	Org.	Conv.	Org.
Guatemala	0.50	—	0.51	—	0.51	—	0.52	—	0.52	—
Ecuador	0.50	0.60	0.49	0.60	0.49	0.62	0.53	0.57	0.50	0.61
Colombia	0.50	0.66	0.52	0.84	0.53	0.84	0.54	0.82	0.56	0.81
Peru	—	0.76	—	0.75	—	0.75	—	0.74	—	0.69
Honduras	0.45	0.43	0.47	0.48	0.47	0.49	0.47	0.49	0.48	0.50
Average	*0.48*	*0.61*	*0.49*	*0.67*	*0.49*	*0.68*	*0.51*	*0.66*	*0.52*	*0.65*

Source: USDA-FAS (2018).

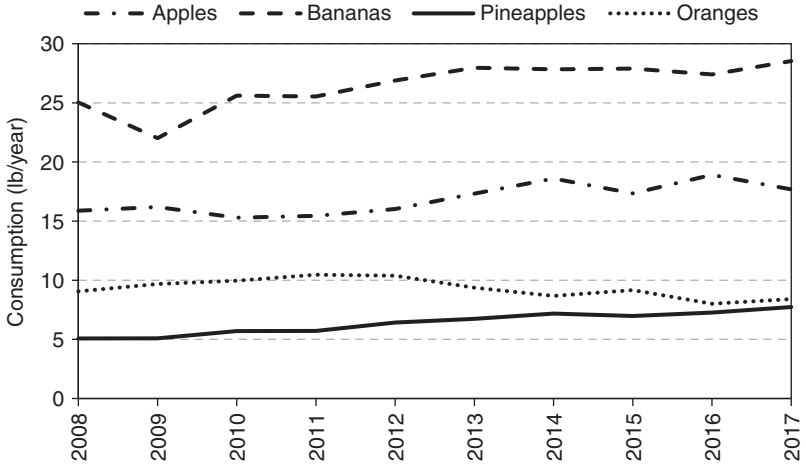

Figure 1.3 US per capita consumption of selected fruits, 2008–2017. Source: USDA-ERS (2018).

(USDA-ERS 2018). Bananas continue to be one of the most affordable fruits on the market, which is important given the wide availability of fruits in the US market. Different banana cultivars are sold in the US market; in terms of volume, "Cavendish" is by far the predominant cultivar, with other important cultivars being "Baby," "Red," "Manzano," "Burro," and "Saba."

Figure 1.4 illustrates US average retail prices for both conventional and organic bananas from 2013 to 2017. Retail prices for conventional bananas fluctuated from a low of $0.43/lb in January 2016 to a high of $0.54/lb in December of the same year. The average retail price for conventional bananas during the period 2013–2017 was around $0.47/lb. Retail prices for organic bananas fluctuated from a high of $0.85/lb in June 2013 to a low of $0.69/lb in May 2017. The average price for organic bananas during the period 2013–2017 was $0.76/lb. On average, the premium price commanded by organic bananas was $0.29/lb, which is 62.1% more than the average price of conventional bananas. During the period 2013–2017,

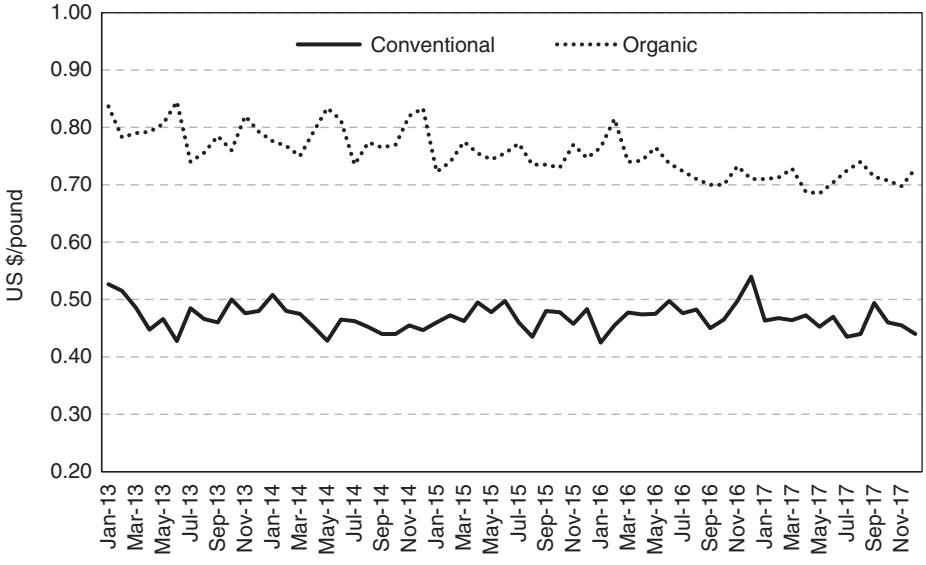

Figure 1.4 US average retail prices for conventional and organic bananas, 2013–2017. Source: USDA-AMS (2018).

the premium price for organic bananas decreased slightly by 6%, from $0.31/lb in January 2013 to $0.29/lb in December 2017 (USDA-AMS 2018).

European Union Market

Banana production destined for markets in the EU occurs in Greece, Spain, France (Martinique and Guadeloupe) Chypre, and Portugal. EU market banana production has grown at an annual rate of 0.9%, from 567,560 MT in 2008 to 613,730 MT in 2017 (Figure 1.5). Domestic banana production accounted for 11.3% of the total supply during the period 2008–2017, Spain is the main banana producer, accounting for 65.3% of the total production in 2017, followed by France (30.4%) and Portugal (3.2%) (European Commission 2018). The increase in domestic banana production has been mainly the result of sustained production gains from Spain.

In 2006, the EU established an import regime to keep a balance between the non-EU suppliers and the domestic EU banana producers. Latin American banana imports were subject to a Most Favored Nations tariff of €176/MT, while the African, Caribbean, and Pacific (ACP) countries were subject to a duty free access quota of 775,000 MT. Later, the EU agreed to cut the tariff in eight steps, from €176/MT in 2009 to €114/MT by 2017 or 2019 (European Commission 2013).

Over a 10-year period (2008–2017), EU banana imports increased by 17.4%, from 4.94 MMT in 2008 to 5.80 MMT in 2017. EU banana imports from Latin American countries accounted for 71.2% of the total supply and the ACP countries accounted for 18.5% during the period 2008–2017.

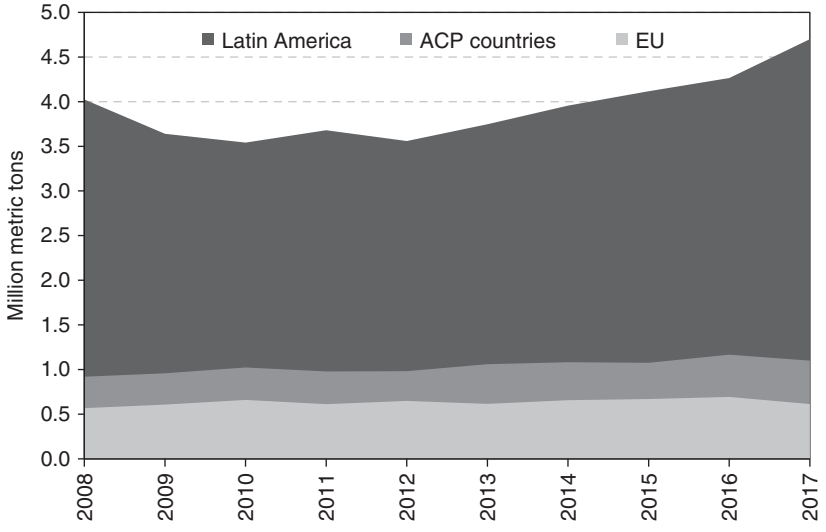

Figure 1.5 EU total banana supply by source, 2008–2017 (ACP = African, Caribbean, and Pacific). Source: European Commission (2018).

Ecuador, Colombia, and Costa Rica are the main banana exporters from Latin America. These three countries supplied more than 85% of the fruit volume from that region. The Dominican Republic, Cameroon and Ivory coast are the main suppliers from the ACP countries, contributing more than half of the fruit from that group.

Figure 1.6 illustrates banana prices for the EU market at the first unloading port for the period 2008–2017. Latin America is the lowest cost supplier of bananas to the EU market; on average the fruit prices from that region were close to €0.60/kg during the period considered. Prices for domestic bananas in the EU market commanded a higher price for most of the period considered; average price for EU produced bananas was €0.72/kg. While banana prices from Latin America and EU sources remained stable during the period, banana prices from the ACP countries increased from €0.61/kg in 2011 to €0.77/kg in 2017.

Market Outlook

During the period 2008–2017, global banana production and trade increased significantly; however, there are signs that demand for conventional bananas in developed countries, particularly the United States, is decelerating.

Because banana production is not seasonal, prices in international markets remain fairly stable. Occasional disruptions in supply will continue to be the result of logistic constraints, complex weather patterns, (e.g., El Niño and La Niña), as well as disease outbreaks in the major export growing regions. Compared with Central America, South America will continue to be the more reliable banana supplier to international markets given its relatively low incidence of adverse weather events, and its well established supply and distribution network.

Short-term increases in organic banana production may come from higher yields as harvested area has trended downward. Price incentives will likely drive long-term increases in organic banana production due to the market premium for organic bananas and the additional conversion of conventional banana areas to organic production.

It is unclear how the shift in market power from suppliers to retailers may result in better market terms for workers and growers in the producing regions. Even though there has been some progress to improve this situation, the debate about fair prices and wages continues to be relevant. For example, Fairtrade represents a success in improving social and economic conditions for small banana growers and workers.

The biggest threat to global banana production is Fusarium Wilt, more specifically TR4, which is a very aggressive disease that has the potential to eliminate all banana plantations. The search for a viable disease treatment is still a work in progress. The arrival of the TR4 disease to the main export growing regions disrupts production and trade, and risks the livelihood of millions of workers. Recent advances in the development of cultivars tolerant/resistant to TR4 show promise for commercial production, but more research is necessary.

Postharvest Handling and Storage

Bananas are harvested at full-mature (green) stage and harvested bunches are hung in a shaded and cool place, which favors flavor development 7–14 days after the harvest (Arvanitoyannis and Mavromatis 2009). Bananas undergo ripening in four distinct phases: (i) pre-climacteric or "green life" stage; (ii) climacteric stage; (iii) ripe stage; and finally (iv) senescence. In order to identify the ripening stage of bananas, standard color charts are used commercially, e.g., *Stage-1*, dark green; *Stage-2*, light green; *Stage-3*, more green than yellow; *Stage-4*, more yellow than green; *Stage-5*, yellow with green tips; *Stage-6*,

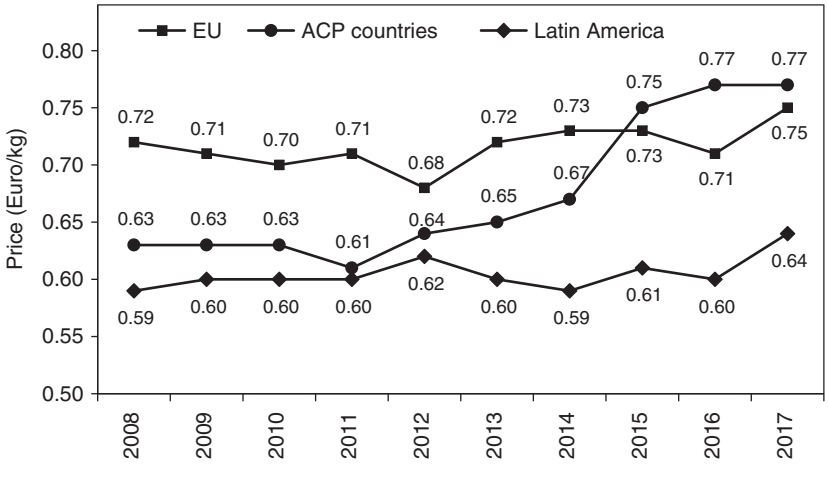

Figure 1.6 EU banana prices at first unloading port by origin, 2008–2017. Source: European Commission (2018).

yellow; and *Stage-7*, yellow with brown freckles. During ripening, different physiological, biochemical, and organoleptic changes lead to a soft and edible ripe fruit during the ripening process. After storage and natural ripening, bananas are then shipped to markets at their optimal ripening stage or at full mature green stage depending on variety and final use (Bello-Pérez et al. 2012).

Postharvest losses are common if harvested fruit is not stored and transported at optimum temperature conditions. Zhang et al. (2005) indicated that about 20% of all bananas harvested may become culls and thus unmarketable. Kader (2005) reported that estimates of fruits and vegetables postharvest losses in developing countries are generally much higher than those in the US, and can be up to 50% for some fresh fruits. These losses may be due to sorting of bananas too small for shipping and damaged, injured or spoiled fruits that could induce microbial contamination of the full bunch in the collection stations (Bello-Pérez et al. 2012). Arvanitoyannis and Mavromatis (2009) suggested that shelf life of bananas could be extended by applying inhibitors that limit respiration and/or ethylene production or by using modified atmosphere packaging (MAP). Kader (2003) recommended maintaining cold-chain throughout the fruit marketing channels to minimize losses and ensure fruit quality (Figure 1.7).

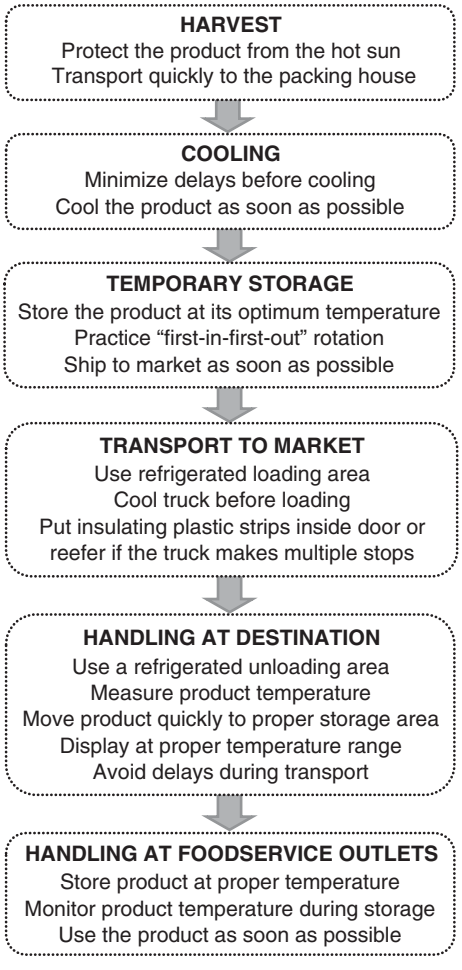

Figure 1.7 Maintaining cold chain for the perishable commodities. Source: Adapted from Kader (2003).

Low-temperature storage is one of the most important factors that can control the respiration rate of banana, however, it also induces chilling injury that results in brown peel spots. Mohapatra et al. (2010) reported that at a ripening temperature of 20 °C using ethylene, a better flavor develops with less astringency and sweetness. High relative humidity (95%) prevents browning spots but induces finger dropping off. Banana stored under low relative humidity will favor ethylene production and respiration prior to climacteric stage (Bello-Pérez et al. 2012). However, low humidity greatly increases water loss in banana by 3–4 times higher than the fruit stored at high humidity.

The use of appropriate packaging to reduce damage is important and cushioning is used occasionally, especially when bananas are sold at high-end markets. Banana shipping containers should preferably be stackable to avoid compression force, which can induce bruising and soften fruit texture. Venting of shipping containers is also recommended to allow efficient cooling to maintain the best quality of the fruit. For bulk packaging, container liners are used. Typically, liners are made of plastic films, such as polyethylene (PE) or polypropylene (PP), mainly to minimize water loss of banana during storage and distribution (Chonhenchob et al. 2017).

Processed Products

Figure 1.8 shows typical steps for preparing various processed products from both green and ripe bananas. The most common products prepared from green bananas include boiled/steamed banana, dried or fried chips, flour, and starch. Ripe bananas are processed into far more diverse products of commercial significance, e.g., pulp/puree, clarified juice, baby foods, dried and fried chips, fruit bars, and flour (Mohapatra et al. 2011). Banana flour has a potential to be used as a healthy ingredient in other prepared products, e.g., as a partial meat and wheat flour replacer in patties and snacks, respectively. In addition to commercial processing, bananas are also used in a variety of culinary applications in foodservice as well as home baked products.

Preparation of processed fruit products requires various preliminary unit operations. During preparatory operations and subsequent processing, polyphenol oxidase (PPO)

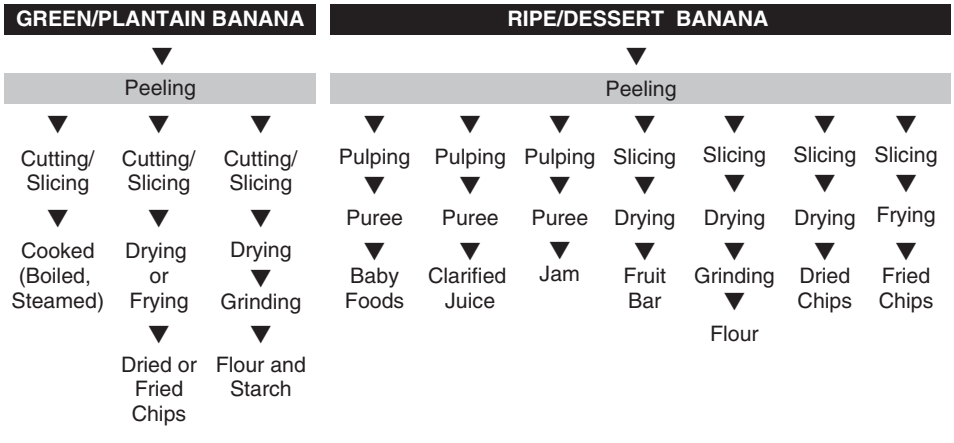

Figure 1.8 Green and ripe banana processing and products. Source: Adapted from Mohapatra et al. (2011).

and peroxidase (POD) induced enzymatic browning in banana, like most other fruits, can produce undesirable quality changes (Bello-Pérez et al. 2012). Vámos-Vigyázó (1981) reported that PPO impairs not only the sensory properties, and hence the marketability of a product, but it often lowers its nutritive value as well. The use of anti-browning agents (e.g., ascorbic acid, citric acid) and/or heat treatment (blanching) are commonly used to ensure color quality of banana pulp/puree, prior to heat processing or freezing preservation. Garcia et al. (1985) reported using mild heat treatment with added citric acid and potassium sorbate for preservation of banana puree.

Banana at a firmer texture stage can also be exploited for the fresh-cut fruit market. Bello-Pérez et al. (2012) reported that fresh-cut banana has not been researched and developed to a scale similar to that of melons or some other fruits marketed in this form. Most applications of fresh-cut bananas are in the foodservice sector, mainly in selected fruit salads or as a garnish on desserts.

In recent years, a number of innovative technologies have been explored for banana processing, such as high pressure processing (HPP), pulsed electric field (PEF), microwave (MW) heating and drying, ionization radiation, ultraviolet (UV) light, and ozone treatment (Ahmed and Ozadali 2012; Xu et al. 2016; Yan et al. 2016; Pu et al. 2018). While these novel technologies offer a number of quality benefits over traditional thermal processing, their application on a commercial scale has not gained a wider acceptance due to cost, process or equipment limitations. However, HPP and MW do offer a greater potential for commercial applications in banana processing.

By-products from Banana Fruit and Plant

During its life span, a banana plant bears one bunch of fruit thereby producing about 200 MMT of agricultural waste worldwide (Kamdem et al. 2013). Banana waste varies in composition but invariably contains cellulose, hemicelluloses, lignin, starch, sugars, protein, and minerals.

The commercial processing of banana to obtain diverse products produces large quantities of peels. Banana peel is about 40% of the total fruit weight and can present a huge environmental problem. The peel, being rich in hemicelluloses and pectin polysaccharides, could be used to produce a variety of by-products, e.g., fiber-rich powder, which can be added to different bakery and pasta products (Emaga et al. 2007; Bello-Pérez et al. 2012). Pectin, as a value-added ingredient, has been extracted from banana peel by different methods (Emaga et al. 2008; Oliveira et al. 2016). Emaga et al. (2008) reported that dessert banana peel had higher galacturonic acid and higher degree of methylation than the plantain subgroup. Banana peel, due to its energy-rich carbohydrates, is a good substrate for single-cell protein production for food and feed applications. Another potential use of banana peel includes the production of biogas in an anaerobic digester (Bello-Pérez et al. 2012).

Besides the peel, there are a number of banana plant wastes, namely, pseudostem, petioles, leaf blade, floral stalk, leaf sheaths, and rachis. The use of these parts of banana plant has been reported for producing value-added by-products. In addition to their use in animal feed, a variety of products has been processed from these banana plant wastes, such as starch, enzymes, paper and paperboard, nan-fibers, and fuel briquettes (Mohapatra et al. 2010).

Nutritional Profile and Health Benefits

Bananas are one of the world's leading staple crops, after rice, wheat, and maize. A major portion of production (about 90%) is consumed mainly in the banana producing areas, especially in most of the countries in Africa, Asia, and Latin America. Banana fruit is a rich source of carbohydrates, several minerals, and vitamins. Potassium content in bananas is among the highest compared with all other fruits. In many developing countries, mashed/pureed banana is the first solid food given to infants (Aurore et al. 2009). According to Forster et al. (2002), there are differences in the chemical composition among banana varieties from Europe (e.g., Tenerife) and South America (e.g., Ecuador). The European banana had higher protein, ash, ascorbic acid, glucose, fructose, and total sugars content than those from South America.

The chemical and nutritional composition of banana varies significantly at different stages of ripeness, especially, with respect to starch and sugars content. At the green stage, bananas have very high starch content and a low amount of sugars, which changes dramatically to high sugars and low starch at the full-ripe stage. Lii et al. (1982) showed that from green to full-ripe stage, starch content decreased from 58.6% to 2.6%, while sucrose and reducing sugars increased from 6.0% and 1.3% to 53.2% and 33.6%, respectively. The changes in carbohydrates are important, as these contribute to the development of desirable sensory attributes of sweet flavor and smooth texture or mouthfeel in ripe bananas. Aurore et al. (2009) reported higher protein and carbohydrate content in the unripe fruit than in its ripe state, with higher carbohydrate level in plantain than in the sweet banana (dessert or table bananas).

Green bananas are rich in resistant starch (RS), the portion of dietary starch which does not undergo rapid digestion and absorption, and instead enters the large intestine where it is fermented partially or wholly (Sajilata et al. 2006). The slow release of glucose induces a relatively small increase in blood glucose, as it is metabolized 5–7 hours after consumption versus normally cooked starch that is digested immediately, which makes banana a low glycemic index food (Thakorlal et al. 2010; Hamad et al. 2018). Banana fruit pulp and powder have been used for developing various functional foods based on cereals, milk, and meat (Segundo et al. 2017).

The significantly high potassium and low sodium content in banana are optimum for people suffering from hypertension and on a low-sodium diet (Appel et al. 1997). Banana is also considered as one of the most important antioxidant-rich staple foods among the relatively affordable fruits. The fruit is a rich source of phytosterols, biogenic amines, and many bioactive compounds having antioxidant properties, such as phenolics, carotenoids, and ascorbic acid. Various pharmacological studies on the health benefits of banana and plantain have attributed these to the presence of antioxidant compounds (Appel et al. 1997; Sajilata et al. 2006; Sidhu and Zafar 2018).

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2

Biology and Postharvest Physiology of Banana

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Introduction

Bananas, grown in more than 150 countries, are the second most produced (153 MMT [million metric tons]) and consumed fruit after tomatoes (182 MMT) (FAO 2017). Bananas are healthy, easily portable and eatable, suitable for anyone of any age (from babies to the elderly), and inexpensive when compared with other fruits. In addition to being eaten raw, bananas are processed into a variety of products, such as puree, juice, and dried products. Similarly, this fruit offers a range of culinary applications in various food formulations, especially baked products.

Bananas are cultivated in the tropics and also in the subtropics, where they are highly influenced by climate, contributing significantly to the economy of many countries and also being a staple fruit in many of them. This chapter provides an overview of banana biology and physiology, including plant and fruit growth, factors affecting plant and fruit development, fruit ripening, nutritional and phytochemical profile, harvesting, and fruit quality disorders.

Botanical Description

Banana is a high-demand fruit because it is very nutritious, and it has good flavor, aroma and texture. Botanically it is classified as follows:

Kingdom:	Plantae – Plants
Subkingdom:	Tracheobionta – Vascular plants
Superdivision:	Spermatophyta – Seed plants
Division:	Magnoliophyta – Flowering plants

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Class:	Liliopsida – Monocotyledons
Subclass:	Zingiberidae
Order:	Zingiberales
Family:	Musaceae – Banana family
Genus:	*Musa* L. – banana

Almost all cultivated varieties of edible banana and plantains are hybrids and polyploids of two wild, seeded banana species, *Musa acuminata* Colla (genome A) and *Musa balbisiana* Colla (genome B). They are classified in different groups according to the number of chromosomes: whether the plant is diploid, triploid, or tetraploid, and a genome-based system introduced by Simmonds and Shepherd (1955) using 15 discriminating characters. The groups and subgroups of bananas are:

- *AA genome group*: all the cultivars have two sets of chromosomes inherited from *Musa acuminata*. AA cultivars are called edible diploids, and are very sweet, but they have been displaced by the triploids that are more productive. "Sucrier," also known as "Pisang Mas" or "Bocadillo," produce small sweet fruits with thin golden skin and are resistant to Panamá disease or Fusarium wilt.
- *AB genome group*: this includes all the cultivars that have two sets of chromosomes, one donated by *M. acuminata* and the other by *M. balbisiana*.
- *AAA genome group*: this includes all the cultivars that have three sets of chromosomes inherited from *Musa acuminata. Triploidy* is the last stage in the process of domestication, and although they are essentially sterile, the reproduction is vegetative through suckers, breeders have been able to take advantage of cultivars' residual fertility to produce improved hybrids.
  - Cavendish subgroup: this is the most edible banana grown for international trade (cultivars "Grande Naine" [GN], "Williams," and "Valery") because it has the organoleptic characteristics demanded by consumers and is resistant to the Race 1 strains of the fungus that produce Panama disease or Fusarium wilt but it is susceptible to Tropical Race 4.
  - East African highland banana subgroup: this is a starchy cooking and beer banana.
  - Gros Michel subgroup: this is susceptible to Fusarium wilt and the main cultivar is "Gros Michel" that is known as *Bogoya* in Uganda and *Kampala* in Kenya.
- *AAB genome group*: this group has two sets of chromosomes one donated by *M. acuminata* and the other by *M. balbisiana*.
  - Iholena subgroup: these are cooking bananas.
  - Maoli-Popoulu subgroup: these are cooking bananas.
  - Mysore subgroup: this is the most produced in India and is resistant to Fusarium wilt.
  - Plantain subgroup: these are cooking bananas.
  - Pome subgroup: this has a sub-acid and apple-like taste (cultivar "Prata"), leading them to be confused with Silk bananas which are the more widely recognized apple bananas.
  - Silk subgroup: this is a sweet dessert consumed raw, normally referred to as apple bananas.
- *ABB genome group*: this group has one set of chromosomes donated by *M. acuminata* and two by *M. balbisiana* and is a vigorous plant resistant to drought.

  - Bluggoe subgroup: this comprises starchy cultivars used primarily for cooking but that can also be eaten raw. In Venezuela, it is known as "Topocho."
- *Fei bananas*: these are easily recognized by their erect bunch.
  - Asupina: a group of domesticated bananas with orange pulp with high provitamin A (α and β carotene) content.
- *AAAB, AABB, ABBB groups*: natural tetraploid hybrids are not common but breeding programs have led to varieties that are resistant or tolerant to Fusarium wilt and black Sigatoka, and adapt well to different climatic and edaphic conditions.
  - Dessert types similar to "Gros Michel" (AAAB): FHIA-17, FHIA-23, and SH-3436.
  - Dessert types similar to "Pome" (AAAB): FHIA-01 or "Goldfinger," FHIA-28, and SH-3640.
  - Cooking types similar to "Bluggoe" (AAAB): FHIA-20 and FHIA-21.
  - Special bananas: SH-4001, a plantain with high β-carotene content.

Plant and Fruit Growth and Development

Two phases are clearly marked during banana plant development: a vegetative phase characterized by leaves emission; and a reproductive phase easily identified by the bunch emission. However, during the vegetative phase, there is a dependent sucker phase since its growth coincides with the development of the mother plant. Until the shoot does not emit the F10 leaf (10 cm wide), it does not enter the independent vegetative phase. Moreover, during flowering of the mother plant, the sucker is in the vegetative phase.

Banana Plant

Banana plants are large perennial monocotyledon herbs, 2–9 m tall and 20–50 cm in diameter depending on the variety but wild varieties such as *Musa ingens* can reach 15 m and 80 cm in diameter (INIBAP 2000). There is an underground true stem, tuberous rhizome or corm, with roots 50–100 cm in length. The root system, like that of all monocotyledons, is adventitious spreading out laterally as far as 5.5 m and forming a dense mat mainly in the top 15 cm of the soil. The corm produces aerial shoots that arise from the lateral buds which develop into eyes and later suckers. It is an important storage organ that allows the growth of the bunch and the growing shoots. The perennial status of bananas is due to the continuous vegetative growth of suckers that perpetuates the corm's life. They arise from the rhizome at roughly six-month intervals and the number produced varies with the type of cultivar (Figure 2.1).

Two types of suckers can be differentiated morphologically: *sword suckers*, characterized by narrow leaves and a large rhizome, with a strong connection to the mother plant coming from the deep axillary buds located in the mother rhizome; and *water suckers*, which have broad leaves and a small rhizome due to the weak connection to the mother plant as they come from buds located closer to the surface. In old crops, there is a greater proportion of water suckers. The sucker selected to replace the mother plant after fruiting is called the follower or ratoon and is the one that grows vigorously at the furthest position from the mother plant since it is the first to emerge and its growth is faster too. This will allow

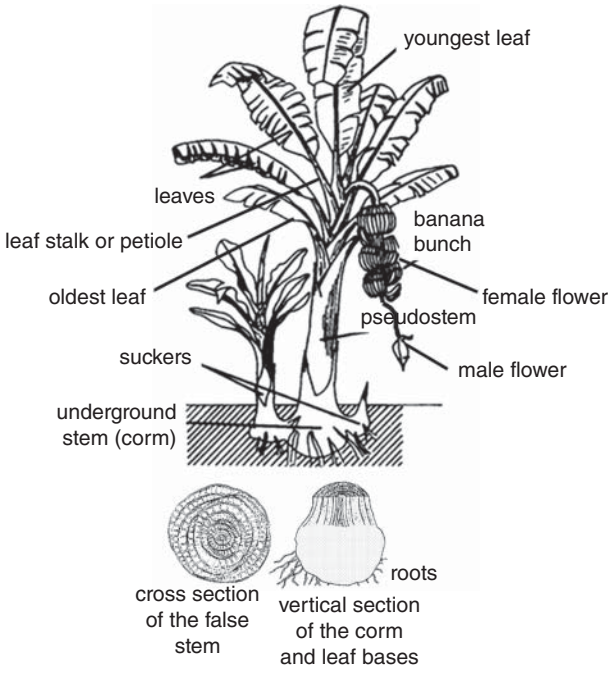

Figure 2.1 Various parts of a banana plant. Source: FAO (2019).

the alignment of the crop to be maintained. Figure 2.2A shows three generations in a banana plantation: grandmother (1), mother (2), and sucker (3).

The above ground "trunk" is a false stem called a pseudostem and consists of large overlapping leaf bases tightly rolled in an anticlockwise spiral manner (Barker and Steward 1962) forming a cylindrical structure (Figure 2.1). The leaves are composed of a "stalk" (petiole) and a blade (lamina). Most banana plants produce 30–40 leaves in their growth cycle (3–3.5 m length and 65 cm width), but as older leaves are pushed outwards they eventually die leaving 5–15 fully functional leaves on a mature plant. A minimum of 8–10 functional leaves are required to allow proper maturation of a bunch of fruit. Banana leaves can unfurl at the rate of one per week in summer but only one per month may be produced in the subtropics in winter (Morton 1987). The leaf takes between six and eight days to open completely since it emerges from the foliar crown. The length, disposition, and coloration of the pseudostem depend on the cultivar and the cultivation conditions. Thus, sweet bananas are predominantly green to dark green with black blotches while those of plantains are yellowish-green with brown blotches (Pillay and Tripathi 2007).

The meristem of the apical bud which initially gives rise to the leaves then elongates up through the pseudostem and 6–9 months after planting in the tropics or 8–10 months in the subtropics (Table 2.1), at about the time when the eleventh-last leaf has been produced, emerges a great terminal inflorescence (only one for each pseudostem) (Figure 2.2B).

The inflorescence is a compound spike of female (pistillate, on the base), hermaphrodite or neutral (in some cultivars in the middle) and male (staminate, at the tip) flowers arranged in groups of two rows of flowers, closely appressed to each other and covered

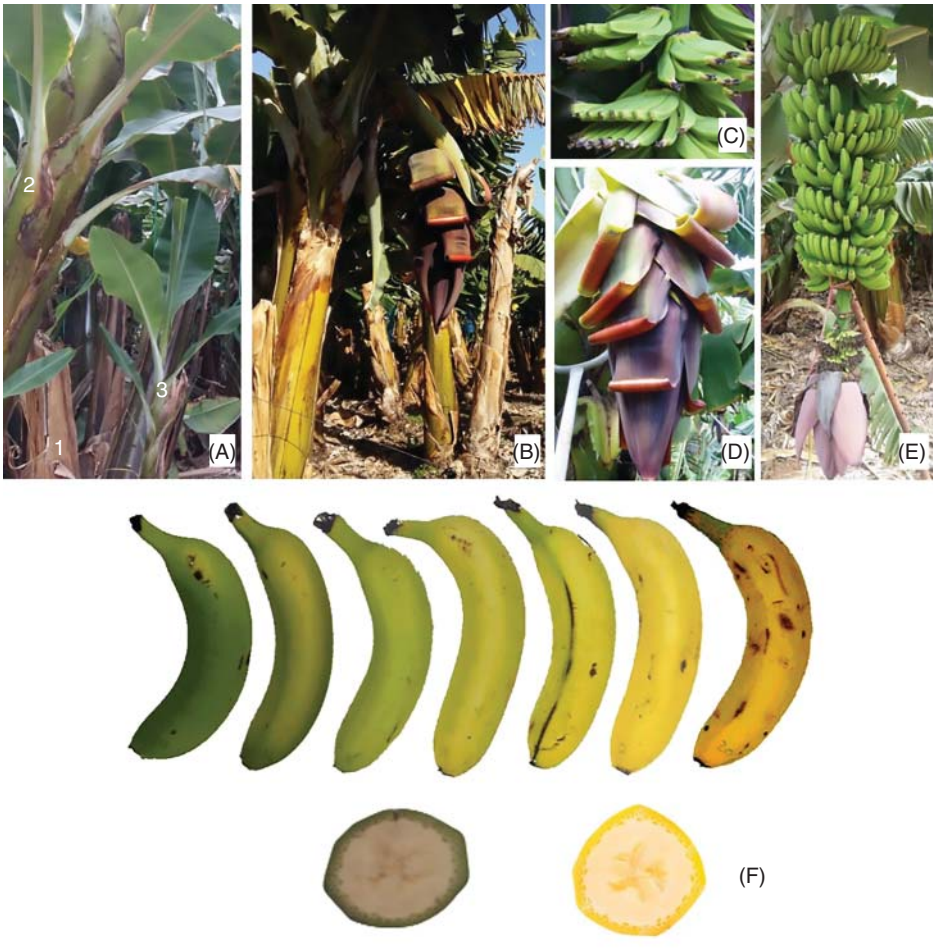

Figure 2.2 Banana plant and fruit: (A) 1, grandmother; 2, mother; 3, sucker; (B) flower emergence; (C) clusters; (D) flower opening; (E) bunch; and (F) fruit from mature green to yellow (left to right).

Table 2.1 Expected time to reach bunch emergence and harvest.

Stage	Tropics (mo)	Subtropics (mo)
Planting to bunch emergence	6–9	8–10
Bunch emergence to harvest	2–3	4–8
Planting to harvest	8–12	12–18

by large purple-red bracts or modified leaves (Figure 2.2C–E). In cultivated bananas, the ovary develops into a seedless fruit by parthenocarpy (without being pollinated), while the male flowers produce pollen that is more or less fertile, and the hermaphrodite or neutral flowers do not develop into fruit and their stamens do not produce pollen. The bracts open

in sequence (one per day) from base to tip and bend backward before being shed. As the hands of fruits start to develop from the female flowers, the male flowers are usually shed leaving the peduncle bare except for the very tip, which consists of a "male bud" (also referred to as the "bell") containing the last-formed of the male bracts and flowers. In some cultivars, this male part is shed quickly, and this may be a useful distinguishing characteristic.

The female flowers develop into fingers or individual fruits that constitute the bunch (Figure 2.2E). The number of hands in the bunch depends on the number of female clusters in the inflorescence and varies from 4 to 30 depending on the genotype, crop cycle, environmental conditions, and agronomic management of the crop. Thus, the weight of a Cavendish AAA bunch can vary from 15 to 70 kg depending on the number of fingers/hand (10–30), while a Williams AAA, with an average of 12 hands and 22 fingers/hand, is around 40 kg (Robinson and Galán Saúco 2012). Average annual banana yields are 10–25 t/ha but yields of more than 60 t/ha are obtained in commercial plantations of Latin America and elsewhere.

Fortescue and Turner (2004) reported that *M. acuminata* and *M. balbisiana* had three times more viable pollen than the edible tetraploids (AAAB), and that the tetraploids contained three times more viable pollen than the edible triploids AAA, AAB, and ABB. The genome A or B did not affect pollen viability within the triploid cultivars examined. Pollen viability rates were 71% for *M. acuminata* and 98% for *M. balbisiana*, while among the triploid studied, the highest percentage was found in the "Gros Michel" (13%). Most cultivated bananas are triploid and are characterized by high male and female sterility (Nyine and Pillay 2007) that give rise to seedless fruit with just minute vestiges of ovules that usually shrivel within 9–14 days of anthesis, visible as brown specks in the slightly hollow or faintly pithy center, especially when the fruit is overripe (Robinson and Galán Saúco 2012). Thus, Cavendish AAA subgroup cultivars are highly female sterile and cannot normally be pollinated successfully, while "Gros Michel" AAA gives one or two seeds per bunch if pollinated with diploids and although it is not completely sterile, it is regarded commercially sterile in the absence of pollen. The ABB cultivar "Pisang Awak" has a high degree of female fertility and can produce edible, seedless fruits if it is unpollinated, but can bear 10 or more seeds if pollinated by wild or garden pollen-bearing diploids. Wild types may be nearly filled with black, hard, rounded or angled seeds (3–16 mm wide) and have scant flesh. The seeds have linear embryos, large amounts of endosperm, and a thick hard testa.

In the tropics, the banana bunch is harvested two to three months after the inflorescence emerges while in the subtropics four to eight months are necessary (Table 2.1).

Banana Fruit

Each fruit is a berry and is known as a "finger." The skin or peel, is a fusion of the hypanthium (floral receptacle) and outer layer (exocarp) of the pericarp (fruit wall derived from the ovary wall) and is easily removed from the fleshy pulp that originates mainly from the endocarp (innermost layer of the pericarp). During the development of the fruit from the ovary, the tepals, style, and staminodes abscise leaving a characteristic calloused scar at the tip of the fruit. The fruit apex can be tapered, rounded, or blunt and can be used to distinguish between varieties.

Color, size, shape, texture, and flavor of common Musa bananas depends on the cultivar. They are generally elongate-cylindrical (3–40 cm long and 2–8 cm in diameter), straight to curved. The skin which varies in thickness is fibrous and can be green, yellow, or red. The flesh, white to cream, yellow, or yellow-orange to orange, is starchy to sweet.

Factors Affecting Plant and Fruit Development

Banana is a tropical/subtropical plant commercially grown from the equator to latitudes of 30° or more, in warm climates with at least 100 mm precipitation or supplied by irrigation.

Temperature

Temperature is the most significant climatic factor in the growth, development and flowering of banana being the optimum between 21 °C and 33 °C. Cool temperatures retard growth although susceptibility to the cold varies among cultivars. Thus, temperatures below 13 °C cease rot growth, below 6 °C leaf chlorophyll is destroyed, and frost temperatures (0 °C or below) kill the plant. The bud may not emerge from the stem (Choke Throat condition) if temperatures are low during flowering. Temperatures lower than 6 °C at the time of bunch initiation results in abnormal flowers, a reduction of hands of fruit, and irregular sized, twisted fruit. Over 38 °C the growing stops, the stomata close and the leaf temperature can reach 45 °C, resulting in death.

Relative Humidity and Rainfall

A humidity of at least 60% or more is preferable. In general, banana is successfully cultivated in areas where annual rainfall ranges from 2000 to 2500 mm. For a successful crop, the annual distribution of rainfall is important. In the dry tropics and subtropics where rainfall is less, supplementary irrigation is necessary for commercial production.

Water

Crop growth and yields are adversely affected if the banana has not an ample and frequent supply of water. The establishment period and the early phase of the vegetative period determine the potential for growth and fruiting and an adequate water and sufficient nutrient supply is essential during these periods. A reduced leaf area caused by deficit of water will reduce the rate of fruit filling; this leads, at harvest time, to bunches being older than they appear to be and consequently the fruits are liable to premature ripening during storage.

Regular water supply under irrigation during the total growing season produces taller plants, with greater leaf area, and results in earlier shooting and higher yields than those rain-fed with seasonal differences in water supply. In general, 100% of the water is obtained from the first 0.5–0.8 m soil depth with 60% from the first 0.3 m.

The irrigation interval may vary from 3 days under high evaporative conditions and light soils up to 15 days under low evaporative conditions and high water-retaining soils. When

rainfall and irrigation water is limited, it is advantageous to reduce the depth of each water application rather than to extend the irrigation interval (FAO 2019). Commercial plantations usually use overhead sprinkler systems with few applications but at frequent intervals. Surface irrigation methods include the basin, furrow, or trench (which also serves as a drain during the rainy periods). When drip irrigation is used under conditions of high evaporation, low rainfall and particularly if the water contains a small amount of salt, the boundary of wet and dry soil accumulate salts being necessary since banana plants are highly salt-sensitive.

Soil

Bananas can be grown on a wide range of soils, but they have to be fertile and well-drained. The best soils are deep, well-drained loams with a high water-holding capacity and humus content, and an optimum pH of 5–7. It is important to keep the optimum pH because higher or lower values lead to deficiencies in mineral absorption. Stagnant water will cause diseases such as Panama disease or Fusarium wilt.

Mineral Nutrition

Fruit quality is the result of the action of several factors, in particular the individual and combined effect of mineral nutrients (Aular and Natale 2013). Since the early stages of growth are critical for later development, nutrients must be ample at the time of planting and at the start of a ratoon crop. Macronutrients required by banana plants include nitrogen, potassium, phosphorus, calcium, magnesium, and sulfur. The demands for nitrogen and especially potash are high. A lack of potassium can result in reduced buoyancy, which can interfere with postharvest production line processes as the fruit sinks when dipped for washing or for hot water treatment against certain diseases. Short intervals between fertilizer applications, especially nitrogen, are recommended. Fertilizer requirements are 200–400 kg/ha N, 45–60 kg/ha P, and 240–480 kg/ha K per year.

Other micronutrients required by bananas include iron, manganese, copper, zinc, chlorine, molybdenum, cobalt, and boron. Deficiencies in these elements can lead to morphological malformation of the leaves, reduced growth and yield, and poor fruit quality (Nelson et al. 2006). Boron deficiency can result in fruit that does not "fill" (Broadley et al. 2004).

Light

Musa species grow best in the open sun when moisture or the presence of pests or diseases are not limiting factors. A maximum of 50% shade is recommended because plants in deep shaded areas result in a thinner pseudostem, lower production of leaves and suckers, smaller bunches, and delayed fruiting. Shading and insect-proof screens are widely used in agriculture for passive microclimate control and for insect exclusion. The use of screens reduces solar radiation and air velocity by about 15–39% and 50–87%, respectively; increases air relative humidity (RH) by 2–21%; and decreases air temperature and evapotranspiration by 2.3–2.5 °C and 17.4–50%, respectively (Mahmood et al. 2018).

Wind

Bananas are also susceptible to strong winds (40–72 km/h), which can twist and distort the crown, shred leaves, and even topple plants especially after heavy rains. In areas prone to windy conditions, dwarf varieties are often grown. However, some leaf tearing is believed to be beneficial as it effectively causes the leaf to be split into many smaller segments that leads to a more favorable photosynthesis to transpiration ratio during times of environmental stress (Taylor and Sexton 1972). Winds, even moderate, cause scratch marks on the fruit when the bunch is not bagged in the plantation, making them unacceptable for marketing.

Growth Regulators and Other Treatments

Many growth regulators are used in micropropagation. Cytokinins (CKs) induce both axiliary and adventitious shoot formation from meristematic explants in banana increasing the number of shoots. Benzylaminopurine (BAP), 2-isopentenyl adenine (2-iP), kinetin (Kin), zeatin (ZEA), and derivatives of diphenyl urea such as thidiazuron (TDZ) are the most used. Auxins and other growth regulators such as gibberellins play important roles in the growth and differentiation of cultured cells and tissues. Auxins such as naphthalene acetic acid (NAA) have been reported to promote plant rooting *in vitro*. Bhaya and Al-Razzaq Salim (2019) recommend using BAP at a concentration of 5 mg/l or TDZ 0.2 mg/l plus 1.5 mg/l NAA in nutrient medium of the multiplication and the use of LEDs (red:blue) at 2:18.

Yadlod and Kadam (2008) found that the spray application (on both sides of leaves) of indole-3-acetic acid (IAA, 80 ppm), gibberellic acid (GA3, 80 ppm) and two sprays of micronutrients 1% were effective for increasing plant growth, size and weight of finger. Nevertheless, under some cultivation conditions, excessive growth of the pseudostem of banana plants can be considered a limiting factor, and thus, the use of growth regulators can constitute a valid alternative. Paclobutrazol (PBZ) is a plant growth retardant and acts by inhibiting gibberellin biosynthesis. El-Otmani et al. (1992) applied this substance either as granular soil or liquid foliar application at a rate of 1 g of active ingredient/plant, two months prior to flowering and observed a significant reduction of the plant height, leaf size and fruit bunch length and an increase of fruit grade and weight. Nevertheless, no effect was appreciated on pseudostem circumference, leaf number, sucker production, yield, or fruit composition.

Ethephon or ethrel is used in many fields such as a plant growth regulator to release ethylene that causes defoliation, reduces postharvest losses, and improves the color development of fruit. It is also used in fruit ripening to accelerate the process. Nevertheless, its use is not allowed in all countries.

Banana is a climacteric fruit that has high rate of deterioration which contributes to high postharvest losses. GA3 is able to delay the climacteric peak of "Berangan" bananas, to retard the peel color changes and fruit softening, and to extend its shelf life up to 16 days (Huang and Jiang 2012). Postharvest dipping of "Grand Nain" bananas in 150 mg GA3, 50 mg 6-benzylaminopurine, or 2% $CaCl_2$ retarded ripening and retained quality during their shelf life. Moreover, GA3 was more effective in reducing peel browning and retaining green color than the other treatments including control (Al-Qurashi and Awad 2019).

Natural Ecosystems

Natural ecosystems near to agricultural landscapes can provide richer environments for growing crops by enhancing the natural control of pests and diseases (Tomas et al. 2009), nutrient cycling, erosion control, and carbon sequestration (Jarvis et al. 2007). Thus, organic crop farming and agro-environmental management within and around production areas could increase crop resilience and reinforce food security against climate change and resource scarcity (Frison et al. 2011). Castelan et al. (2018) observed that a natural ecosystem (natural forest, NF) surrounding a conventional banana crop improves plant health and fruit quality. Fruits near NF showed higher green-life and a more homogeneous profile during ripening when compared with those harvested from distant NF due to lower IAA and higher abscisic acid (ABA) levels which are associated with accelerated physiological processing of fruit leading to a faster ripening and senescence. Moreover, plants from near NF showed a lower severity index of black leaf streak disease (BLSD) and higher levels of phenolic compounds in leaves compared with plants from distant NF.

Fruit Ripening

After inflorescence emergence, bunch fingers develop and accumulate starch in the pulp. Fingers continue growing longitudinally 80–90 days after flowering and from this moment ripening begins and the fingers start to thicken. Harvest should be carried out until 3/4 caliper width to avoid peel fruit splitting during postharvest.

As a climacteric fruit, bananas are harvested at physiological maturity and then generally ripen in ripening rooms, although in some regions they are naturally ripened.

Physiology and Biochemistry of Banana Ripening

Ripening is an irreversible process that can be divided into four distinct phases: pre-climacteric or "green life," climacteric, ripening, and, finally, senescence. There are commercial standard color charts to identify the ripening stage of bananas (1, dark green; 2, light green; 3, more green than yellow; 4, more yellow than green; 5, yellow with green tips; 6, yellow; 7, yellow with brown freckles) (Figure 2.2F). During ripening different physiological, biochemical and organoleptic changes lead to a soft and edible ripe fruit.

Pre-Climacteric Phase

This phase ranges from harvest at physiological maturity to the visible respiratory climacteric state. During this period the metabolic activity is low being the main commercial objective to enlarge it as much as possible either by improving the pre-harvest practices, harvesting before 3/4 caliper width, decreasing storage/transport temperature but never below 13 °C to avoid chilling injury, and applying treatments that block ethylene receptors, i.e., potassium permanganate ($KMnO_4$) and 1-methylcyclopropene (1-MCP) (Jiang et al. 2004; Kumar et al. 2017), or decreasing metabolic activity (controlled atmospheres, growth regulators [auxins, gibberellins, CKs, polyamines, and jasmonates]) (Rademacher 2015), and coatings (polyethylene wax emulsion, bee wax, carnuba wax, chitosan, and paraffin) (Suseno et al. 2014).

In this phase bananas changes from stage 1 (dark green) to stage 2 (more green than yellow). Starch, total soluble solids, and water content do not change significantly while mechanical fruit resistance increases (Robinson and Galán Saúco 2012). The great strength of green fruit is due to the protopectin or water insoluble pectin which is partially esterified with polygalacturonic acid. Malic and citric acids are responsible for tartness in the unripe banana while oxalic acid contributes to the astringent taste of the fruit (Seymour et al. 1987). Astringency is caused by the tannins present in the peel and pulp that diminish with ripening.

Climacteric Phase

Metabolic activity increases and the climacteric ethylene peak that precedes the climacteric respiration peak occurs. The production of endogenous ethylene is mediated by two enzymes: 1-aminocyclopropane-1-carboxylic acid (ACC) synthase, and the ethylene forming enzyme (EFE) (Figure 2.3). In this phase, peel color changes from stage 3 (more green than yellow) to stage 4 (more yellow than green). Total soluble solids content increases due to the conversion of starch into sugars, chlorophyll degrades, water content increases, and peel and pulp start to soften. Patil and Magar (1975) reported that pectin methylesterase (PME) activity, implicated in fruit softening, is highest at color stage 4 and fell sharply in the advanced stages of ripening.

Ripening Phase

Several evident changes take place simultaneously during the ripening process from stages 4 to 6. Tissue softening continues and at the end of ripening almost all the starch has been degraded to sugars in both the pulp and peel. The peel of the fruit turns completely yellow as chlorophyll is broken down, while pulp becomes softer and sweeter as the ratio of sugars

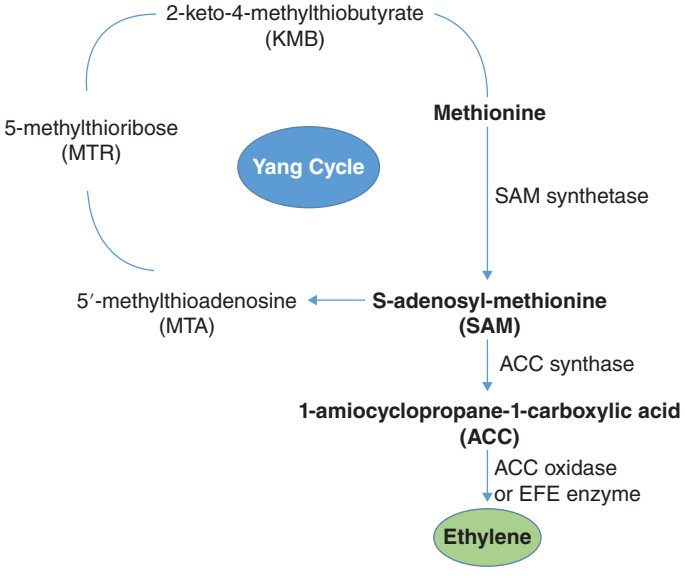

Figure 2.3 Ethylene biosynthesis.

to starch increases, and a characteristic aroma is produced. The water content increases considerably in the pulp (10% more) due to the degradation of starch caused by respiration and the osmotic movement of water from the peel to the pulp. Peel water content diminishes owing to transpiration. Various enzyme systems are involved in all the changes.

Senescence

After stage 6, the peel becomes spotted brown and then completely brown, and the pulp loses its firm, white texture to become brown and gelatinous.

Role of Ethylene and Other Hormones

Briefly, ethylene is synthesized from methionine. First methionine is converted to S-adenosyl-L-methionine (SAM) which is catalyzed by SAM synthetase. Then SAM is converted to ACC. This conversion is catalyzed by the enzyme ACC synthase and then ACC is converted to ethylene catalyzed by ACC oxidase, also called EFE enzyme. Methionine is regenerated from SAM through the Yang cycle (Figure 2.3).

The ABA facilitates initiation and progress in the sequence of ethylene-mediated ripening events, possibly by enhancing the sensitivity to ethylene (Jiang et al. 2000).

Moreover, Aghofack-Nguemezi and Kanmegne (2008) reported that the role of ethylene in the regulation of the ripening process may be modulated by the endogenous concentration of auxin.

Application of gibberellic acid (GA3) at a concentration between 50 mg/l and 250 mg/l in the Cavendish variety increased the green life of banana by 3–4 days (Vargas and Lopez 2011).

Several studies suggest that jasmonates might be positive regulators of fruit ripening through induced expression of ethylene synthesis pathway genes. Salicylic acid (SA) levels have not been determined during ripening, however application of exogenous SA to different fruits including banana, reduced respiration and ethylene production and decreased cell wall deterioration. Finally, CKs are usually associated with delayed senescence, cell death and fruit ripening (Yakir et al. 2018).

Compositional Changes During Fruit Growth and Maturity

Changes involve several biochemical pathways such as degradation of starch to sugar, modifications in the peel and pulp color, cell wall, volatiles and acids concentration, and astringency reduction.

During the ripening process, starch (20–25% of fresh weight in unripe bananas) is converted into simple sugars through an enzymatic browning process (from 1−2% in green pulp fruit to 15–20% at ripeness) (Maduwanthi and Marapana 2017). The soluble sugars detected in ripened banana are mainly sucrose, glucose, and fructose.

According to Adão and Glória (2005), starch content was reduced from 15.7 to 3.40 g/100 g in “Prata” banana during ripening, while total soluble sugar content was increased from 1.26 to 14.3 g/100 g. Adewale (2013) reported that unripe bananas have high amylase activity (3900 units/mg protein) that decreased rapidly to a very low value (100 units/mg protein) when the bananas are fully ripened.

The peel color changes from green to yellow during ripening. Chlorophyll content decreases and chlorophyll is absent in ripe fruit. The level of total carotenoids decreased to half the level at the color break and subsequently again reached a level similar to that in green fruit. According to Gross et al. (1976), the major components (percentage of total carotenoids) of pulp carotenoids are α-carotene (31%), ß-carotene (28%), and lutein (33%). Banana peel contained 3–4 μg/g carotenoids content as lutein equivalent and the components were lutein, ß-carotene, and α-carotene.

Proximate/Nutritional and Phytochemical Composition

Proximate/Nutritional Composition

The composition and nutritional profile of raw bananas, based on USDA data, is shown in Table 2.2 (USDA 2019). Varietal differences, climatic and soil conditions, agricultural practices and postharvest handling may contribute to variations in the composition and nutritional profile. About 93% of the calories come from carbohydrates, 3% from fats, and 4% from proteins of a high quality due to their amino acids profile. One hundred grams of edible banana provide a very good source of vitamin B6 (18% of the daily value [DV]), vitamin C (15% DV), dietary fiber (10% DV), potassium (10% DV), and manganese (13% DV). It is very low in saturated fat (0% DV), cholesterol (0% DV), and sodium (0% DV). The glycemic load of banana, which is related to how glucose levels rise in blood when a meal is ingested, is low (8 g per 100 g serving), but higher than other fruits (apple 3, orange 6, or pineapple 6).

Phytochemicals and Antioxidants

Banana fruit as well as other parts of the fruit and plant (peel, pseudostem, leaves, and flower) are important sources of bioactive compounds with potential health-promoting activity. Banana fruit is rich in carotenoids, flavonoids, phenolics, amines, and vitamins C and E that provide health benefits (Singh et al. 2016). Among the carotenoids present in banana fruit (peel and pulp), α-carotene, β-carotene, and β-cryptoxanthin have provitamin-A activity, but others such as lycopene and lutein have a strong antioxidant capacity. Their antioxidant effect is related to their capacity to remove reactive oxygen species (ROS), as vitamin C does, protecting the human body against diseases associated with oxidative stress. Moreover, carotenoids affect gene expression regulation which partly explains the association between higher carotenoids intake and lower risk of certain diseases (cardiovascular, some types of cancer, osteoporosis, infectious, cataract, etc.). Yellow- and orange-fleshed banana cultivars are known to be richer in *trans*-β-carotene content.

Among the flavonoids detected in banana, quercetin, myricetin, kaempferol, and cyanidin provide health benefits mainly because they act as free radicals, ROS, and reactive nitrogen species (RNS) scavengers (Kevers et al. 2007). Most of these phenolics are also known to exhibit antibacterial, antiviral, anti-inflammatory, antiallergenic, antithrombotic and vasodilatory activities. Leucocyanidin is a predominant flavonoid present in unripe banana pulp that showed significant anti-ulcerogenic activity (Lewis et al. 1999). Banana

Table 2.2 Composition and nutritional profile of banana fruit (per 100 g).

Nutrient	Units	Raw	% Daily value
Proximate, sugars, and energy			
Water	g	74.91	—
Energy	kcal/kJ	89/371	4
Protein	g	1.09	2
Total lipid (fat)	g	0.33	—
Ash	g	0.82	—
Carbohydrate, by difference	g	22.84	8
Fiber, total dietary	g	2.6	10
Sugars, total	g	12.23	—
Sucrose	g	2.39	—
Glucose (dextrose)	g	4.98	—
Fructose	g	4.85	—
Starch	g	5.38	—
Minerals			
Calcium	mg	5	1
Iron	mg	0.26	1
Magnesium	mg	27	7
Phosphorus	mg	22	2
Potassium	mg	358	10
Sodium	mg	1	0
Zinc	mg	0.15	1
Manganese	mg	0.27	13
Selenium	µg	1	1
Vitamins			
Vitamin C, total ascorbic acid	mg	8.7	15
Thiamin	mg	0.03	2
Riboflavin	mg	0.07	4
Niacin	mg	0.67	3
Pantothenic acid	mg	0.33	3
Vitamin B6 (pyridoxine)	mg	0.37	18
Folate, total	µg	20	5
Choline, total	mg	9.8	—
Vitamin A, RAE	µg	3	—
α-Carotene	µg	26	—
ß-Carotene	µg	25	—
Vitamin A, IU	IU	64	1
Lutein + zeaxanthin	µg	22	—
Vitamin E (α-tocopherol)	mg	0.1	1

Source: USDA (2019).

peel is rich in many high-value health-promoting antioxidant phytochemicals, such as anthocyanins, delphinidin, and cyanidins (Shidhu and Zafar 2018).

Various phenolics have been identified not only in banana fruit but also in the rhizome and pseudostem: gallic acid, catechin, epicatechin, tannins, anthocyanins, ferulic, sinapic, salicylic, *p*-hydroxybenzoic, vanillic, syringic, gentisic and *p*-coumaric acids. The content of phenolics is usually higher in the peel than in the pulp of the fruit.

Banana peel and pulp are good sources of certain biogenic amines (catecholamines: dopamine, serotonin, epinephrine, and norepinephrine). Dopamine is a neurotransmitter having a strong influence on mood and emotional stability. Tryptophan, a precursor for the synthesis of dopamine, is an amino acid that exists in banana peel. Pharmaceutical formulations using this by-product of the food processing industry can be used to prevent neurodegenerative diseases, such as Parkinson's disease. Serotonin creates a feeling of well-being and happiness, while epinephrine and norepinephrine act as both neurotransmitters and hormones in the body.

The lipophilic extract of ripe banana pulp from several cultivars of the *M. acuminata* and *M. balbisiana* species has been found to be a source of ω-3 and ω-6 fatty acids, phytosterols, long-chain aliphatic alcohols, and α-tocopherol, thus offering well-established nutritional and health benefits (Vilela et al. 2014). Health professionals recommend the consumption of a plant sterol-rich diet to lower the low-density lipoproteins (LDLs) cholesterol in patients who do not tolerate cholesterol lowering statin drugs. Various phytosterols have been reported in the banana pulp and peel (stigmasterol, ß-sitosterol, campesterol, 24-methylene cycloartenol, cycloeucalenol, and cycloartenol).

Bananas are rich in pectin and, when unripe, contain resistant starch moderating blood sugar levels after meals and slowing the emptying of the stomach and thus reducing the appetite. Moreover, resistant starch improves insulin sensitivity to those patients with metabolic syndrome (a combination of diabetes, high blood pressure, and obesity).

Potassium and magnesium are important minerals for heart health – especially, for blood pressure control.

The health benefits of eating different parts of the banana plant and fruit are: boosts energy levels, anti-diarrheal (green banana), help circulation, lower blood pressure, reduce risk of stroke, fight infections, anti-ulcer, anti-diabetic, protect skin against damage from UV light, fights depression and anxiety, suppressed oxalate kidney stones (stem extract), prevent age-related macular degeneration, etc.

Harvesting

Harvesting Indices

Selection of the right stage of maturity for harvest is an important aspect which has considerable influence on storage life and quality, and therefore, final acceptance by the consumer.

The banana plant typically produces fruit 8–12 months after planting in the tropics, while in the subtropics needs 12–18 months (Table 2.1). Harvesting depends on the variety and the distance of the market where the banana is going to be commercialized, but as a climacteric fruit has to be when physiological maturity has been reached. After the flower has opened, the fingers start to grow and get fatter but stay green. Bagging bunches results

in a cultural practice which is very convenient to avoid fruit defects caused by thrips, anthracnose, and even by hard winds or high temperature differences between night and day. Fernandes et al. (2019) observed that bagging bunches at emission reduces incidence and severity of anthracnose by up to 67% and did not interfere in the physical and chemical characteristics of the fruit.

Maturity measurements must be simple, readily performed in the field (if possible), and should require relatively inexpensive equipment. They should be preferably objective and non-destructive. Although maturity of the fruit is assessed largely by the producers' experience of the visual appearance of the fingers (angularity, diameter, length, and color), new objective and non-destructive techniques are being developed (image processing or visible/near-infrared [VIS/NIR] spectroscopy).

Based on these maturity indices, the banana bunches can be classified into three categories: un-mature, mature, and over-mature fruit (Muchui et al. 2010).

Age Bunch Control

Lack of age control may result in the harvesting of under-filled or under-mature (immature) bunches with fruits off-flavor and off-color, or over-mature bunches predisposing banana to ripe, cracked, or rot in transit to the final destination. Under-mature fruits could not produce characteristic flavor and color whereas over-mature fruits cause splitting and spoilage.

Age control is important in the proper assessment of green life as well as scheduling harvesting and marketing operations efficiently (Dadzie and Orchard 1997). Colored ribbons or the tagging of the plants in the field immediately after flower emergence are used to provide information regarding bunch age. Calculating the number of days from anthesis to harvest provides one of the best indicators of maturity of banana, cooking banana or plantain although variations in development will be noted among cultivars/hybrids, or field conditions.

As bunches advance in age fruit changes in size, shape, length, volume (circumference), and color. In most Musa cultivars/hybrids, during the early stages of development, individual fingers are angular, however as growth progresses, the fingers lose angularity and become more rounded and full in shape (as fruit advance in age). The final degree of roundness is cultivar dependent. Fruit diameter (or caliper grade of fruit) and fruit length may be used as criteria to determine when to harvest.

On most banana plantations, fruits destined for distant markets are harvested at a stage known as "three quarters full," when the fingers are still clearly angular, while for local markets fruits are often harvested when fingers are full or rounded. Length is also used to assess the maturity of the bunch before harvest and it is determined by measuring the middle finger on the outer whorl of the second hand. Finger color also changes from dark green to green, and finally to yellow with fruit age.

There is both a linear relationship and a strong correlation between pulp to peel ratio and bunch age. Regardless of the fruit growth rate, the physiological age of banana fruits is closely correlated with the mean daily temperature sum accumulated by the fruit during its development. Thus, 900 degree-days (at the 14 °C threshold) from the shooting stage are needed by Cavendish bunches to have a green life duration sufficient to support exportation (Ganry and Chillet 2008). Green life is calculated as the period (in days) between harvest and commencement of ripening.

Image Processing

Image processing is an innovative field of science where the acquired image is transformed into useful information. Prabha and Kumar (2015) found that the mean color intensity and area features were more significant among the different maturity stages than other features such as perimeter, major axis length, and minor axis length. Mean color intensity algorithm was more accurate (99.1%) for differentiating under-mature, mature, and over-mature, than area algorithm (85%) which is useful for differentiating under-mature banana, but not to distinguish between mature and over-mature. Since both the color and size value are a reliable index to determine the right time to harvest, the mean color intensity algorithms in conjunction with area algorithms developed in this study could be employed commercially to develop a field-based completely automatic detection system for banana growers to decide the right time to harvest.

VIS/NIR Spectroscopy

Non-destructive prediction of banana fruit quality using VIS/NIR spectroscopy has been done based on determining fruit chlorophyll and sugar contents (Zude-Sasse 2003). Nevertheless, no studies in predicting bunch age or maturity have been developed.

Harvest

Harvesting must be done manually, carefully, and using appropriate tools to avoid bruises and bumps. In very hot weather, bananas should be harvested during the coolest part of the day. During cultivation in order to avoid the plant falling due to the weight of the bunch, some forks are used on which it rests, and/or a cable system that then facilitates its removal. Bananas are always harvested by hand using a two-person team. One person cuts the bunch and the other carries it away. A cut with a sharp knife is made on the facing bunch stem, while the receiver is placed under the bunch with his or her shoulder covered with a blanket. The bunch stem begins to bend because of the weight, and it is lowered to the receiver's shoulder padding and finally the bunch stem is cut with a saw.

The method of harvesting will depend on the height of the plant. Low-growing varieties can be harvested by cutting through the bunch stalk about 30–35 cm above the top hand, while in taller varieties, the stem of the plant will be partly cut through to bring the bunch to within the harvester's reach, and then the bunch stalk can be cut through. Harvested bunches are best carried wrapped in foam protective blankets and positioned vertically in padded trailers to minimize friction during transport from the field to the packing house. At the packing house, banana bunches are hung, the covers removed, washed or not, and de-handed. The hands or cluster are washed and finally packed into boxes.

Bananas should be carefully handled at all stages of the harvesting and packing process. Rough handling can result in damage that does not become evident until the carton is opened at the markets after the ripening process.

Fruit Quality Disorders

Both banana quality and market value are affected by the development of many physiological disorders that occur in all growing regions of the world. They are not caused by either

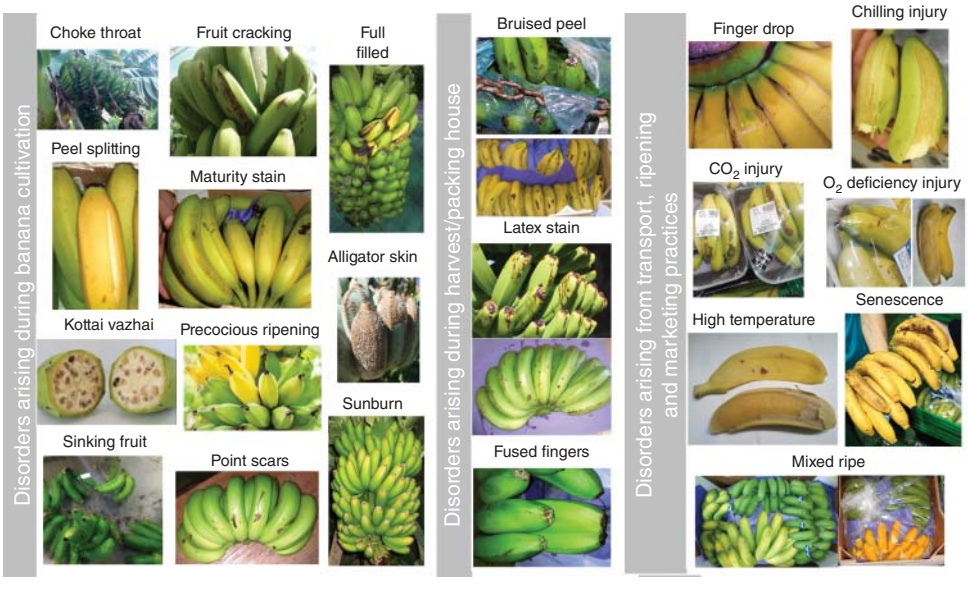

Figure 2.4 Physiological disorders of banana fruit.

invasion by pathogens (disease-causing organisms) or by mechanical damage; they develop largely in response to an adverse environment, especially temperature, or to a nutritional deficiency during growth and development (Wills et al. 1989). The major physiological disorders (Figure 2.4) that may occur in banana, cooking banana, and plantain are discussed in the following.

Disorders Arising During Banana Cultivation

Choke Throat

This disorder results from low temperature conditions in the field. Low temperature causes yellowing of leaves and under severe conditions the leaves become necrotic. Low temperature, at the time of flowering, affects the bunch formation which cannot emerge from the pseudostem properly. Moreover, the maturity time of the bunch is extended from 3–4 months up to 5–6 months. This disorder is called choke throat because although the distal part of the inflorescence comes out of the pseudostem, the basal part is stuck up at the throat.

The management of choke throat includes the use of varieties that tolerate low temperature and the use of Casuarina or Eucalyptus as a shelter belt to prevent the effect of cold winds in the orchard.

Peel Fruit Splitting

Fruit cracking is a serious physiological disorder that has a negative effect on the fruit appearance, decreases its shelf-life, and is considered as a preferential entry site for fungal pathogens, thus rendering the fruit unmarketable. Split peel of green banana in the fields results from a too rapid filling of the fingers due to highly favorable growing conditions or if the harvest time is delayed. Peel split also occurs during transport, and when ripening. The peel of the fruit is split into bisects and consequently the pulp is exposed as the cracks

widen as a consequence of a high relative humidity of over 90% combined with temperatures over 21 °C. When the finger is too full, this can be observed 3–6 days after ripening induction when stored in saturating humidity conditions. Cavendish cultivars (GN) are less susceptible to splitting than other varieties, e.g. "Gros Michel."

Brat et al. (2016) tentatively found that splitting intensity was associated with an inverse water flux at high relative humidity through an osmotic peel to pulp water flux resulting from the higher sugar content in the pulp than in the peel. Rheological properties were measured, and although the peel resistance and elasticity in cv. 925 (a hybrid produced by CIRAD's plant breeding program, CIRAD925 [*M. acuminata*, AAA group, hereafter called 925]) were surprisingly higher than in cv. GN, saturating humidity conditions (100% RH) substantially reduced the peel resistance. However, the peel epicuticular wax in cv. 925 was clearly thinner than that in cv. GN, thus leading to limitation of peel hydration in cv. GN. Peel splitting in cv. 925 was also associated with a boost in respiration, an increase in oxidative stress markers (H_2O_2), resulting in an increase in cellular damage markers (content of malonyldialdehyde, and peel electrolyte leakage). Overall, their results suggest that peel splitting at high relative humidity in cv. 925 was related to fast decrease peel water content and the induction of high oxidative stress damage.

Management of this disorder is to avoid harvesting the fruit >3/4 caliper width and storing full fingers at high humidity.

Sinking Fruit

The fruit sinks to the bottom of the wash tank hindering the packaging chain and negatively affecting the appearance of the hands and clusters when rubbing the peel with the bottom of the tank. It is due to a potassium deficiency and tends to occur in plump clusters, especially after heavy rain and warm weather. It is important to take care at fertilization during cultivation (potassium application should be from 400 to 800 kg/ha).

Maturity Stain

Maturity bronzing can be an important economic problem in some banana-growing regions. Fruit affected by this disorder does not meet Number 1 grading standards, showing a reddish-brown or brown discoloration, developing a scabby, cracked peel, and making the fruit unacceptable for sale. They must be culled at the packing house during de-handing and before washing, drying, and boxing. Nevertheless, yield and eating quality of affected fruits are not compromised. Maturity bronzing appears on peels at or near harvest, at about the 3/4 caliper stage of fruit development. The symptoms become more severe as fruits fill beyond the 3/4 width. This disorder may be confused with damage caused by red rust thrips (*Chaetanaphothrips signipennis*).

Although the cause of the maturity stain remains unclear, the symptoms appear to be a physiological disorder resulting from an undefined stress to the exterior layers of the banana peel, followed by rapid growth and expansion of the fruit. The condition has also been associated with water deficit at bunch emergence during periods of rapid fruit growth when air temperatures and relative humidity are high and in contrast with periods of heavy rain accompanied by high humidity and overcast conditions.

It is important to irrigate at the early stages of bunch phenology to avoid moisture stress, and to harvest when the fruit attains 3/4 mature diameter.

Leaf Rubbing Injury (Alligator Skin)

Bunch fruits present raised, cracked, brown areas with corky appearance that sometimes group together in large, separate masses on the peel. This disorder is often attributed to leaf rubbing injury during bunch development caused when peel cells are killed by the edges of leaf blades rubbing against immature fruits during wind events. Leaves near bunches should be removed weekly to prevent this disorder.

Bumpy Finger

Banana peel show bumps due to swollen pulp that can be associated with poor soils, boron deficiency, or rapid filling of fruit pulp. Management practices are to maintain good plant nutrition and avoid boron deficiency (Nelson and Pethybridge 2019).

Point Scars

The symptom is bruises on fruit peels associated with the position of the flower-end of proximal fingers. Rough handling of harvested bunches causes fingers from proximal hands to rub together and affect each other. Thus, it is important to avoid rough handling of bunches after harvest (Nelson and Pethybridge 2019).

Sunburn/Sunscald

Sunburned fruits are yellow when unripe and sometimes even get black. Bunches formed on the west- or south-west-facing side of the pseudostem are most prone to sunburn. Those bunches that do not hang vertically are more susceptible. Defoliation due to BLSD can increase this disorder. Sunburn can be controlled by draping a lightweight cloth or a polythene sleeve over the bunch.

Kottai Vazhai

It is a serious malady in some banana varieties, specifically in "Poovan" in which production losses can reach 10–25%. The symptoms are distinctly conical and ill-filled fruits with a prominent central core having many underdeveloped seedy structures making the fruit inedible. The pseudostem exhibits streaks, striations and blotches on the surface. Bunches are held at an angle above the horizontal position. Pollen grains are infertile, shriveled, shrunken, and broken while the pericarp is smaller and the locular cavity is bigger than normal. The absence or the occurrence of auxin, gibberellin and cell dividing factors at subepidermal levels affect the development of parthenocarpy fruits.

Application of 2,4-D (25 ppm) and GA (100 ppm) after the opening of the last hand favors development of parthenocarpy fruit.

Potassium Deficiency

The most characteristic potassium deficiency symptom is chlorosis that causes yellowing of older leaf tips followed by inward leaf curling and finally leaf death. Banana plants grow slowly and have a sturdy appearance due to the shortening of internodes, with short, slim and deformed bunches due to the poor fruit filling caused by reduced photosynthesis and sugar transportation. The crop requires adequate fertilization during cultivation to avoid this disorder.

Yellow Pulp

Excessive shading of plants, magnesium deficiency, or drought delay fruit filling shortening green life and diminishing fruit quality (pulp yellow pale and poor texture). The management of this disorder consists of removing excess shading (windbreaks), avoiding soils with poor aeration, low organic matter or high clay content, irrigating during periods of drought, and applying fertilizers to avoid magnesium deficiency and that of other nutrients.

Precocious Ripening

Individual fingers ripen prematurely on hands before the bunch is harvested. Ethylene gas from leaves with Sigatoka disease favors premature fruit ripening. The management to control this disorder is to de-trash plants with Sigatoka disease weekly.

Disorders Arising During Harvest or at the Packing House

Bruised Peel and Pulp

Rough handling of unripe fruits during harvest and packing produces blackish bruises in the peel with regions from gray to black and softened pulp beneath the bruised areas. Careful handling of bunches, hands, and clusters during and after harvest diminish this disorder.

Latex (sap) Stain

Latex coming out of the hands or cluster crowns can stain the fruit surface when not removed from wash tanks. Washing fruits immediately after de-handing, using sharp knives to ensure smooth cuts, in water with products that agglutinate the latex such as aluminum sulfate can help prevent staining. Before bagging bunches in the field remove female flowers because when they become dry and brittle, this creates sap flow.

Fused Fingers

The fusion of banana fingers is the result of a genetic mutation or defect, seen particularly in Cavendish varieties. Hands with fused fingers may not be marketable but are completely safe to eat. The affected plant and its suckers should be destroyed if found on a commercial farm.

Disorders Arising from Transport, Ripening, and Marketing Practices

Finger Drop

Cooking banana, plantain and especially dessert banana are often marketed as hands or clusters conserving the crown attached. Finger drop is a physiological disorder which occurs as a result of the softening and weakening of the pedicel which causes individual fruit of a hand to separate or dislodge very easily from the crown during ripening (Semple and Thompson 1988). It is associated with inherent genomic susceptibility (A genomes > B genomes; tetraploids > triploids > diploids) (Putra et al. 2010), deficiency in soil nitrogen during the production period, advanced stages of fruit maturity, and rapid ripening precipitated by too high a temperature in the ripening room (Marriott 1980). Finger drop is further exacerbated by prevailing cultural and marketing practices (harvesting fruits at full size or maximum caliper width, and displaying bunches on hooks).

Retailers and consumers do not want fingers falling easily from the crown during handling. Greater dropping resistance is related to higher accumulation of dry mass and starch in the pedicel, being the activity of polygalacturonase (the key enzyme in the solubilization of the cell wall that accompanies ripening) positively related to dropping susceptibility (Ruiz et al. 2016). Salazar and Serrano (2013) observed that the application at the pedicel-end portion of 200 ppm gibberellic acid (GA3), 4% calcium chloride ($CaCl_2$), or 60% v/v ethanol (EtOH) were effective postharvest treatments against the disorder, with no finger drop occurrence in "Cuarenta días" bananas 15 days at ambient storage. Control of finger drop by any of these chemical treatments was associated with delayed peel color development and ripening events. Thus, it is important to control finger drop disorder by selecting varieties less prone to this disorder and treat the crown and fruit pedicels with substances that control the activity of enzymes related to cell wall degradation (polygalacturonase and pectylmethylesterase), and improve the stability of calcium bonds.

Chilling Injury

Chilling injury incidence and severity depends on cultivar, maturity stage, and temperature and duration of exposure. Chilling injury occurs when a product is exposed to an injurious, low temperature for sufficient time to initiate irreversible injury.

Chilling injury is one of the most important physiological disorders affecting bananas. Green fruit is slightly more susceptible to chilling injury than mature fruit. The chilling of banana results when the pre- or postharvest temperature falls below 14 °C. The peel of banana becomes dark and the fruit reveals uneven ripening, watery dark patches, and dull yellow to smoky yellow color of the ripening fingers, brittleness, and fungal invasion. Brown streaks are also observed on the subepidermal layer of the vascular bundle. These result from enzymatic oxidation of dihydroxyphenylalanine.

The main control strategy for chilling injury involves avoiding exposure to temperatures below 13–14 °C for long periods.

CO_2 Injury

Exposure to CO_2 concentrations greater than 5% in ripening rooms may cause fruit to soften while still green. The fruit has an undesirable texture and flavor. It is important to ventilate ripening rooms adequately.

Oxygen Deficiency Injury

Oxygen concentrations below 2% causes dull yellow or brown skin, failure to ripen, and off-flavor. It is necessary to ventilate ripening rooms adequately to avoid anaerobic conditions.

High Temperature Injury

Bananas ripened at a high temperature show dull gray green color, under-peel discoloration, and off-flavor development. Air temperatures over 30–35 °C during transport can irreversibly inhibit ripening. It is very important to avoid exposing fruits to high temperatures.

Withered Pedicels

Pedicels appear withered, wrinkled and desiccated when bananas are stored in areas of low relative humidity. To avoid this disorder ripening should be performed at 95% RH, and fruits then stored over 75% RH.

Mixed Ripe

Hands once in boxes ripen prematurely during shipment or ripen non-uniformly at any point before commercial ripening. More mature bananas ripen first and ripeners find it very difficult to ripen the banana pallets to reach the same maturity stage. It is important to label bunches in the field to harvest, pack and ripen those which are at the same stage of ripening.

Senescent Spots

Brown spots less than 1 mm deep or flecks appears on the peel that do not enlarge, coalesce, or blacken. They are due to the banana fruit's senescence or the death of small groups of cells in the outer peel after the banana is treated in a ripening room. The condition is associated with the forced ripening of overly mature banana fruits, so avoid ripening fruits >3/4 caliper width.

Peel Abrasion

Mechanical injury during transport, ripening or marketing handling can make the fruit unmarketable due to the appearance of blackened areas on the peel. Avoid rubbing or abrading peels at the packing house. Transportation should be carefully done, as well as management in the wholesalers and retailers.

Conclusions

Bananas are produced in tropical and subtropical regions having a highly significant economic importance, and are a staple fruit in many countries. The fruit is rich in nutraceuticals and due to its health benefits is recommended to be included in the daily diet. Maintenance of banana quality during the supply chain depends on many aspects including pre- and postharvest management: adequate orchard management practices, harvesting practices, packing operation, postharvest treatments, temperature management, transportation and storage conditions, and ripening at destination. Postharvest losses rise during the supply chain when fruit is harvested at improper maturity, mechanical damage has occurred, fruits develop physiological disorders, and/or disease and pest damage have not been controlled. Thus, management practices are indispensable to create suitable conditions or environments to retain the quality attributes, and nutritional and functional compounds of the banana, and to extend the storage life.

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3

Banana Pathology and Diseases

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Introduction

Diseases have been considered the main factor responsible for yield losses in banana plantations worldwide. Severe reduction in banana production can lead to a threat to global food security, as it is one of the most consumed fruits in the world (Blomme et al. 2017). Several pathogens, including fungi, bacteria, and virus, can impair banana production as emergent threats or established and widespread diseases (Table 3.1).

Sigatoka Disease Complex

Sigatoka disease complex is caused by an ascomycete fungus belonging to the genus *Pseudocercospora* (sexual morph *Mycosphaerella*). The disease complex comprises black Sigatoka, yellow Sigatoka, and eumusae leaf spot diseases, caused by *Pseudocercospora fijiensis*, *Pseudocercospora musae,* and *Pseudocercospora eumusae*, respectively (Arzanlou et al. 2007). The pathogen causes large lesions in leaves which leads to decrease of photosynthetic area, causing a reduction in the quantity and quality of fruits and premature ripening of them (Marin et al. 2003).

Pseudocercospora musae appeared first in Java, Southeast Asia, in 1902, and was found worldwide during the 1940s. Even though *P. musae* was first reported, *P. fijiensis*, discovered on the Fiji Islands in 1963, has become the dominant species spread in all continents (Marin et al. 2003; Arzanlou et al. 2010). *P. fijiensis* is able to infect a wide range of cultivars, including those resistant to *P. musae*, and in comparison, *P. fijiensis* can cause considerably more damage, with losses reaching up to 76% (Marin et al. 2003). The third species, *P. eumusae*, was reported occurring in diseased leaf samples collected from Nigeria in 1999, although analysis revealed that the pathogen has been present in that country since at least 1989 (Carlier et al. 2000). Up to now, *P. eumusae* appears to be restricted to parts of Asia and some parts of Africa, which confers any advantage to other parts of the world producing banana. *P. eumusae* can infect banana cultivars that are resistant to both *P. musae* and

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Table 3.1 Major diseases caused by fungi, bacteria, and virus affecting banana plantations.

Banana diseases	Causal agent	Main symptoms	Management	References
	Fungi:			
Sigatoka complex Black Sigatoka Yellow Sigatoka Eumusae leaf spot	*Mycosphaerella fijiensis* *Mycosphaerella musae* *Mycosphaerella eumusae*	Dark brown leaf streaks, yellow leaf streaks, faint brown leaf streaks	Systemic fungicides application; removal of plants heavily infected; resistant cultivars plantation	Ploetz et al. (1994), Carlier et al. (2000), Marin et al. (2003)
Fusarium wilt	*Fusarium oxysporum* f.sp. *cubense*	Vascular wilt; yellowing of the oldest leaves	Pathogen eradication; resistant genotypes plantation	Ploetz (2015)
Anthracnose	*Colletotrichum musae*	Sunken black lesions on fruits resulting in rot	Avoid any bruising or injuries on fruits; prune banana mats; use of copper fungicide; cool the bananas to 13–14 °C in transportation and markets	Nelson (2008)
Crown rot	Fungi complex including *Musicillium theobromae*, *Colletotrichum musae*, *Ceratocystis paradoxa*, *Lasiodiplodia theobromae*, *Nigrospora sphaerica*, *Cladosporium* sp., *Acremonium* sp., *Penicillium* sp., *Aspergillus* sp., *Fusarium* spp., Verticillium, and Curvularia	Brown to black rot develops on the crown of the banana bunch; fungus can penetrate deeply into the crown, reach the fingers, and cause a dry black rot	Postharvest fungicide treatment; preventive measures in packing stations; deflowering, water quality care and sanitation; Storage conditions: temperature controlled at 13–14 °C, high relative humidity; hot water treatments; UV and gamma radiation treatment	Lassois et al. (2010), Nelson (2008)
Freckle	*Phyllosticta maculate* *Phyllosticta musarum* *Phyllosticta cavendishii*	Freckle-like spots on fruits and leaves	Bag the fruits; fungicide treatments	Wong et al. (2012)
Cordana leaf spot	*Neocordana musae* *Neocordana johnstonii*	Large, pale brown, oval necrotic lesions with a dark brown border surrounded by a bright yellow halo	Control of leaf diseases and nutritional deficiencies once the pathogen is secondary invader	Hernandez et al. (2015)

(*continued*)

Table 3.1 (Continued)

Banana diseases	Causal agent	Main symptoms	Management	References
Moko disease	*Ralstonia solanacearum*	Vascular discoloration in the pseudostem, rhizome, and leaf sheaths; black, deformed and shriveled fruits	Limitation of access to the infected fields; regular tool disinfection; killing and removing diseased plants/mats; build channels around the infected plants to limit the movement of superficial water bacterial inoculum; elimination of secondary host plants; removal of male flowers (de-budding); early bagging of fruit; crop rotation	Tripathi et al. (2009), Blomme et al. (2017)
Banana Xanthomonas wilt	*Xanthomonas campestris* pv. *musacearum*	Wilting of the male bud; fruits turn yellow prematurely; pulp of the fruits rotten; leaves turn yellow and dry out		
Pseudostem and rhizome rot	*Dickeya paradisiaca*	Pseudostem wet rot in bananas of El Salvador, Nicaragua, Panama, and Dominican Republic; slow plant growing, chlorotic, and flaccid leaves		
Head rot or rhizome rot	*Pectobacterium carotovorum*	Soft rot of the rhizome in the humid tropics, slow and retarded growth of plants, and toppling over of mature plants and fruits		
	Virus:			
Banana bunchy top disease	Banana bunchy top virus	Clustered leaves on the top of plant; series of dark green dots and dashes on leaves; leaves short and narrow with chlorotic curled margins	Control of the insect vectors; removal and destruction of infected plants; quarantine; use of healthy and certified planting materials; planting of disease-resistant cultivars when possible	Elayabalan et al. (2015), Tripathi et al. (2016)
Mosaic disease	Banana bract mosaic virus	Reddish-brown mosaic pattern on the bracts of the inflorescence		

(*continued*)

Table 3.1 (Continued)

Banana diseases	Causal agent	Main symptoms	Management	References
Streak virus disease	Banana streak virus	Discontinuous and/or continuous chlorotic dots or streaks that turn necrotic from the midrib to the leaf margin Streaks turn dark orange, brown, or black		
Infectious chlorosis disease	Cucumber mosaic virus	Chlorotic streaks on leaf lamina; necrosis of emerging leaves and internal tissues of pseudostem; mosaic symptoms on fruits		

P. fijiensis and cause losses of up to 40% (Carlier et al. 2000; Chang et al. 2016). The fact is that there are more than 20 *Pseudocercospora* species on bananas, some of them co-existing on the same leaf or even in the same lesion, which contributes to the genetic material exchange (Arzanlou et al. 2008). Phylogenetic studies have demonstrated that the three main species associated to Sigatoka Disease Complex share a common ancestor (Arzanlou et al. 2010).

Lesions caused by *P. musae* and *P. fijiensis* may look similar, one being distinguished from the other by molecular analysis and conidiophore structure. *P. fijiensis* produces conidiophores in small groups, its conidium and conidiophore present basal scars at their points of attachment, and it produces most conidia and spermagonia (male sexual spores) on the underside of the leaf. *P. musae*, in turn, produces conidiophores in large clusters and its conidia are predominantly produced on the upper side of the leaf (Ploetz et al. 1994; Bennett and Arneson 2003).

The symptoms of black Sigatoka appear first on the abaxial surface of the third or fourth open leaf as chlorotic tiny spots that grow and become thin brown streaks. Characteristic of the disease type, the streaks become darker, visible on the top surface of the leaf and, according to their enlargement, they become fusiform or elliptical. Under high disease severity and conditions of high humidity, large areas of the leaf may become blackened and water-soaked (Figure 3.1). On the necrotic tissue, it is possible to observe several reproductive structures containing asci filled with ascospores that will emerge from the underside of the leaf and will be wind spread (Ploetz et al. 1994; Bennett and Arneson 2003). Regarding yellow Sigatoka, the first symptoms appear as small pale yellow spots or streaks parallel to

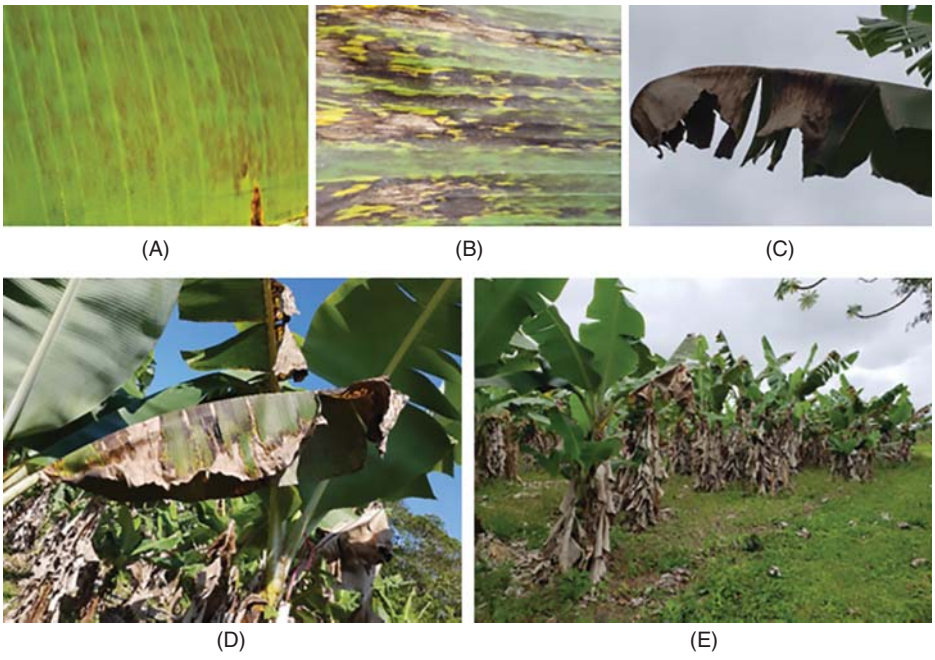

Figure 3.1 Black Sigatoka symptoms: (A) initial symptoms appear as thin brown streaks that become (B) large and dark with chlorotic spots; (C, D, and E) streaks and spots coalesce resulting in large necrotic areas of the oldest leaves. Source: Reproduced with permission of Dr. Wilson da Silva Moraes (APTA, Regional Polo of Ribeira Valley, SP, Brazil).

the side vein of the leaf that become elongated and brown with light gray centers. Such spots enlarge, and the tissue around them becomes yellow and dies (Figure 3.2). Adjacent spots coalesce and form large lesions (Ploetz et al. 1994). The symptoms caused by *P. eumusae* are very similar to those described for the other leaf spot diseases. The initial lesions appear as faint brown streaks that in high density coalesce, and large areas of the leaf tissue become necrotic (Carlier et al. 2000).

For Sigatoka disease complex control, it is important to know its epidemiology. The evolution of the disease depends on favorable climatic conditions and the infection starts only in young leaves including unfurled ones. Then, the disease evolves from the top to the bottom of the banana plant and fungicide applications should be aimed at the top of the plant to control new infections. Ascospores are produced in necrotic tissues, therefore, it is important to control the disease from the beginning, and heavily spotted leaves should be removed. Nonetheless, as ascospores are easily wind spread, it is essential that all banana producers of one region follow the same strategies for disease control. In tropical countries, bananas are grown both on a large scale in fields and in house gardens, therefore, once the disease has reached a region it will be quickly spread (De Lapeyre de Bellaire et al. 2010). Fungicide application is the only method to control the disease (Marin et al. 2003). Thus, strategies aimed at efficient elimination of infected banana plants and the neighboring bananas should be implemented to stop the spread of disease until its eradication (Henderson et al. 2006).

(A) (B)

Figure 3.2 Yellow Sigatoka symptoms: (A) elongated and brown streaks with light gray centers parallel to the side vein of the leaf; (B) adjacent spots coalesce and form large necrotic lesions. Source: Reproduced with permission of Dr. Wilson da Silva Moraes (APTA, Regional Polo of Ribeira Valley, SP, Brazil).

Contact and systemic fungicides can be used for disease control (Marin et al. 2003). Contact fungicides such as mancozeb and chlorothalonil have only a preventive effect and so they are generally applied weekly to protect all new unfurling banana leaves. These fungicides inhibit fungal germination by a multisite action and do not induce the development of resistant strains. Among systemic fungicides the following different chemicals have been used: (i) benzimidazoles that inhibit tubuline polymerization; (ii) triazoles that are inhibitors of ergosterol biosynthesis; (iii) amines, also inhibitors of ergosterol biosynthesis; (iv) strobilurins that bind to the cytochrome b complex and inhibit mitochondrial respiration; and (v) pyrimethanil, a supposed inhibitor of methionine biosynthesis. In areas with early disease detection and in those that a strong curative effect is required, application of systemic fungicides is essential. The curative effect is more pronounced on young streaks, lower on older lesions and has no effect in the necrotic stages. The fungicide treatments are usually more than 35% of the total production costs (Romero and Sutton 1997).

Nonetheless, as systemic fungicides act on a single target, they provoke the emergence of resistant strains, mainly those fungicides belonging to the benzimidazoles class (De Lapeyre de Bellaire et al. 2010). In order to prevent numerous applications of fungicides, researchers have tested the efficiency of microbial fungicide based on *Bacillus subtilis* against black Sigatoka and found reductions of the disease comparable with those obtained with the protectant fungicides in combination with systemic fungicides (Gutierrez-Monsalve et al. 2015).

Black Sigatoka affects the most popular dessert banana (AAA and some AAB genomes) and plantain (AAB genome) cultivars. The AAA banana cultivars belong to the Cavendish subgroup and are the genomic group typically grown in monoculture (Churchill 2011). Two types of resistance have been described for the disease. One is found in cultivars Yangambi km 5 (AAA, Ibota) and in different diploids used in breeding programs (Paka, AA), and it is characterized by high resistance and so can block the symptoms of the disease in the early stages. The other is partially resistant since the evolution of the symptoms occurs slower in

comparison with susceptible varieties and is present in cultivars belonging to the subgroups Pisang Awak (ABB) and Mysore (AAB). However, there are reports that changes in the fungal population have led to an increase in its pathogenicity even in these resistant cultivars (De Lapeyre de Bellaire et al. 2010). Therefore, researchers are relying on the knowledge of the complete genome sequence of the pathogen to facilitate the development of resistant cultivars in banana breeding programs (Arango Isaza et al. 2016; Chang et al. 2016). Meanwhile, models to monitor the disease at field level and to predict potential changes in aggressive traits in fungal populations are essential to implement strategies for disease control (De Lapeyre de Bellaire et al. 2010).

Fusarium Wilt Disease

The disease is caused by the soil-borne fungus *Fusarium oxysporum* f.sp. *cubense* (Foc) and it is one of the most destructive diseases of banana worldwide. The pathogen was first described in Australia (Bancroft 1876), but it probably originated in Southeast Asia (Ploetz 2015). Until 1960, export trades were mainly based on the banana cultivar "Gros Michel" that presented high susceptibility to Foc race 1 (Ploetz 2005). This problem was temporarily solved by plantations of race 1-resistant Cavendish cultivars that expanded into large global monocultures, which evidently posed a threat, especially for black Sigatoka and Panama diseases (Zheng et al. 2018). However, in the early 1990s, *Fusarium* symptoms reappeared in new plantations of Cavendish in Southeast Asia. There had emerged a new genetic lineage of Foc (vegetative compatibility group [VCG] 01213), colloquially called Tropical Race 4 (Foc TR4). Since then, TR4 has been reported in Australia, China, Indonesia, Malaysia, the Philippines, Taiwan, and Africa, (Ploetz 2015; Zheng et al. 2018).

Fusarium causes in banana a vascular wilt disease. Even though the pathogen can infect roots of both susceptible and resistant banana cultivars, the fungus only invades the vascular tissue through the roots of susceptible genotypes. In response to infection, tyloses, gums, and gels are produced in the xylem resulting in blockage of the pseudostem. Affected xylem becomes reddish brown and obstructed which impedes water and nutrient transport. Thus, the first signs of the disease are usually wilting and yellowing of the oldest leaves around the margins. The yellow leaves may remain erect or collapse at the petiole. Yellowing of leaves is most common, although sometimes the leaves remain green, except for spots on the petiole. Eventually, younger leaves develop symptoms and the plant collapses (Ploetz 2015). The leaf symptoms of *Fusarium* wilt can be confused with those of the bacterial disease *Xanthomonas* wilt, however, in contrast to *Fusarium* disease, in plants affected by *Xanthomonas*, wilt symptoms can be present in any leaf and it tends to snap along the leaf lamina.

Foc is disseminated mainly by infected suckers. Thus, after tissue-culture plantlets became available, it was possible to produce clean planting material (Ploetz 2015). Foc race 1 and TR4 can survive in the absence of its banana host in roots of grasses and other weed species. Chlamydospores can also remain in dead host material (Hennessy et al. 2005). Therefore, as Foc can be disseminated in soil, growing plantlets prior to field establishment is recommended (Buddenhagen 2009). Furthermore, contaminated water and farm equipment can facilitate Foc dissemination around a plantation (Ploetz 2015).

There are few effective options to avoid Foc wilt owing to the epidemiology of the pathogen. Chemical treatment of a huge volume of soil is not plausible. The best alternative to avoid the disease is the plantation of resistant genotypes, as GCTCV somaclones and other resistant cultivars (Xu et al. 2011). Nonetheless, such resistant cultivars may not be productive and attractive to markets. Genetic transformation techniques and genetic improvement of Cavendish and other susceptible cultivars to Foc resistance are greatly needed, mainly in regions where a TR4 lineage has been established (Buddenhagen 2009; Ploetz 2015).

Anthracnose

Anthracnose in bananas is a postharvest disease caused by *Colletotrichum musae* and can result in 30–40% losses of marketable fruits (Ranasinghe et al. 2003). *Colletotrichum* species are capable of causing lesions on fruits even without skin injury (Nelson 2008). Besides *C. musae*, *Colletotrichum gloeosporioides*, a polyphagous species, has also been reported to cause anthracnose in bananas (Riera et al. 2019). The symptoms appear first as sunken black or brown spots of various sizes on the fruit (Figure 3.3). The lesions become large and appear more rapidly when the fruits are damaged and/or ripening, which can be accelerated by the infection (Nelson 2008).

Colletotrichum species can colonize endophytically different parts of the plants which becomes a source of inoculum. In the case of banana plants, floral parts and bunch bracts are the main source of inoculum, so when these parts are removed at flowering, the severity of anthracnose disease can be considerably reduced (Bellaire et al. 2000). In addition to this procedure, integrated management practices to deter postharvest disease consist of carefully handling the fruits to avoid any bruising or injuries; prune banana mats to increase air

Figure 3.3 Anthracnose symptoms: sunken black spots of various sizes on fruits that become large. Reproductive structures of *Colletotrichum* are observed in the center of lesions. Source: Reproduced with permission of Dr. Wilson da Silva Moraes (APTA, Regional Polo of Ribeira Valley, SP, Brazil).

circulation and reduce relative humidity; weed control; use of copper fungicide on banana fruits after deflowering fingers and before bagging; harvest bunches when fruits are still green, measuring about 3/4 of the mature width of fruit in order to avoid bruising; use of clean and fresh water in packing houses; pack dried banana fruits within plastic boxes designed to maintain high humidity; and cool the bananas to 13–14 °C in transportation and market storage (Nelson 2008).

Moko, Bugtok, and Banana Blood Diseases

Moko disease refers to symptoms observed in "Cavendish" plantations and it is caused by *Ralstonia solanacearum* biovar 1, race 2: IIA-6, IIA-24, IIA-41, IIA-53, IIB-3, IIB-4, and IIB-25 (Blomme et al. 2017). This destructive bacterial wilt is currently found in countries on all continents: Mexico, Venezuela, Guyana, Colombia, Peru, Brazil, Grenada, Dominican Republic, Jamaica, the Philippines (AAA types), and Malaysia (Belalcazar et al. 2004). The *SFR* (small, fluidal, round) and *A* (Amazon basin) strains are known to be transmitted by insect whereas the *B* (banana) strain is mainly transmitted through root contact and contaminated planting equipment (Sequeira 1998; Blomme et al. 2017). Currently, four phylotypes of *R. solanacearum* complex are recognized: phylotype I strains are from Asia, phylotype II strains are from America, phylotype III strains are from Africa and the Indian Ocean, and phylotype IV includes strains are from Indonesia, Japan, and Australia (Fegan and Prior 2006; Albuquerque et al. 2014).

When the bacterial infection initiates in roots and rhizomes it moves toward the pseudostem; oldest leaves turn yellow and wilt, fruits become black, deformed, and shrivel up. When fruits are almost mature, symptoms may not be apparent, but the inner pulp can be dry rot and the entire plant may die. Light to dark brown vascular discoloration can be observed in the pseudostem, rhizome and in sheaths of the leaves (Figure 3.4). Bacterial ooze may exude from the cut surface of vascular tissues. The disease can also be transmitted by insects visiting the male inflorescences. In this case, symptoms occur initially in the flower buds and peduncles, which become blackened and shriveled. The bacteria spread into the fruits, reach the stem, and move toward to the rhizome (Buddenhagen 2007).

In the Philippines, *R. solanacearum* strain IIB-3 causes atypical symptoms on ABB balbisiana cooking banana cultivars; the disease is known as Bugtok. In this case, symptoms are restricted to the inflorescence, pulp of the fruit and vascular system at the loculus, pedicel and serial stem. Fruits become discolored grayish black to yellowish red and later become hard. Vascular discoloration rarely extends into the lower part of the pseudostem. The bacterial inoculation resulting in Bugtok disease occurs by insect vectors through the male flowers (Molina 2006; Blomme et al. 2017).

The banana blood disease is caused by *Ralstonia syzygii* subsp. *celebesensis* (phylotype IV) and is currently spread in peninsular Malaysia (Teng et al. 2016). Symptoms of banana blood disease are similar to those of Moko, however, discoloration of vascular tissue, dry rot of the fruit pulp and bacterial ooze exuding from cut tissue present a reddish coloration. Older leaves become yellow followed by necrosis and collapse; younger leaves also become necrotic and dry. The pathogen colonizes the entire plant, and suckers also wilt and die (Blomme et al. 2017).

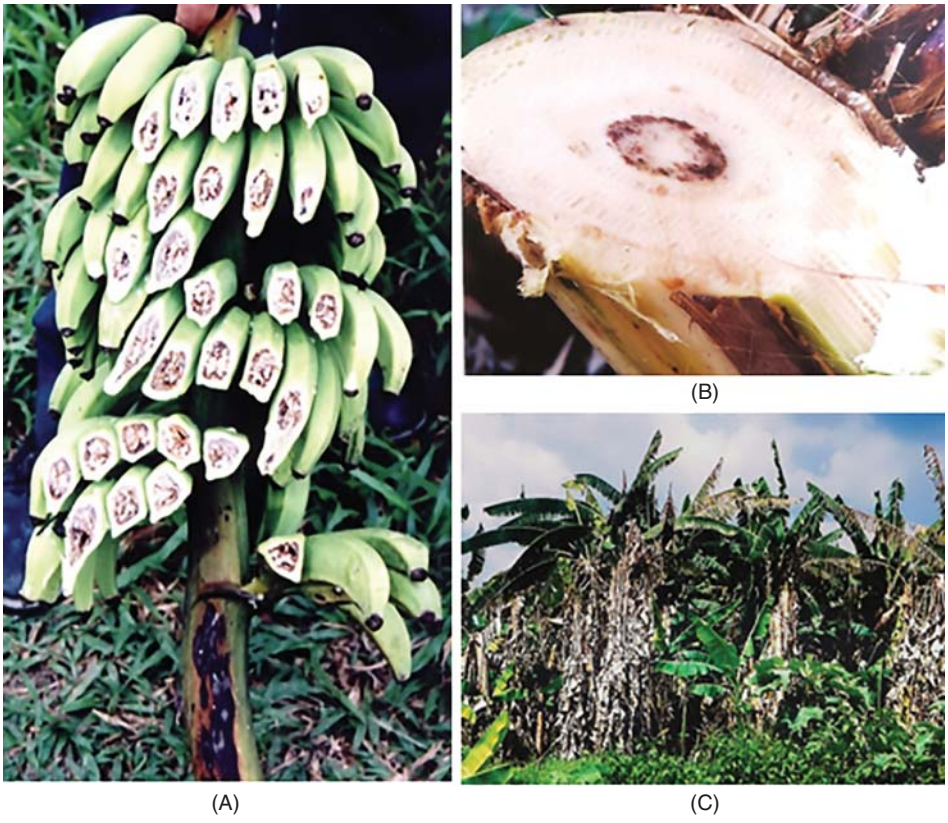

Figure 3.4 Moko symptoms: (A) inner pulp of fruits become dry rot; (B) light to dark brown vascular discoloration can be observed in the pseudostem; (C) oldest leaves turn yellow and wilt. Source: Reproduced with permission of Josiane Takassaki Ferrari (Biological Institute, SP, Brazil).

A set of measures is required to prevent bacterial diseases of bananas and manage infected areas: (i) the practice of de-budding just after the formation of the last fruit hand prevents the transmission of bacteria by insect vectors, since the male inflorescence is their primary infection site. Moreover, this practice results in bigger and evenly filled fruits. (ii) Another strategy aiming to prevent bacterial transmission by insect vectors includes bagging the inflorescence shortly after emergence. Bags can be removed after establishment of the fruits followed by removal of the male inflorescence. (iii) Cleaning and sanitation of field tools with sodium hypochlorite or effective ammonia-based disinfectants before and after pruning or de-suckering can be carried out. (iv) Another measure is the continuous and timely destruction of all infected mats and those located within a 5–8 m radius around infected mats using injection of herbicides. (v) Culture rotation or fallow for 1–3 years can be implemented to reduce bacterial population. The pathogen can survive in the absence of the primary host; thus, crop rotation might be more effective in reducing bacterial inoculum. (vi) Chemical control, such as the use of Dazomet, a soil sterilizer, can provide good control of Moko and Bugtok diseases (Blomme et al. 2017).

Characteristics of resistance to bacterial wilt are often polygenic, which restricts the transfer of all quantitative trait loci into commercial cultivars. Nevertheless, cultivars with persistent male bracts/flowers or bud-less mutants are available and offer a suitable solution to bacterial wilt. Despite difficulties in developing bacterial wilt resistant plants, researchers have sought to achieve this aim (Blomme et al. 2017). Hybrids of diploid (AA) banana genotype have showed resistance to Moko disease following artificial inoculation (Silva et al. 2000). Finally, until resistant cultivars are not commercially available, farmers and technicians should be trained on disease recognition, epidemiology and management practices aiming to support banana crops around the world (Blomme et al. 2017).

Banana Xanthomonas Wilt

The banana Xanthomonas wilt (BXW) disease, caused by the bacterium *Xanthomonas campestris* pv. *musacearum*, was first reported occurring in bananas in 1974 (Yirgou and Bradbury 1974). Until 2001 the disease was restricted to Ethiopia, and since then it has been reported in Uganda, Tanzania, Kenya, Rwanda, Burundi, and the Democratic Republic of Congo (Carter et al. 2010; Shimwela et al. 2017). BXW can affect almost all commonly grown banana cultivars, including the Cavendish subgroup. Fields infested with this bacterium cannot be replanted with banana for at least six months owing to carryover of soilborne inoculum (Tushemereirwe et al. 2004; Tripathi et al. 2009).

Plants are infected in the flowering period by insect-transmitted bacteria. Generally, the initial symptoms are wilting and withering of the male bud, with a gradual shrinking along the rachis. As the infection progresses, the fruits start turning yellow prematurely, most often those nearer to the male bud (Tripathi et al. 2009). The fruits appear ready to reap, but inside the pulp is rotten and discolored. As the diesease progresses, leaves turn yellow, wilt, and eventually die. In the terminal stages of infection, all leaves dry out and stems die gradually from the top downward. Pale yellow ooze from cut surfaces in addition to the symptoms in the fruits can distinguish BXW from Panama disease (Tripathi et al. 2009). Before flowering, plants can be infected by contaminated tools and by roots in contact with contaminated soil (Mwangi et al. 2007). In this case, the initial symptom is the progressive yellowing of leaves from the leaf tip toward the petioles (Tripathi et al. 2009).

The management of this disease in banana crops is a challenge; a combination of measures is required (such as exclusion, eradication, host resistance, and protection). In fields where disease incidence is below 50%, the removal of infected banana mats is necessary to decrease the inoculum source as well as removal of the male flowers and bunch of infected plants. Besides the insect vector of the disease, farm tools are an important source of inoculum, thus tools must be disinfected after use on each banana mat. When BXW occurs, the strategy to be followed is to cut down all infected plants, completely dig out the rhizomes, and make the field fallow or undergo a prolonged crop rotation regime (Tripathi et al. 2009). Transgenic banana lines over-expressing *hrap* and *pflp* genes, isolated from sweet pepper (*Capsicum annuum*), that can intensify the hypersensitive response, have been successfully obtained and shown to be effective at field level. The release of these cultivars is awaiting completion of legal formalities (Tripathi et al. 2014).

Banana Bunchy Top Disease

Banana bunchy top disease (BBTD) is caused by the banana bunchy top virus (BBTV), a nanovirus measuring 18–20 nm, whose genome consists of at least six circular single stranded DNA components encoding for six major proteins (Hu et al. 2007). BBTV is widely present in many banana growing regions of the world and is one of the most serious pathogens of banana in Asia, Australia, and the South Pacific. Fortunately, BBTV incidence is still absent in Latin America and the Caribbean (Elayabalan et al. 2015).

BBTV is transmitted by the banana aphid *Pentalonia nigronervosa* Coquerel and by vegetative propagation (Hu et al. 1996). The aphids can retain the virus for up to 20–23 days and may cover large distances, especially when aided by the wind. Species of the Musaceae family, including Cavendish, are susceptible to the virus and can be infected at any age. The symptoms become evident within 25 days after virus infection, depending on the age of the plants and the temperature (Elayabalan et al. 2015).

The major characteristic of the disease refers to its name, a group of clustered leaves on the top of plants gives a bunchy appearance. Symptoms of BBTD include dark green, dot-dash flecks along leaf veins, midribs, petioles, and pseudostem (Tripathi et al. 2016). With progression of the disease, leaves at the top of the plant become short and narrow with chlorotic margins that tend to curl upward. Plants can produce small fruits and distorted male buds (Elayabalan et al. 2015).

There are no banana varieties resistant to BBTV. Thus, the management of the disease consists mainly of the control of the aphid vectors and removal of infected plants followed by their complete destruction (Almeida et al. 2009). There are also strict quarantine restrictions to prevent movement of potentially infected plant materials.

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4

Harvesting and Postharvest Technology of Banana

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Introduction

Globally, 114 million tonnes of bananas were produced worldwide in 5.6 million hectares in 2017 (FAOSTAT 2019). Bananas are predominantly produced in Asia, Latin America, and Africa. The biggest producers were India with 30.5 MMT (million metric tons) and China with 11.2 MMT, but the production in both countries mostly serves the domestic market. Other large producers are Indonesia (7.20 MMT), Brazil (6.7 MMT), and Ecuador (6.3 MMT).

Latin American countries are the main exporters to the USA and the EU. India is one of the major producers, but a major part goes to the domestic market (Mohapatra et al. 2010). The Cavendish subgroup is the most cultivated and demanded in the world. As a climacteric fruit, banana is harvested mature green and naturally or artificially ripened. Postharvest losses can largely vary, due to the level of technology and whether the final use is for domestic or more demanding markets (USA and EU).

Nowadays, challenges in banana postharvest handling and commercialization include both knowledge of physiological and quality changes during production and handling of the fruit, and improvement of logistic and rapid transit of the product, to reach the market demands on quality and prices in very competitive markets.

Although there are differences among postharvest handling processes around the world, the goal is to preserve the quality and safety of banana fruit all the way to the consumer with competitive prices, looking for ambient protection and sustainability. This chapter covers banana harvesting indices and practices, fruit grade and standards, postharvest handling and losses, postharvest operations, and storage technologies.

Harvesting Indices

It is unquestionable that good production practices lead to quality fruit, and defining the proper maturity indices to harvest is one of the most important decisions in order to obtain

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maximum productivity and fruit quality with minimum postharvest losses, in accordance with quality requirements of final markets.

As a climacteric fruit, banana bunches are harvested green in color, but at physiological maturity, in order to assure proper ripening at the final market. Bananas must reach the market still green, with fresh appearance and good quality. Then, transit time and conditions have also to be taken into consideration to pick the right moment to harvest, so the "green life" or pre-climacteric phase of the fruit, keep the fruit green long enough to reach the final market (Turner 1997; Soto Ballestero 2015). During transportation, the fruit should stay green, and once it reaches the wholesaler, artificial ripening is induced so the fruit reaches an even consumption maturity at the retailers.

Harvesting indices define the best time to cut the fruit, trying to maximize fruit growth and production yield before harvest, but assuring that the fruit is close to its physiological maturity but still has enough green life period for commercialization to distant markets (Soto Ballestero 2017).

For the definition of the fruit grade to harvest, several factors influence the fruit response during transportation. For example, the distance to the final markets and the time required to reach them, the supply–demand relationship, the clone type that is used, the physiological state of the plants, nutrition, diseases, toxicity, and other stresses could affect both the size and premature maturation. Weather also affects fruit quality and postharvest behavior because of lack or excess water (drought, flood, rain, soil moisture) and temperature. Uniform fruit age is convenient, since it results in uniform fruit quality and avoids ripening differences throughout transport.

Commercially, several indices are used, based on maximizing fruit production, the development of the fruit up to near physiological maturity, long "green life" along transportation and uniform ripening. Such indices include the following.

Fruit Diameter

Fruit diameter at the middle of the central finger of the second hand of the bunch is an important criterion. It is measured with a caliper as grades (one grade equals 0.79375 mm or 1/32 in.), so a grade 40 corresponds to a fruit with 31.75 mm diameter. As a reference, for the subgroup Cavendish, bananas with 46–48 grades are harvested in Central America for the USA market, while bananas with 43–45 grades are harvested for the European market (Soto Ballestero 2017).

Banana Harvesting Grade Combined with the Age of the Bunches

It is a two-factor index commonly used in the banana industry to decide the best time to harvest. Bunch age generally varies from 12 to 14 weeks in the tropics. When this index is used, the stage of maturity of the fruit is usually even, which is convenient in order to get uniform fruit which generally results in a uniform ripening. The combination of fruit grade with age of the bunches has been used in Costa Rica, Honduras, the Philippines, and Ecuador since the 1970s. The age of the bunches is controlled with the use of color ribbons in each bunch, which facilitates harvesting labor.

Banana bunches are marked with color ribbons two weeks after the bunch opens. Those marks are used to determine the correct time of harvest, together with the measurement of the fruit size, which is measured with a caliper of the external central finger of the second hand from the top. Usually, for the Cavendish subgroup, harvest is done when the fruit reaches the physiological stage needed for a rather long green life but proper ripening at the end market, and that happens 10–13 weeks from the bunch set (Céspedes 2004). Small variations are common according to the time of the year, weather, final market, and other factors.

Fruit Weight, Finger Diameter, and Length

Fruit weight, finger diameter and length parameters change along production in the field. At first, the finger's transversal area is the shape of an irregular pentagon referred to as "light three-quarters," and as it develops the finger fills with starch and the area becomes circular and the finger is a cylindrical shape referred to as "full green" (Figure 4.1). On most banana plantations, fruits destined for distant markets are harvested at a stage known as "full three-quarters," when the fingers are still clearly angular while for local markets fruits are often harvested when fingers are "full green" or rounded.

Weight gain was described by Lassoudière (1978) as a three-stage process. In the first stage, there is a rapid weight gain (up to day 28) which corresponds to cell division, followed by the second stage which is a low growing period (days 28–38) with predominant cell growth, and then a third stage which shows an exponential weight gain because of the filling of starch (from day 38 up to harvest).

On the other hand, fruit size varies along the bunches; some of them can have 6–10 hands, and grade can vary from 2 to 4.9, respectively, along the bunches, at an average of 0.5 grade variation between hands next to each other; there are also differences between the internal and external fingers in each hand, with gaps between 2 and 4 grades (Soto Ballestero 2017).

Thus, differences in fruit weight, associated with plantation productivity and normal variability of the diameter of the fingers along the bunch and even between hands, result in a variety of hands and finger sizes for packaging.

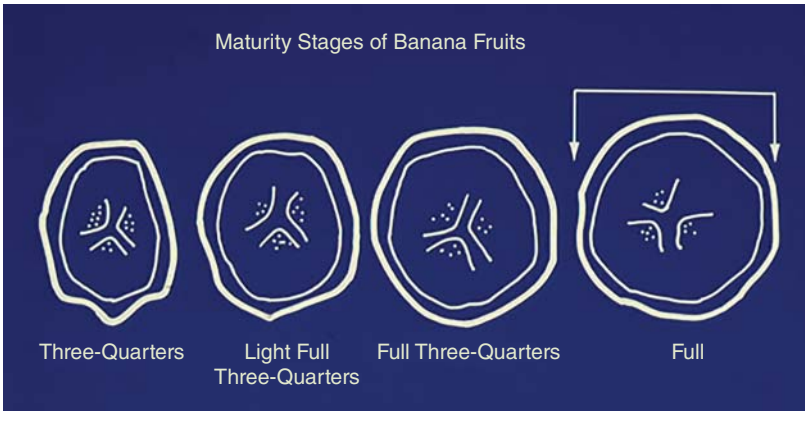

Figure 4.1 Changes in angularity of banana finger as an index of maturity. Source: Postharvest Technology Center. Reproduced with permission of University of California, Davis.

Growth Degree Days

In some regions of the world, where temperature differences vary considerably during the year, the harvest age significantly changes. Ganry and Chillet (2008) recommended a methodology to forecast the harvest date of banana bunches, by measuring the temperature accumulation (above 14 °C) by the bunches; this is 900 degree days of physiological age for Cavendish bunches. They pointed out that banana growth is highly dependent on temperature, and its physiological age is closely correlated with the mean daily temperature sum accumulated by the fruit during development. The harvest age could vary several weeks because of low temperatures.

Amin et al. (2015) reported the optimum maturity stage for harvest of "BARI Kola 1" and "Sabri Kola" in Bangladesh as 130 and 110 days after emergence of flowering in the summer and winter season, respectively, which correspond to 1750 and 1620 degree days. However, they calculated these values using a minimum temperature of 10 °C, which resulted in a much larger value of degree days than the bananas from the subgroup Cavendish.

Image Processing

Image processing is an innovative field of science where the acquired image is transformed into useful information. Prabha and Kumar (2015) found that the mean color intensity algorithm was more accurate (99.1%) for differentiating under-mature, mature, and over-mature banana, than the area algorithm (85%) which is useful for differentiating under-mature banana, but not to distinguish between mature and over-mature fruit. Since both the color and size value are a reliable index to determine the right time to harvest, the mean color intensity algorithms in conjunction with the area algorithm developed in this study could be employed commercially to develop a field-based completely automatic detection system to determine the right time to harvest by the banana growers.

Harvest Practices

Harvest planning is an important step which requires inspection of the banana bunches considering the time from setting and fruit growth and development, as well as requirements from the packing house or the buyers. Even though banana bunches are marked with color ribbons, climate, plant nutrition and other factors can affect the fruit characteristics, and the time needed to reach the desirable quality parameters, and that requires insight sampling to determine the physiological state of the fruit.

Harvesting consists of cutting banana bunches and transporting them to the packing house. It is done with work crews of three or four members who are assigned to specific areas of the plantation. Generally, a day ahead of the harvest, a supervisor is assigned to check the bunches and ribbons and mark those ready to be harvested, and then the harvest crew looks for those marks and harvests marked bunches.

Harvest tools include a long knife and a pole with calipers of the size of the requested caliper for the day. The crew also carries the implements needed for hanging the bunches on the cable at 1 m intervals. Harvest usually is done from 6 a.m. to 4 p.m. The crew starts

Figure 4.2 Harvesting bananas employing one (A) or two (B) workers. Source: Images from Maria Gloria Lobo.

to harvest in an organized way throughout the assigned location. It takes two people, the harvester and the receiver; the harvester does a first cut in the pseudostem, at the height of the bunch and eliminates any leaves that may damage the banana bunch. This causes the bunch to move down slightly so that the receiver can grab the rachis or pinzote at the lower end of the bunch with one hand and guide the bunch to fall carefully on to his or her shoulder when the harvester cuts to detach the bunch from the plant (Figure 4.2). The receivers typically cover their shoulders with a pillow type cushion/foam as a protection for both the worker and the bunch. Another way to receive the harvested bunch used in several regions consists of tying the banana rachis before cutting to a rope previously attached to a pole. The pole is held by two members of the crew, so when the bunch is cut, it does not hit the receiver's shoulder, but swings, and from there it is taken to the cableway (Soto Ballestero 2017).

The cut made on bunches should be clean and straight, and it must be treated to reduce latex flow coming out from the cut. This is commonly achieved using a chemical product to seal the cut, such as aluminum hydroxide (DONVIC 500 Gel, astringent product for the control of latex exudation of the pinzote), and covering it with some absorbent fabric to avoid latex staining on the banana surface. The harvest crew should avoid touching the banana fingers directly while handling (Soto Ballestero 2017).

Banana peel of the subgroup Cavendish is very susceptible to mechanical damage so careful handling is essential. In many growing areas, separators between hands are used to avoid damage due to movement as the fruit is transported to the packing house.

Once the bunch is harvested, the receiver takes it to the cable transportation system, which passes through the banana plantations, in such a way that walking distances of the fruit carriers are minimized (Figure 4.3A–C). Fruit stays in the field until a train with 25

Figure 4.3 Transportation from the field to the packing house. Source: (A) https://es.wikipedia.org/wiki/Archivo:Cable_via_para_BananoJPG (Costa Rica); (B) https://www.flickr.com/photos/clizbiz/8590250336 (Costa Rica); (C) http://www.centroaceros.com/cablevias/banano (Costa Rica); (D) https://www.flickr.com/photos/rod_waddington/8049495329 (Ethiopia); (E) https://www.flickr.com/photos/kayugee/14736635530 (Tanzania); (F) https://www.flickr.com/photos/usarmyafrica/5117954034 (Uganda); (G) image from Jose Manuel Torres (Canary Islands).

bunches is ready, and another member of the work crew pulls the load of bunches to the packing shed, which should be a relatively short distance (1.0–1.5 km or so). Mechanical devices can also be used to pull the train. The number of bunches in a train varies, 25 being the largest when carried out manually.

In small plantations, such as those in the Canary Islands, Madeira, Azores, or developing countries such as Ethiopia, Uganda, and Kenya, the worker carries the bunch on his or her shoulder to the transportation system (bicycle, donkey, or truck) because there is not a cable transportation system (Figure 4.3D–G). The cultivation in the Macaronesian region is in terraces at half altitude (more than 400 m above sea level), due to the slope of the land

Figure 4.4 Banana plantations in Costa Rica (A) and in the Canary Islands (B, C, D). Source: Images from Jesús Rodrigo.

(Figure 4.4). Owing to the subtropical conditions of the Canary Islands, 30% of the banana crop is grown under mesh or plastic greenhouses.

At the time of harvest and subsequent fruit handling, care has to be taken to preserve the fruit quality, minimizing mechanical stresses, such as impacts between fruit or against other surfaces, compression stresses during handling because of excessive weight loads or overloading of boxes with fruit, and vibration, which can cause damage on the surface of the fruit because of stresses on the fruit caused by excessive speed of the trucks used for transportation, rough roads, or problems related to the suspension of the transport vehicles.

Some production farms cut the hands of the banana bunches in the field for later transportation to the packing house. This is the case for small growers who do not have cableway systems for transportation, but it is also used as a means to reduce the postharvest operation costs (Jiménez Ruiz et al. 2016), as it is claimed that water consumption is greatly reduced, since de-sapping is done in the field and not in the packing house. Since the de-handing is done in the field, the produce handling capacity of the packing house increases because fewer operations are carried out there. The same authors reported a reduction in water consumption from about 100 l per packaged box of bananas to about 5 l per box, without problems of latex stain in the fruit at the final market, as well as a reduction in labor required at the packing house.

Fruit Grades and Standards

The CODEX standard for bananas (CODEX STAN 205–1997, AMD 1–2005) applies to commercial varieties grown from *Musa* spp. (AAA) of the Musaceae family, in the green state, prepared and packaged for fresh consumption. Bananas intended for cooking only

(plantains) or for industrial processing are excluded. The standard includes cultivars from the groups AA, AB, AAA, and AAB (CODEX 2005).

According to the CODEX standard, bananas must be whole, clean, free from visible foreign matter, practically free of pests and damage caused by pests, free of external moisture, foreign smell or test, they must also be firm, free of low temperature damage, bruises, malformations or abnormal curvature. They must have the pistils removed. Moreover, clusters and hands must include a portion of the crown of normal coloring and free of fungal contamination. Using this standard, fruits are classified into three classes:

- *Extra class*: Bananas must be characteristic of the variety and/or commercial type. Fingers must be free of defects with the exception of very slight superficial defects which may not affect the general appearance of the produce, the quality, the keeping quality and presentation in the package.
- *Class I*: Bananas in this class must be of good quality and characteristic of the variety. Only slight defect of fingers may be allowed such as slight defects in shape and color, slight skin defects due to rubbing and other surface defects which do not exceed 2 cm^2 of the total surface area. The defects must not affect the general appearance of the produce, the quality, the keeping quality and presentation in the package, and, in any case, the flesh of the fruit.
- *Class II:* This class includes bananas which do not qualify for inclusion in higher classes but satisfy the minimum requirements pointed out above, but some defects may be allowed such as those in color and shape, skin defects due to scraping, scabs, rubbing, blemishes or other causes not exceeding 4 cm^2 of the total surface area. The defects must not affect, in any case, the flesh of the fruit.

Provisions concerning size: The minimum length should not be less than 14.0 cm and the minimum grade not less than 2.7 cm (grade 34, i.e., 34/32 in.). Size tolerance for all classes is 10% by number or weight of bananas not satisfying the requirements.

Provisions concerning presentation: The content of each package must be uniform and contain only bananas of the same origin, variety and quality, packed to protect the produce with new, clean and good quality, hygiene, ventilation and resistance characteristics, suitable for handling, shipping, and preserving the bananas.

There are not banana grade standards in the USA, but the U.S. Department of Agriculture has a market inspection instruction for bananas (USDA 2004). These inspection instructions are specifically developed by the Fresh Products Branch to assist officially licensed inspectors in the examination and inspection of bananas. They are intended to provide useful information and guidelines to facilitate inspection and marketing of bananas.

Postharvest Handling

Appropriate food safety has to be practiced while handling bananas in the field and the packing house. This involves Good Agriculture Practices (GAPs) in the field and the packing house, which are common practices to avoid any type of contamination. Food safety includes caring for water quality and safety, proper preparation, handling and application of manure, care to restrict wildlife and pets in the fields and packing facility, worker sanitation

at harvest and postharvest handling practices during washing, packaging, storage, transportation, and distribution of the produce.

The packing facility should allow the product to move to a cleaner area during each step of processing, and implement Standard Operating Procedures (SOPs). Light fixtures should be protected to avoid contact with the product if they break. All equipment in contact with the bananas should be cleaned and sanitized frequently.

Field and Packing House Sanitation

Washing and cleaning procedures remove visible contaminants and may require soaps and water, proper rinsing and the use of potable water. Sanitizing refers to the reduction of pathogens to non-harmful levels. It is important to clean first and sanitize later on. In order to define efficient cleaning and sanitation procedures in the packing house, the process line should be studied, making sure to include how the produce is received as well as every operation it should pass through, looking for contamination risks. All walls, ceilings, and floors should be washable.

Postharvest Operations

Figure 4.5 shows the postharvest handling operations of banana used traditionally, while in Figure 4.6 the de-handing is done in the field with no washing and no de-sapping treatments.

Transportation to the Packing House

Bunches are transported to the reception area from every part of the fields by the cable system, which should be designed to minimize distances from different sections of the farm to the packing house. They are transported in groups of approximately 25 banana bunches, hanging from the pinzote. To protect the fruit against mechanical damage, it is necessary to keep a distance of 1 m between bunches, to use implements to hang the bunches, to reduce the impact and friction between fruit hands (pillows, foams or other materials are placed between hands), and to design a cable system with minimum level differences along

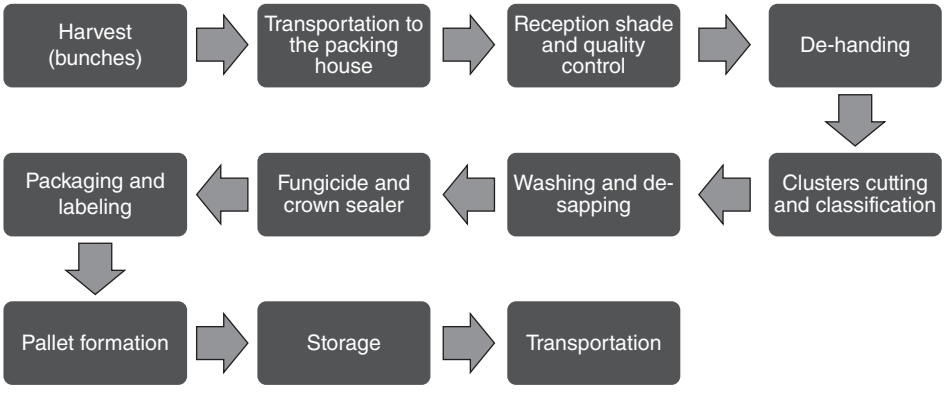

Figure 4.5 Traditional postharvest handling of bananas for the export fresh market.

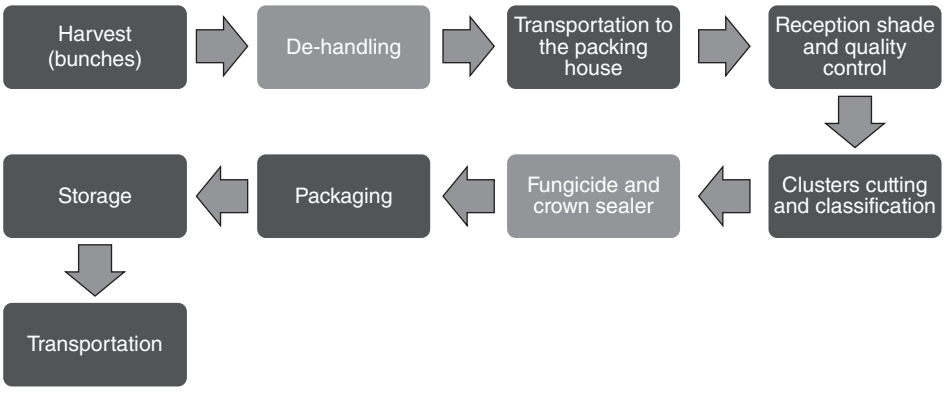

Figure 4.6 Alternative postharvest handling of bananas with reduced water consumption and no washing or de-sapping treatments.

the path to the packing house. These actions minimize impact, compression and vibration stresses during transportation. As pointed out before, other transportation systems such as trucks, donkey carts, and bicycles are used depending on the size of the plantation, and the incomes of the farmers.

Reception and Quality Control

The bunches after arrival at the packing house are weighed and detailed information of the harvest location of the bunch, including age and quality, are registered for proper traceability.

Bunches are placed in the shade before entering the packaging process. This area should have enough room for harvested fruit, according to the packing plant program, so that no bunches are kept directly in sun light. Soto Ballestero (2015) suggested that the shade area should be able to keep two loads per harvest work crew (two trains with 25 bunches each), since every crew has two sets of implements, and it is common for all crews to gather at the packing house during the lunch period.

When transportation is done with the cable system, the bunches are distributed as they arrive in parallel lines waiting for processing, leaving enough space between lines to reduce the risk of mechanical damage. If transportation is done in trucks or by other means, the shade area must have enough room to hang the bunches and wait for processing.

The quality of the fruit is controlled in this area, and size, dimensions, weight and age are registered. The internal appearance of a sample of fruit is also evaluated.

Hand Separation from the Bunch (De-handing), Quality Control, and Washing

The first operation in the processing line starts carrying the fruit to the de-handing area, where a quality control is undertaken, which consists in measuring the length and grade (caliber) of the fingers (second hand from top, middle finger). Required measurements are 15 cm length and 42 grade (42/32 in.) for that finger, but some variation can be allowed depending on the quality request of the buyers, the final market, local weather, etc. General quality and stage of maturity is also evaluated. In all cases, fruit should be free of mechanical damage of the necks (space between the crown and the fingers), fruit skin or finger tips, and free of insect damage, diseases and finger malformations (Umaña 2002).

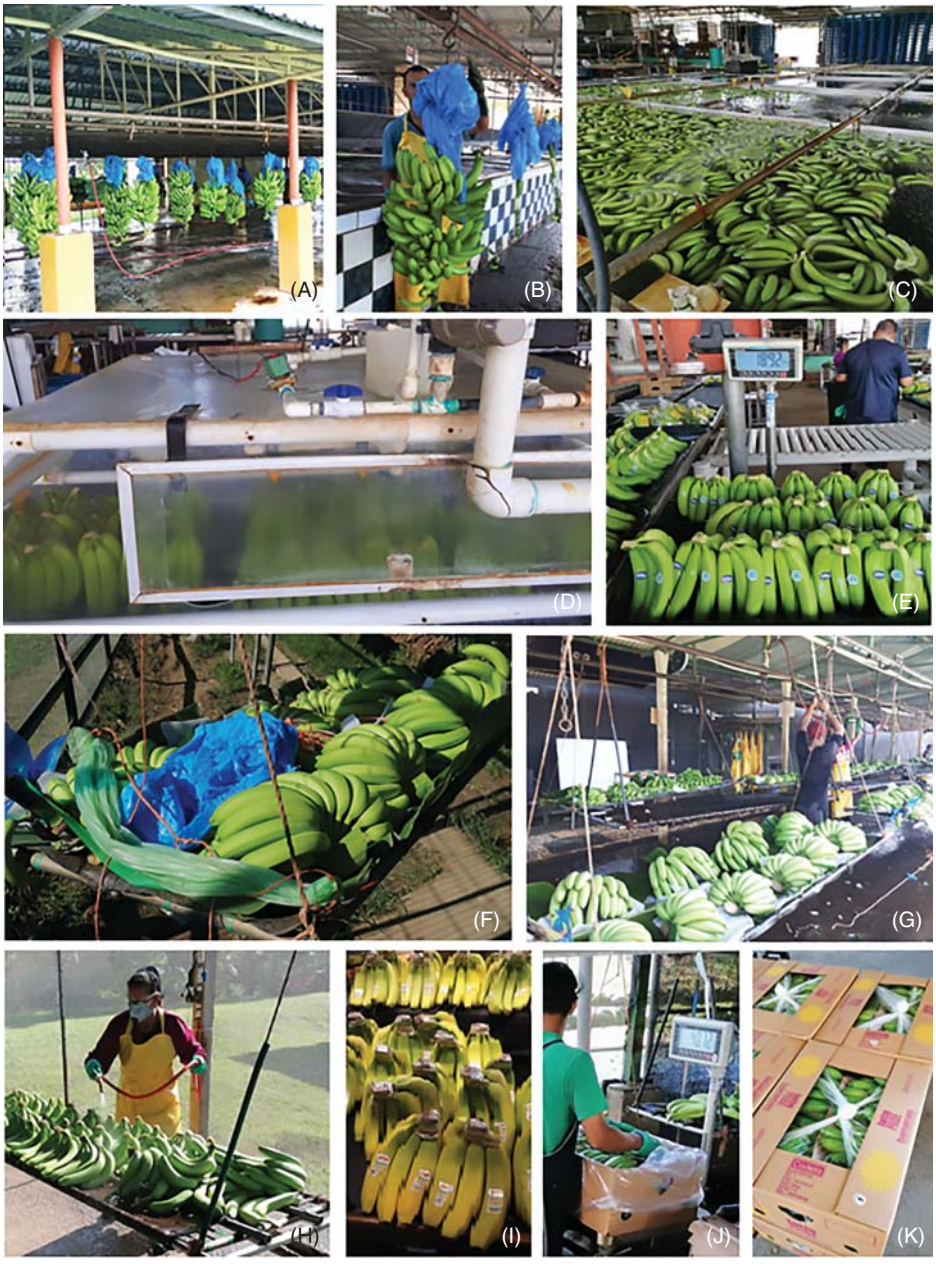

Figure 4.7 Banana processing in Costa Rica, traditional line (A–E) or water saver line (F–K). Source: Images from Javier Fernández and Maria Gloria Lobo.

Figures 4.7 and 4.8 show the banana processes at the packing houses of Costa Rica and the Canary Islands. It is usual to wash the bunch before de-handing. This operation can be done manually or mechanically (Figures 4.7A and 4.8A,B).

De-handing is done by three or four operators, who cut the whole hands in an upward direction with a sharp curved knife (Figures 4.7B and 4.8C), taking care to avoid any cuts to

Figure 4.8 Banana processing in the Canary Islands, using tanks (A, B, C, D, G, I) or conveyor belts (A, B, C, E, F, H, J). Source: Images from Javier Fernández and Maria Gloria Lobo-Rodrigo.

the fingers and necks of the fruit. The hands are dropped into a tank of running water. The purpose of this first wash is to prevent contact of the latex coming out from the cut with the fruit surface, which could stain it and reduce the appearance of the fruit (Figure 4.7C). This first wash helps to remove dirt and foreign matter. In some facilities in regions where water is not plentiful (Canary Islands), the water is maintained in the tanks for several days (Figure 4.8D), and in facilities using conveyor belts, where it is usual to wash the fruit by aspersion, the water is recirculated (Figure 4.8E,F). To avoid latex stain, it is recommended to add 1% aluminum sulfate in the water tanks or other chemicals, such as a surfactant solution (Bacterol) alone or combined with hydrogen peroxide (Super-Bacterol).

Before washing, the floral part that still remains has to be removed. In the Canary Islands, the floral part is always removed before harvesting or at the time of harvesting so never arrives at the packing house.

Fruits can also be de-handed in the field (Figure 4.7F), and then transported to the packing house using the cable system with special trays or beds where the fruit is immobilized or arranged to reduce the risk of mechanical damage during transportation. At the facility the fruit is washed, as shown in Figure 4.7G.

Cluster Cutting and Fruit Selection

At the other side of the water tank, workers remove the hands from the water and cut the hands into clusters or the required size, and again check the fruit to remove fingers which might have some defects or malformations. Then, the clusters are transferred to the washing tanks according to their size. Fruit is classified at this point in many packing houses, while in others, classification is done at the end of the washing tank stage.

Latex flows out from the cut in the fruit crowns, which can cause staining on the fruit skin. For this reason, in some packing houses, the cutting of hands and separation into clusters is done under water.

Washing tanks in banana packing houses are usually long (about 9 m and 1 m depth), and the fruit movement forward can be favored by the use of water injectors or some other system to force the cluster to move forward, staying in the tanks for 20 minutes (Ortiz Vega et al. 2001). This reduces the temperature of the banana clusters. Chemical products are added to the washing tanks to control latex staining. This process consumes huge amounts of water, and effort has been made to reduce the amounts involved by reducing the volume of the washing tanks.

Washing can also be done by aspersion. Clusters are placed into moving trays, which go under a cascade or aspersion washer. This method uses far less water and reduces the risk of contamination, since washing tanks can rapidly spread fungi or other microorganisms, and pass them into the fruit if the water quality is not properly checked.

Fungicide and Crown Sealer

Crown rot largely affects banana quality and postharvest life. Banana fruit is very susceptible to microbial growth during transport or later ripening processes. To reduce this incidence, it is important to do clean cuts during the de-handling and cluster preparation. At the packing house different fungicides can be used depending on the producing country (thiabendazole, benzimidazole). It is very important to use authorized fungicides and at the appropriate doses to avoid exceeding the maximum residue level (MRL). Generally,

0.5% alum is added to the fungicide or mixture of fungicides because of its healing ability. In Costa Rica, a solution of citric acid that reduces oxidation of crowns and the presence/appearance of marks or rubs is subsequently applied by spraying.

Grapefruit extract (2–3 ml per liter of water), or alum (aluminum sulfate, 400 g per 20 liters of water) can be applied by immersion of the organic fruit (FAO 2019). Two species of epiphytes – *Bacillus* spp. strain DGA14 and *Trichoderma* spp. strain DGA02 – are both proven effective as microbial control agents (MCAs) in combating crown rot disease (International Tropical Fruits Network 2019).

After washing, fruit is placed into special trays, with the 20 clusters or segments needed to pack a 18.45 kg box, organized by length and shape size of the fruit, including short, medium, and long fruits as well as flat or curved clusters. Trays are then placed in roller transportation bands to pass through the fungicide or the natural product and alum (aluminum sulfate) treatment (applied by aspersion or immersion), and finally drained and packed (Figure 4.7D). In the Canary Islands fungicide is applied by cascade or aspersion (Figure 4.8G and H, respectively). In Costa Rica some companies wrap the banana crowns with a tight plastic (ParaSeal or Plastidole) (Figure 4.7I)

Packaging

When the fruit is already selected and placed into trays with the suggested fruit for a single box, packaging is quite simple. The worker just has to organize the fruit in the tray as instructed. If no trays are used, the packing worker has to select, weigh, and pack each package. Figures 4.7E,I–K and 4.8I,J show how packing is performed. Clusters are organized in three or four levels. At the bottom are the smaller fruit, followed by medium fruit in the middle, and the larger fruit on the top. This pattern allows better use of the internal volume of the boxes, maximizing the fruit quantity per box (about 18.45 kg). Nowadays, the tendency is to use biodegradable plastics both in boxes and in bagged clusters.

Boxes are arranged and fixed on wooden pallets (48 boxes per pallet), and a total of 20 pallets can be loaded in a maritime container.

Cooling and Transportation

It is very important to reduce banana temperature after packaging and during transportation to extend fruit shelf life. Nevertheless, temperature has to be above 12 °C to avoid chilling injury. At this temperature, the respiration rate diminishes, and ripening is delayed.

Artificial Ripening and Commercialization

Bananas for the local market or at the end of the transportation need to be artificially ripened in chambers in which it is very important to control the ethylene concentration and the time and temperature of exposure, the pulp temperature, the oxygen and carbon dioxide concentration, and the relative humidity (RH) during the process. This treatment is necessary for uniform ripening of the fruit and to allow the fruit to acquire its characteristic flavor and texture. Pulp temperature should be around 14 °C or higher to favor the interaction between the exogenous ethylene and the banana ethylene receptor. Once the ripening chamber is loaded and the pulp (internal) temperature is around 16 °C (even higher if the banana has to ripen quickly), 100–500 ppm of gas mixture (ethylene in nitrogen) is sprayed and the treatment lasts 24–36 hours. The relative humidity should be kept at least at 90%. The fruits ripen within 3–7 days under normal conditions.

Lobo et al. (2005) observed that fully ripened bananas exposed to ethylene at 15 or 20 °C and stored either at 15 or 20 °C were acceptable in terms of peel color and fruit flavor and texture. Nevertheless, those treated with ethylene at 12 °C were considered to be of lower quality. Figure 4.9 shows the peel color evolution of the bananas at different exposure temperatures (20, 15, and 12 °C), treated with different ethylene concentration (5, 50, 500, and 5000 ppm), and then stored at 20 or 15 °C.

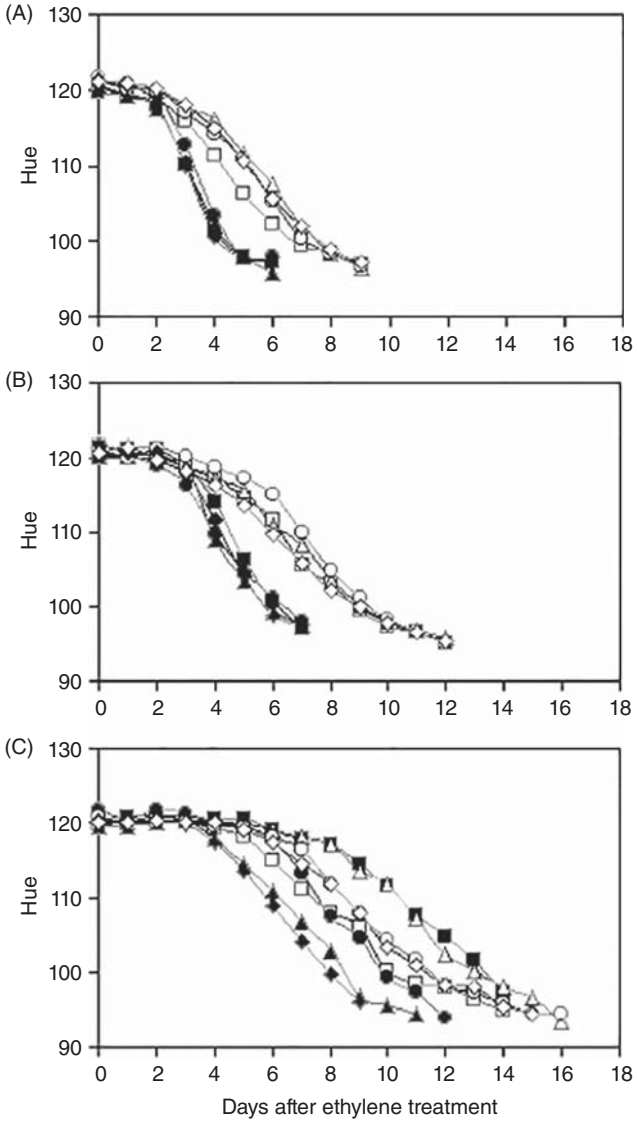

Figure 4.9 Peel color (Hue) evolution of bananas treated with different ethylene concentrations (5 µl/l [■], 50 µl/l [▲], 500 µl/l [●], 5000 µl/l [♦]) and stored at 20 °C and with 5 µl/l (□), 50 µl/l (Δ), 500 µl/l (○), and 5000 µl/l (◇) ethylene and stored at 15 °C. (A) $T_{Exposure}$: 20 °C (SE 20 °C = ±9.92, SE 15 °C = ±9.66); (B) $T_{Exposure}$: 15 °C (SE 20 °C = ±9.38, SE 15 °C = ±9.95); (C) $T_{Exposure}$: 12 °C (SE 20 °C = ±10.44, SE 15 °C = ±10.22). Source: Lobo et al. (2005). Reproduced with permission of SAGE Publishing.

Storage Technologies

To ensure high quality of ripe banana, it is essential that green bananas during transportation to maturity chambers are maintained at optimum temperature, relative humidity, and air circulation.

Immediately after harvest, fruits should be rapidly cooled to the storage temperature using cold air (room cooling, forced air cooling), cold water (hydro-cooling), or evaporating the water from the fruit (evaporative cooling, vacuum cooling). Plantain and banana are usually cooled with cold air to prevent temperatures becoming too low, which can cause chilling injury.

High humidity reduces water loss and increases storage life. A relative humidity of 90% provides the best compromise for storing plantain and banana. Humidity can be raised in a container or room by spraying water in a fine mist. Nevertheless, excessive wetting leads to fruit splitting and reduces market quality.

Air circulation is an effective method used to reduce temperature in storage rooms. However, ventilation also increases water loss from fruit by removing the saturated layer of air that surrounds the fruit.

Plastic films have also been found to increase the shelf life of banana fruit. Modified atmosphere packaging (MAP), low in oxygen and/or high in carbon dioxide, influences the metabolism of the packed product or the activity of decay-causing organisms increasing storability and/or shelf life. In addition, MAP vastly improves moisture retention, which can have a great influence on preserving quality (Jayasheela et al. 2015). Furthermore, packaging isolates the product from the external environment and helps to ensure conditions that if not sterile at least reduce exposure to pathogens and contaminants thereby extending the shelf life of the produce (Hailu et al. 2013). El-Kashif et al. (2010) showed that preharvest bagging of banana bunches using cotton cloth or jute material reduced physical injury and sunscald, increased yield, increased green life, and improved fruit quality. They also found that postharvest packaging of banana fruit in cartons lined with polyethylene film increased green life and improved fruit quality.

The marketability of bananas over long distances is limited due to their highly perishable nature and sensitivity to ethylene. Ripening in bananas can be delayed by using an ethylene scrubber. There are several compounds that can be used as inhibitors of ethylene, for example aminoethoxyvinylglycine (AVG), an inhibitor of ethylene synthesis; 1-methylcyclopropene (1-MCP), an inhibitor of ethylene action; and potassium permanganate ($KMnO_4$), an oxidizing agent. For banana, 1-MCP and $KMnO_4$ are the most commonly used ethylene scrubbers (Sen et al. 2012). To increase the banana shelf life several edible coatings (ECs) can be used. Baez-Sañudo et al. (2009) stored bananas at ripeness stage 3 for eight days at 22 °C, 85% RH treated with 1-MCP (SmartFreshSM) and a chitosan-based EC (FreshSeal®), applied alone or combined. After three days, control and EC-treated fruits were completely yellow, while 1-MCP-treated fruits alone and combined with EC were still showing some green colorations on tips and neck of fingers, being firmer than the other treatments. The combined treatment of EC + 1-MCP can be used to extend the commercial life of bananas for up to four more days.

Hot water treatment delayed ripening and prolonged the green life of fruit (Alvindia 2012). Amin and Hossain (2012) found an increase in the shelf life of bananas and a

reduction in postharvest losses when fruits were treated with hot water (53 °C for 9 minutes or 55 °C for 7 minutes). Hot water treatment at 50 °C for 20 minutes can be used to control anthracnose (*Colletotrichum musae*) (Mirshekari et al. 2012).

Postharvest Economic Losses

The major factors contributing to banana postharvest losses are unreliable transport, poor communication and coordination between producers and processors, lack of or inefficient temperature management, and poor sanitation. Over-ripening and mechanical damage caused by bruising and compression are the main causes of losses in banana supply chains.

Cultivars of the AAA group, Cavendish subgroup are more susceptible to mechanical injuries during postharvest handling than other cultivars, requiring protection all the way from harvest to packaging and transportation, in order to avoid undesirable postharvest losses, which in some parts of the world (Taiwan, Brazil, Jamaica, Ecuador, and some countries in Africa) reach levels of up to 40–45% (Soto Ballestero 2015). In Ecuador, the main banana exporter, postharvest losses can reach 20% even for organic banana (Vásquez-Castillo et al. 2019). Postharvest loses in developing countries, up to 60–80%, are mainly due to the combination of poor infrastructure and logistics, poor agricultural practices, lack of knowledge about postharvest handling, and a convoluted marketing system.

Postharvest losses can be minimized by adopting a certain preharvest strategy and postharvest management/technology.

Proper harvesting tools and assessment of maturity improve the shelf life of the fruits and reduce the postharvest losses to a great extent. Bananas harvested at full maturity will develop good peel and pulp color, with full aroma and flavor at the ripe stage. Fruits harvested at an immature stage are of poor quality upon ripening. Harvesting at an advanced stage of maturity, on the other hand, may be unsuitable for long-distance shipment since ripening will occur during shipment and result in fruit having a shorter shelf life, and some fingers can even split. Farmers have to cover the bunches properly and on time to avoid the fruit being sunburnt and attacked by thrips.

During the harvest, workers have to be very careful to avoid damaging the bunches by stacking, bumps, falls, etc. as the fruit will show black sunken areas on the skin after ripening. Harvesting during the warmest part of the day and exposure to unnecessary high temperatures should be avoided.

At the packing house, transportation, retailers, and wholesalers, the fruit has to be handled carefully. Poor transport conditions, rough handling, unsuitable transport containers, and delays in transportation contribute to losses in banana supply chains. Air circulation in the stacks or piles of produce is of critical importance in preventing heat build-up. It is important not to overload the transport vehicle because heat build-up leads to a premature ripening during transit (Esguerra and Rolle 2018).

Postharvest losses also occur by rough handling, the use of unsuitable packaging material or overfilling containers or boxes, in addition to lack of quality standards. Inadequate ventilation and high temperature during storage, or lack of uniformity and homogeneity of the produce and high temperatures during artificial ripening affects banana quality and may cause significant economic losses.

The control of crown rot starts in the field with the regular removal of leaf trash. Proper field sanitation can greatly reduce the number of crown rot fungi spores present. The rotting fruits or plant waste materials have to be kept away from the packing house (Hailu et al. 2013). De-handing should be done carefully with a sharp knife so as to avoid leaving a ragged cut. Finally, postharvest treatment of fruits with an effective fungicide is essential (Gowen 1995; Dionisio 2012).

Nutritional and Quality Losses

Banana fruits are in high demand as nutritious and economically important fruits, but they experience different marketing problems. The banana is a living entity that is still alive even after harvest and it is subject to continuous changes in appearance, flavor, texture, and nutritive value until it completely deteriorates. These postharvest changes cannot be stopped but can be slowed down within certain limits through the application of good postharvest management practice.

Bananas have high water content, and when harvested they can no longer replace the water that is lost from the peel. If they are stored under conditions of low humidity, they shrivel and lose weight, which diminishes their quality and marketability.

Bananas are an excellent source of vitamin A, vitamin C, vitamin B6, potassium, and fiber, and are low in fat and sodium, and are cholesterol-free. An average sized banana has about 95 cal. Stress conditions accelerate banana metabolism and changes in flavor, carbohydrate concentration, and vitamin C occur. Bagging the fruit in a wrong plastic can lead to anaerobic respiration of the fruit by consuming the oxygen inside the bag, with the consequent appearance of strange aromas, inadequate ripening, etc.

High temperatures used during artificial ripening soften the pulp very quickly. The accumulation of carbon dioxide in the chambers due to poor aeration affects the ripening of the fruit and its homogeneity. Low relative humidity magnifies banana bruises when ripened.

About 20–25% of the harvested banana fruits are decomposed by different fungi during postharvest handling because bananas contain high sugar levels and have low pH, making them particularly suitable for microbial growth. Everyday 1.6 million bananas are thrown away in developing countries (Idris et al. 2015).

Conclusions

The reduction of postharvest food losses is a critical component of ensuring future global food security and banana cultivation sustainability. Postharvest losses can be minimized by adopting a certain preharvest strategy and postharvest management/technology. It is crucial to control each step from the field to the consumer. Therefore, adequate preharvest treatments, as well as the correct stage of harvesting, proper harvesting method, transportation, washing, cleaning, grading, packing, cold storage, ripening process, air and relative humidity during storage or in the ripening chambers, and efficient marketing are crucial phases to ameliorate postharvest losses.

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5

Packaging Technologies for Banana and Banana Products

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Introduction

The importance of packaging has well been recognized for centuries. It has become a significant part of the food value chain not only for containing and delivering products from farm to consumer but also protecting and preserving products. The role of packaging has evolved in communication and utility, which has become more and more important in business. Novel food packaging techniques have been extensively focused in the past two decades. Among these, active and intelligent packaging has received an immense amount of interest for research and applications (Wilson 2007; Dainelli et al. 2008; Shinde et al. 2018). Active packaging technologies have been aimed at extending shelf life or to enhance safety, whereas intelligent packaging provides an indication of the quality of products, as discussed in more detail in this chapter.

Novel packaging technologies have emerged primarily to serve the consumers' need. Novel food processing technologies such as high pressure processing (HPP), pulsed electric field (PEF), ohmic heating, microwave heating, ozone, ultrasound, radio frequency (RF) and pulsed ultraviolet treatments have also emerged in recent years (Jermann et al. 2015; Ahmed et al. 2016). Packaging plays an important role when maintaining various aspects of food quality and safety using these technologies. For many food products such as drink/juice and canned and retorted products, packaging is essentially a part of food processing. As a result, packaging needs to be developed to serve the requirements of the specific processing technologies. Furthermore, packaging technologies have an effect on processing and preservation methods. Examples are the changes from frozen vegetables to chilled vegetables and from fresh fruits and vegetables to fresh-cut products with novel breathable packaging films.

Material innovation has become one of the major challenges for the packaging industry. Innovative materials are among the leading-edge technologies for packaging. New packaging materials are constantly being developed to improve diverse properties for food applications including mechanical, barrier, optical and sealing properties. Efforts on developing and commercializing biodegradable plastics have taken great steps forward over recent decades. Nanomaterials have achieved a major place in the future market of food packaging

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by playing a promising role in improving mechanical, barrier and heat-resistant properties (Silvestre et al. 2011; Bumbudsanpharoke et al. 2015; Wróblewska-Krepsztul et al. 2018).

Different products need different packaging systems and technologies. Both fresh and processed bananas primarily require packaging to protect the products from mechanical damage along the value chains. However, while fresh bananas require packaging with high oxygen permeability, most processed banana products require packaging with limited oxygen permeability. Global concerns on food safety have increased the importance of food packaging in recent decades. As a result, packaging technologies have been explored for different ways of ensuring safety; for example in the use of intelligent packaging for the tracking and tracing and migration of substances into food packaged products.

Bananas (*Musa* spp.) are one of the major food crops consumed worldwide. They are known to be an important source of bioactive compounds with potential health benefits such as phenolics, carotenoids, biogenic amines, and phytosterols (Singh et al. 2016). Banana fruit are eaten as both fresh and various processed products including dried/dehydrated bananas, banana flour/powder, paste, syrup, jam, jelly, juice, candy, and frozen products. This chapter addresses various aspects of packaging for fresh banana and banana products. Packaging's primary functions include containment, protection/preservation, communication, and utility. These functions make packaging an important part of every product. Current and innovative packaging technologies for fresh and major processed banana products in the markets are also covered in this chapter. Furthermore, packaging design/material selection is a significant criterion for positive and sustainable impact.

Packaging for Fresh Bananas

Bananas are sold in different forms to meet various consumer demands, for example, in bunches, as a few or a single fruit with and without packaging. With the enhanced buying convenience and in response to growing health awareness, banana production and sales have increased in recent years. In addition, ripening stages are important criteria when selling bananas. Most convenience stores and shops carry ripe yellow bananas, which are ready for consumption.

One of the major problems for damage and loss of bananas during marketing is mechanical injuries that occur during handling and distribution caused by shock, vibration, and compression. Bruising and skin abrasion are the most common mechanical injuries which cause unacceptable quality or low price of banana at the market. Browning in banana can occur both externally (skin) and internally (flesh). Bruising can accelerate browning due to enzymatic browning of the banana flesh without being visible on the banana skin. Cell breakage causes phenolic substances to come into contact with enzymes such as polyphenol oxidase (PPO), which in the presence of oxygen results in the formation of brown pigments. Cell breakage due to mechanical injuries can also accelerate respiration resulting in shortened shelf life of bananas. Abrasion can result in skin browning or blackening due to water loss, which can be minimized by storage under high relative humidity (>90% RH). Skin abrasion can be minimized by proper packaging and cushioning to avoid the impact between fruit or against the inner surfaces of packaging containers.

Bruising has been shown to have a negative impact on the banana fruit quality. Bugaud et al. (2014) studied the genotypic factors and post-climacteric storage conditions that affected bruise susceptibility of banana peel. Five cultivars of banana were stored either at 18 °C throughout ripening or at 13 °C between the 2nd and 6th day after ethylene induction. Indicators of bruise susceptibility, such as peel electrolyte leakage (PEL), total polyphenolic content, hardness, water content, and peel thickness were investigated. Bruise susceptibility was defined as the lowest impact energy required to produce visible bruising by an object dropped on post-climacteric banana fruit from a predetermined height, converted into impact energy (20–200 mJ with a 20 mJ increment). They reported that "Grande Naine" and hybrid "Flhorban925" bananas were not bruised even at the maximum impact energy (200 mJ) during ripening irrespective of the storage conditions. However, a gradient in bruise susceptibility was observed among the other cultivars, "French Corne" > "Fougamou" > hybrid "Flhorban916." They also reported that bruise susceptibility enhanced during ripening particularly at 18 °C. Banana stored at 13 °C resulted in a two-day delay to fruit maturity as well as in bruise susceptibility. From the positive correlation of bruise susceptibility with PEL ($R = 0.78$) and negative correlation with peel hardness ($R = -0.45$) and no correlation with polyphenol content, they concluded that membrane permeability provided the first indicator to understanding bruise susceptibility.

Banana fruit after harvest is more susceptible to mechanical damage. Kkaravessapong et al. (1992) investigated the effect of relative humidity (50%, 70%, and 90%) on mechanical damage susceptibility of banana cv. "Williams" (Cavendish subgroup AAA) from day 2 after harvesting to day 5 after ripening. The bruise resistance coefficient (ml damaged tissue per J of energy absorbed) was used to assess susceptibility to damage. They found that the susceptibility of the fruit to mechanical damage increased rapidly on the 2nd day by 4–8 times after ripening initiation. It was also found that relative humidity did not influence the bruise resistance coefficient, carbon dioxide or ethylene production, or starch or sugar content. However, low humidity greatly increased water loss by 3–4 times more than high humidity. It was concluded that humidity did not influence susceptibility to mechanical injury, but the tissues damaged at low humidity were dried to a black color while those damaged at high humidity remained light brown.

Banks and Joseph (1991) investigated the factors affecting the resistance of banana fruit to bruise by estimating the minimum (threshold) compression forces and impact energies needed to produce bruises on banana. Both forces were applied through 8 mm diameter balls. Fruit harvested in early morning required 5.49 N of compression to cause bruises than late harvested (4.55 N) fruit due to high turgidity in early morning. When the fruit were left for 1–2 days at ambient temperature between harvest and application of bruising treatments, water loss reduced the threshold for compression bruising from 5.35 to 4.32 and 4.29 N, respectively. Fruit at 30 °C had a lower compression bruising threshold (3.31 N) than those at 13.5, 19, and 24.5 °C (4.52, 4.72, and 4.46 N, respectively). The impact bruising thresholds were affected by a delay after harvest and temperature with an increase from 93 to 120 μJ following a two-day delay after harvest and from 74 to 104 μJ as a result of elevating temperature from 19 to 30 °C.

An important function of fresh produce packaging is to protect the fruit from mechanical injuries. Bananas are harvested, loaded on a truck or packed in a variety of containers for transport to the packing houses, distribution centers, wholesale markets, export, or

processing plants. At packing houses and distribution centers, bananas are cleaned, sorted, and graded into shipping containers for their destined markets and desired purposes. Loading banana without packaging can result in significant mechanical damage and losses. Precooling is an important postharvest step. Bananas are precooled in refrigerated containers or cold rooms to remove field heat as quickly as possible. Packaging used during precooling should be properly ventilated for efficient precooling

Reducing damage by proper packaging and cushioning is important, especially when bananas are sold at high-end markets or as individual fruit at retailers and shops because of the high expectation of consumers concerning quality. Shipping containers should also be stackable to reduce the compression force applied to the fruit as well as to provide load stability during distribution and storage. In addition, shipping containers should be properly vented to allow efficient cooling to maintain the best quality of the fruit.

Proper packaging and cushioning design were shown to reduce mechanical damage in several tropical fruits (Chonhenchob and Singh 2003, 2005; Chonhenchob et al. 2008). Major forms of bulk packaging for bananas are reusable plastic containers (RPCs) and paper containers including corrugated and solid fiberboard containers (Figure 5.1). Various cushioning and accessories help protect banana fruit from mechanical damage. RPCs are available in specific common footprint dimensions. Corrugated fiberboard containers (CFCs) and solid fiberboard containers can be specially designed to accommodate varying sizes and shapes of banana bundles with unique print for display and marketing purposes. CFCs are more commonly used for fresh produce packaging than solid fiberboard containers. The most common flute types used for fresh produce packaging are shown in Figure 5.1 (A) and (C), the latter (flute) is mainly used in the United States. There are many different corrugated box styles. The most common styles used for fresh produce applications are the regular slotted container (RSC), telescoping box, rigid or bliss container, and tray (Chonhenchob et al. 2017). Banana bunches are not in uniform or common shapes. Different packaging styles of bananas are used in various shipping containers (Figure 5.1).

With the adoption of a common footprint standard which specifies container base dimensions and stacking features, both RPCs and corrugated containers from different manufacturers and suppliers can be stackable on the standardized pallets. The most commonly used pallet in the fresh produce industry in the United States is the Grocery Manufacturers' Association (GMA) pallet (40 in. × 48 in.), which has similar dimensions to the 1200 mm × 800 mm Euro pallet. Two major sizes of containers used for fresh produce packaging are full-sized ("5-down," 40.64 cm × 30.48 cm) and half-sized ("10-down," 60.96 cm × 40.64 cm) containers, according to the Fiber Box Association (de la Fuente et al. 2018). The European Federation of Corrugated Board Manufacturers specifies the outside dimensions of fruit and vegetable trays as 597 mm × 398 mm, 398 mm × 298 mm, and 298 mm × 198 mm.

Container liners may be used in the bulk packing of bananas. Liners are made of plastic films, usually polyethylene (PE) or polypropylene (PP), mainly to minimize water loss during storage and distribution. Moisture loss is related to weight loss which is an important criterion for selling fruit in the market. Sealed liners can be used to establish modified atmosphere packaging (MAP) for extending the shelf life of banana. MAP can be applied for long distance markets such as transportation via sea freight or long-term storage. MAP for fresh fruit including banana usually requires specific film permeability to allow proper gas exchange between the outside and inside environments that matches the fruit respiration rates. More details about MAP of bananas are discussed later in this chapter.

Figure 5.1 Different bulk packaging systems for fresh bananas: (A) Chiquita® new global banana box; (B) Dole Philippines's banana box for US Shipment; (C) telescoping box style for bananas; and (D) fresh bananas in a liner bag placed in a corrugated box. Source: (A) https://www.freshplaza.com/article/2167086/us-chiquita-r-launches-new-global-banana-box-for-new-year; (B) http://www.fruitnet.com/asiafruit/article/16480/dole-philippines-prepares-us-shipment; (C) https://www.multipack.in/products/banana-packaging-box-exports; and (D) https://www.ec21.com/product-details/Fresh-Green-Cavendish-Banana--6857532.html.

The highly perishable nature and sensitivity to ethylene have limited the shelf life of bananas. Various techniques have been attempted to increase the shelf life, maintain the quality and enhance marketability of bananas. Major quality indices of fresh banana include color changes, softening, and weight loss. Color changes during ripening appear to be associated with the stage of ripeness of the banana. Softening of bananas during ripening is related to processes involving the breakdown of starch, cell walls, and cellulose.

Various technologies have been reported to maintain the quality and prolong shelf life of fresh bananas; for example, edible films and coatings, MAP and ozone treatments.

Packaging for Processed Banana Products

Bananas are processed into many different products, mainly to extend shelf life and to provide a wide variety of value-added products for consumers. Furthermore, banana products are convenient for consumption. Dried/dehydrated products including chip/snack and flour/powder are the most popular banana products in the world market. Bananas are also made into juice or drink alone or mixed with other fruits and packaged in a variety of materials and forms. Bananas are processed into a variety of milk-based beverages,

Figure 5.2 Selected processed banana products in a variety of packaging materials and forms: (A) banana milk; (B) low-fat banana milk; (C) UHT banana milk: (D) steam-dried banana chips; (E) freeze-dried banana chips; and (F) banana-strawberry flavored yogurt. Source: (A) Banana Wave, USA (www.bananawave.love); (B) Saputo Produits Laitiers, Canada (www.saputo.com); (C) Fonterra Brands, New Zealand Limited (www.fonterra.com); (D) Natural Produces Co., Ltd., Thailand; (E) author's own image (Vanee Chonhenchob); and (F) Upstate Niagara Cooperative, Inc., USA (https://www.upstateniagara.com).

banana-flavored yogurt, and dried slices; these products are packaged in a variety of packaging materials and forms as shown in Figure 5.2.

Dried and Dehydrated Bananas

There are a wide variety of dried and dehydrated bananas, for example sun dried/dehydrated slices, powder, flakes, chips, and snack bars. These dried and dehydrated products provide a long shelf life because of the reduced moisture content and water activity. Therefore,

packaging requirements for these types of products are to protect the products from moisture, as moisture will significantly affect the product quality. For example, moisture absorption will cause banana powder to become soggy and cause caking as well as facilitate mold growth, and banana chips to lose crispness. Dried and dehydrated bananas tend to develop a brown color in the presence of oxygen and heat due to non-enzymatic browning reactions which mainly involve reducing sugars and amino acids in bananas. Banana chips become soft due to moisture absorption and also develop rancidity due to lipid oxidation; packaging for these products requires a high barrier to oxygen.

Dried and dehydrated products are commonly packed in different forms of packaging including composite cans, aluminum foil pouches, metalized plastic-based pouches, and multilayer plastic pouches. Glass packaging ideally protects the products from both water vapor and oxygen and is inert to the products. However, it is breakable, difficult for handling, distribution and storage, and not cost-effective. Metal packaging provides an excellent barrier to water vapor and oxygen and protects the products from sunlight which accelerates many reactions. Paper packaging can be made into several forms including pouch, tray, and box. Paper easily absorbs water, hence is coated or combined with other materials to make suitable packaging. Plastic packaging is the most commonly used for food packaging applications. It offers a wide range of properties; it is light weight, can be made into various forms and shapes, and is cost-effective. The plastic packaging should be a high barrier to water vapor and oxygen to meet the requirements for dried and dehydrated banana products. In addition, packaging should provide mechanical strength, sealability, convenience, and utility as well as serve marketing functions and be cost-effective.

Multilayer or composite materials are often used for food packaging to obtain the intended shelf life. For dried and dehydrated banana products, laminated aluminum foil with PE and multilayers containing high oxygen barrier layers such as ethylene vinyl alcohol (EVOH), polyvinyl alcohol (PVOH), nylon 6, and polyethylene terephthalate (PET) are commonly used. However, EVOH, PVOH, and nylon 6 are sensitive to water vapor, hence they have to be buried within high water vapor barrier materials such as PE or PP in the multilayer structures. In recent decades, a stand up pouch has been a common form of packaging for dried and dehydrated fruits and vegetables as well as other snack products as it is attractive on a shelf display and reduces resource usage, storage and shelf spaces and cost compared with rigid packaging.

Banana chips are a common type of dried and dehydrated product. Deep fat frying is a traditional method for making banana chips. Alternative frying techniques have been used to reduce the oil contents of chips such as vacuum frying and microwave frying. Banana chips are both moisture and oxygen sensitive, and hence require a high barrier to both moisture and oxygen. Moisture absorption results in crispness loss while the presence of oxygen results in rancidity due to lipid oxidation and hydrolytic oxidation.

Banana Juice

Banana juice is extracted from banana pulp using different techniques. Typically, banana juice is blended with other fruit or vegetable juices to sell as mixed juices which are becoming increasingly popular. Banana juice is mostly aseptically processed as detailed in other chapters. Like most fruit juice processing, the packaging used for aseptic processing of

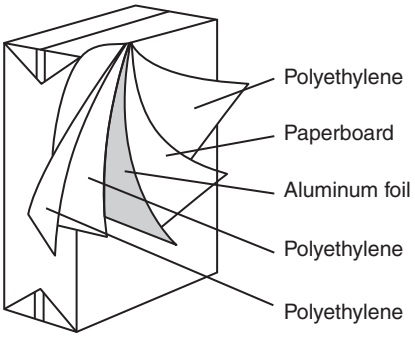

Figure 5.3 The sublayers in a composite material used for making brick-type packages. Source: Pascall and Siddiq (2018). Reproduced with permission of John Wiley and Sons.

banana juice is in various forms, typically cartons and also cans, cups, and bottles. Traditional carton systems contain multilayer materials which provide different functions. The common structure of a "brick-pack" contains outer PE, paperboard, adhesive, aluminum foil, and inner PE layers (Figure 5.3). Aluminum foil offers protection against moisture, oxygen, and light for a longer shelf life. A high barrier material such as EVOH can be used to enhance shelf life of non-aluminum foil aseptic packaging. Banana juice is also packaged in PET bottles, which is another popular form of packaging for the beverage industry. Innovative juice processing and packaging technologies involve the development of machinery in various steps from receiving raw materials through filling and packaging of banana juices.

Frozen Bananas

Freezing is another traditional preservation method to prolong the shelf life of fruit. Bananas are mostly frozen at the ripe stage, either peeled or unpeeled as well as sliced and whole fruit. These products are mostly sold in bulk for further cooking and processing, culinary applications, and food services, etc. Some frozen products are sold by retail markets but on a very limited scale and are not as popular as fresh bananas and other processed products. Temperature control throughout the storage period and the frozen supply chain is an important factor in maintaining the quality of frozen products. Intelligent packaging such as time–temperature indicators (TTIs) are used for tracing and managing the chains. Thermal insulation packaging materials, for example expanded polystyrene (PS), polyurethane (PU), corrugated fiberboard and other composite packaging, which can be combined with phase change materials such as gel packs, are used to transport frozen products in the cold chains to prevent heat loss or gain. The most common forms of thermal insulating packaging are boxes and bags. Retail packaging for frozen bananas should withstand the freeze–thaw temperature for consumer use. In addition, packaging with a high barrier to water vapor is required to prevent moisture loss from freezer burn as a result of sublimation of water vapor from the surface of the fruit.

Current and Innovative Technologies for Bananas

Edible Films and Coatings

Edible films and coatings for whole and fresh cut fruits have been extensively studied over the past decades. This field of study has received increased attention in recent years due

to health and environmental consciousness. They are generally recognized as safe (GRAS) and biodegradable. The major benefits of edible films and coatings include reducing moisture loss or gain and controlling gas exchange. In addition, they improve appearance by providing gloss and shine and can be used as carriers for active substances for extending shelf life and/or enhancing safety of the fruits (Chonhenchob et al. 2017).

Different types of coating have been studied for fresh bananas. Thakur et al. (2019) studied the effects of rice starch edible coating (EC) blended with sucrose esters on Cavendish banana at 20 °C and found that coating effectively delayed ethylene biosynthesis and chlorophyll degradation, reduced respiration rate and weight loss, retained firmness, and extended shelf life of bananas to 12 days as compared with the uncoated (control) bananas (6 days).

The effects of chitosan EC and 1-methylcyclopropene (1-MCP) alone or in combination (EC + 1-MCP) were evaluated on Cavendish banana by Baez-Sanudo et al. (2009) at 22 °C for 8 days. The use of 1-MCP is common to inhibit the ethylene action of various climacteric fruits including bananas. After 3 days of storage, the tips and neck of banana fingers treated with 1-MCP alone and combined with EC were still green, while those coated with chitosan alone and untreated bananas were completely yellow. The 1-MCP treatment alone or its combination with chitosan was also effective in maintaining the fruit firmness and delaying the incidence of sugar spots with no adverse effects on the sensory results.

Zewter et al. (2012) studied the effect of different postharvest treatments ($KMnO_4$ and 1-MCP), packaging (perforated and non-perforated PE bags), and temperature (open air ambient and cold room) on selected physical and sensory quality attributes. Results of visual color scores are shown in Table 5.1. The 1-MCP + perforated PE bag storage was effective in maintaining good peel color (4.3) after 24 days, which corresponded with over 50% peel color change from full-green to partially yellow. Bananas with a peel color score of 6.0 were deemed unmarketable. The change in banana peel color, resulting from

Table 5.1 Effect of postharvest treatments and packaging on color changes of banana peel during storage (storage room temperature ranged from 13.6 to 18.4 °C).

Treatments	Storage period (d)					
	4	**8**	**12**	**16**	**20**	**24**
Control (open-air)	4.0[a]	5.0	6.0	7.0	—	—
Non-perforated PE	2.0	3.0	4.7	5.7	7.0	—
Perforated PE	2.0	3.0	4.7	5.7	6.7	—
Non-perforated PE + $KMnO_4$	2.0	3.0	4.0	5.3	6.7	—
Perforated PE + $KMnO_4$	2.0	2.7	4.0	5.3	5.7	7.0
1-MCP + non-perforated PE	1.0	2.0	2.7	3.7	5.0	6.0
1-MCP + perforated PE	1.0	1.0	2.0	2.7	3.7	4.3
1-MCP	1.3	2.0	3.0	4.0	4.7	5.7

PE, polyethylene; $KMnO_4$, potassium permanganate; 1-MCP, 1-methylcyclopropene.
[a]Color stages: 1 (green), 2 (breaker), 3 (<25% color change), 4 (25–50% color change), 5 (>50% but <100% color change), 6 (fully yellow), and 7 (yellow with black spots).
Source: Adapted from Zewter et al. (2012).

respiration, is closely correlated with pulp softening. The color quality of bananas with all other treatments was limited to between 12 and 16 days.

Coating of banana with Arabic gum (5, 10, 15 and 20%), chitosan (1.0%) and their combination was studied for the inhibition of *Colletotrichum musae* causing anthracnose rot of banana cv. "Pisang Berangan" (Maqbool et al. 2010). The combination of 10% Arabic gum with 1.0% chitosan was the optimal treatment in controlling decay and showed a synergistic effect on the reduction of *C. musae* in artificially inoculated bananas. This combined treatment significantly delayed ripening, weight loss and retained fruit firmness better than the Arabic gum and chitosan alone. Maqbool et al. (2011) further suggested that this composite coating can be commercially used for extending the shelf life of bananas for up to 33 days with delayed color development and reduced respiration rate and ethylene evolution with a good sensory profile.

Soradech et al. (2017) studied the effects of 60% shellac and 40% gelatin coating with and without 5% PEG 400 for the shelf life extension of banana cv. "Kluai Hom Thong." They found that as a physical barrier, coating effectively slowed down the ripening process, weight loss, softening, and maintained the overall quality of banana better than the uncoated fruits during storage of 30 days at 25 °C.

Modified Atmosphere Packaging

MAP use is a common practice in the banana industry using commercially available films. For example, individual clusters of six fingers are packed individually in PE bags prior to being packed together into a shipping carton, transported by sea freight, and allowed to ripen, and then marketed in the same PE bag (Thompson 2011). The benefits of MAP in prolonging the shelf life of fresh fruit and vegetables have been extensively studied for many decades. Several benefits of MAP include reduced respiration rate, ethylene production and sensitivity, enzyme activity and quality changes (Chauhan et al. 2006; Mendoza et al. 2016). In a MAP system, oxygen is typically reduced while carbon dioxide is elevated. Packaging is a significant challenge in MAP as the modification of gas composition inside the package involves the respiration of packed produce and the gas exchange through packaging materials.

The effect of MAP on preventing senescent spotting of banana peel (cv. Sucrier) using polyvinyl chloride (PVC) film wrap was reported by Choehom et al. (2004). The study revealed that the positive MAP effect on peel spotting was mainly due to low oxygen and associated with reduced *in vitro* phenylalanine ammonia lyase (PAL) activity in the peel and increased *in vitro* PPO activity.

A number of studies have reported the combined effects of MAP with other treatments, for example essential oil treatments. Siriwardana et al. (2017) treated the "Embul" banana (*Musa acuminata*) with 1% aluminum sulfate or 1% aluminum sulfate + 0.4% basil oil or distilled water (control) and packaging it in low-density polyethylene (LDPE) bags for controlling crown rot and shelf life extension. After 14 days in 12–14 °C cold storage, oxygen in the packages ranged from 3.1 to 3.7% while carbon dioxide varied from 4.2 to 4.7%. The results showed that 1% aluminum sulfate + oil treatment significantly controlled crown rot disease better than the other treatments. There were no significant differences in the treated and untreated bananas in terms of physicochemical, sensory, and nutritional properties.

Interestingly, this treatment also had better sensory score than the untreated bananas due to the sweet and pleasant taste of basil oil.

In another study, Ranasinghe et al. (2005) investigated the effects of cinnamon bark or leaf (*Cinnamomum zeylanicum*) or clove (*Syzygium aromaticum*) oils to control postharvest diseases of mature Embul (Musa, AAB) bananas. Fruit treated with distilled water and benomyl were served as control. Bananas were stored under MAP using LDPE bags and kept at 14 °C or at ambient temperature (28 °C). Cinnamon bark and leaf oils effectively controlled crown rot, whereas clove oil did not control crown rot development. These results suggested the combined effect of MAP with the cinnamon oils was a safe, cost-effective way to extend the shelf life of Embul bananas up to 21 days at 14 °C and 14 days at 28 °C without any adverse effects on the organoleptic and physicochemical properties.

Stewart et al. (2005) explored the potential of passive silicone membrane and diffusion channel as an inexpensive and easy to use MAP system to preserve the quality and extend the shelf life of Cavendish bananas. The silicone membrane MAP system was shown to achieve gas stability more quickly, maintain more stable gas levels and provide better physiological and sensory quality as compared with the diffusion channel system. The silicone membrane system with 50.29 cm^2 area established a modified atmosphere of 3.5% CO_2 and 3% O_2 after storage for about 10 days at 15 °C, and bananas under this system remained unripe for 42 days.

Mathematical models were studied by several researcher for MAP of various fruits and vegetables, including bananas. Mendoza et al. (2016) developed a model to describe the evolution of the oxygen, carbon dioxide, and ethylene in a MAP system for Cavendish bananas. Fruit were packaged in perforated bags of PP and LDPE at 12 °C for 8 days. This model satisfactorily described the experimental evolution of the gas content in the package headspace with high coefficients of determination.

Typically, most commercially available materials are not suitable for MAP of fresh produce especially for bananas, which is a climacteric fruit with high respiration rate. The effects of MAP using packaging films with different gas permeability on the quality of banana (cv. Sucrier, locally known as "Kluai Kai") were also investigated by our group (*data published in Thai*). The results showed that high gas permeable packages created an equilibrium modified atmosphere (EMA) of about 7% O_2 + 3% CO_2. However, O_2 reduced to nearly 0% and CO_2 increased to about 10% at the end of storage in PE bags. Bananas in the EMA package showed in better quality (e.g., firmness, color) with no off-odor after ripening and stored at 13 °C and room temperature as compared with those kept in just PE bags. Inadequate gas exchange through the PE bags can result in anaerobic respiration leading to a fermentative process causing the development of off-odors and off-flavors in the packaged fruits.

Active Packaging

Active packaging has received increasing attention by researchers and industry in recent decades. It is defined as packaging that acts more than only providing a barrier to the external environment by actively altering the environment inside the package to improve quality, extend shelf life and/or enhance safety of the products (Syamsu et al. 2016; Wilson 2007). Active packaging for fresh and processed food include a wide variety of technologies as summarized in Table 5.2.

Table 5.2 Selected active packaging technologies for fresh and processed food.

System	Substances used
Moisture absorbing	Silica gel, propylene glycol, polyvinyl alcohol, diatomaceous earth
Oxygen absorbing	Enzymatic systems (e.g., glucose oxidase-glucose, alcohol oxidase-ethanol vapor)
	Chemical systems (e.g., iron oxide, catechol, ferrous carbonate, iron-sulfur, sulfite salt-copper sulfate, photosensitive dye oxidation, ascorbic acid oxidation)
Carbon dioxide absorbing/emitting	Iron oxide/calcium hydroxide, ferrous carbonate/metal halide
Ethylene absorbing	Porous solids impregnated with $KMnO_4$ (e.g., silica gel-$KMnO_4$), activated charcoal, Kieselguhr, bentonite, Oya stone, zeolite, ozone
Antimicrobial releasing	Sorbates, benzoates, propionates, peroxide, sulfur dioxide, ethanol, ozone, microbial secondary metabolites, silver-zeolite, quaternary ammonium salts
Antioxidant releasing	Ascorbic acid, tocopherol, BHA, BHT, TBHQ
Flavor absorbing/releasing	Baking soda, active charcoal/food flavors
Light absorbing/regulating	UV blocking agents, hydroxybenzophenone

Source: Adapted from Ozdemir and Floross (2004).

Active packaging systems that are commonly used for fresh fruits and can be applied to bananas are oxygen absorbing, carbon dioxide releasing and absorbing, ethylene absorbing and moisture absorbing systems. Ethanol and other antimicrobial releasing systems have increasingly been studied for delaying microbial growth, which can also be applied to fresh bananas and moisture sensitive processed banana products. The most common form of active packaging for commercial applications is a sachet containing active substances because it is easy to use and can be readily applied without additional equipment/system. In recent years, there have been attempts to incorporate active substances in packaging materials such as film or parts of packaging such as labels and pads. These are successfully commercialized and have been used for several products.

A number of positive effects of active packaging on the quality of bananas have been reported in the literature, especially the applications of ethylene absorbers, which are used to reduce ethylene levels in the package as ethylene has pronounced effects on banana senescence and ripening. Potassium permanganate is one of the most widely used ethylene absorbers and has been extensively studied by many researchers. Active packaging has been studied in combination with MAP for bananas and has shown positive results compared with the use of MAP alone.

Chamara et al. (2000) packaged banana cv. "Kolikuttu" in LDPE bags with clay bricks impregnated with $KMnO_4$ as an ethylene absorber. The results showed that bananas packaged with ethylene absorber had lower ethylene and carbon dioxide and higher oxygen contents in the package atmosphere while maintaining better quality compared with the control. Further, ethylene absorber was shown to enhance the beneficial effects of MAP.

Another study of an active ethylene absorbing system on bananas was reported by Satyan et al. (1992). Banana bunches cv. "Williams" were sealed in a PE tube (0.1 mm) with and

without 100 g vermiculite impregnated with a saturated solution of $KMnO_4$ and stored at different temperatures (28, 20, or 13 °C). The average storage life of bananas packaged in PE tubes with and without ethylene absorber was increased 3–4 and 2–3 times, respectively, compared with the control (no package). However, high concentrations of carbon dioxide and/or ethylene were observed in the package atmosphere suggesting that PE was not suitable for MAP of bananas and higher gas permeable films were needed to avoid carbon dioxide and ethylene accumulation in the package.

Kudachikar et al. (2011) evaluated banana cv. "Robusta" fruit quality and the shelf life under active (MAP+GK, i.e., green keeper) and passive MAP at 12 °C with the openly kept banana as control. For both MAP and MAP+GK treatments, LDPE films were used. For the active MAP (MAP+GK), three sachets containing $KMnO_4$ (10 g/sachet) were placed inside the LDPE film bag. After 3 weeks of storage, a steady-state atmosphere of 8.6% CO_2 + 2.8% O_2 and 8.2% CO_2 + 2.6% O_2 were established in the passive MAP and MAP+GK packages, which extended the shelf life up to 5 and 7 weeks, respectively, with good quality attributes, compared with 3 weeks for the control.

In another study, the effects of MAP and ethylene absorbent was investigated on banana cv. "Sucrier" stored at 20 °C for 7 days after ripening treatment (Romphophak et al. 2004). MAP using a foam tray with PVC film wrap and PE bag, with ethylene absorbent using $KMnO_4$ were compared with the control (corrugated box). Bananas in PVC + ethylene absorbent and PE + ethylene absorbent had significantly higher dopamine contents and less senescence spotting compared with the control. Bananas in PE bags showed abnormal ripening and fermentative flavor. This was due to the limitation of gas exchange in the PE bag especially at high temperature.

Nguyen et al. (2004) studied the effects of MAP, ethylene absorber and carbon dioxide scrubber on the chilling injury (CI) of banana cv. "Sucrier" stored at 10 °C and 90% RH for 30 days. Bananas were packed in non-perforated PE bags, containing three sachets of ethylene absorbent and carbon dioxide scrubber and placed in corrugated cardboard boxes. Bananas stored in corrugated boxes without PE bags and no ethylene absorbent or carbon dioxide scrubbers were used as control. The atmosphere of about 12% O_2 and 4% CO_2 was obtained which significantly prevented CI compared with the control. It was found that banana fruit in MAP had higher total phenolic and lower PAL and PPO activities than the control fruit which suggests that MAP effectively reduced the CI effects.

Recently, nano-zeolite $KMnO_4$ was studied to extend the shelf life of "Ambon" banana at 25 °C to 23 days (17 days longer than the control) (Syamsu et al. 2016). Furthermore, metal–organic frameworks of synthetic porous materials were studied to determine the ability to bind ethylene and the ethylene action inhibitor, 1-MCP. Basolite C300 was more effective at binding and retaining ethylene than Basolite A520 and zeolite Z13X. Ethylene was rapidly released from Basolite C300 into packaged bananas and induced ripening suggesting its potential use to sorb, store, and release gaseous compounds for produce applications (Chopra et al. 2017).

Other active packaging systems have been combined with ethylene absorbers to extend the shelf life of bananas. Carbon dioxide scrubbers and ethylene absorbents were included to reduce the increase of carbon dioxide and ethylene levels during storage of banana in PVC wrap in the study by Choehom et al. (2004), as mentioned above. The combined effects of active packaging with MAP prevented peel spotting on "Sucrier" bananas.

Chauhan et al. (2006) compared passive MAP (in PE bags), active MAP (flushed with 3% O_2 and 5% CO_2 in PE bags), and partial vacuum with and without active packaging system containing ethylene scrubber, silica gel as moisture absorber and soda-lime as carbon dioxide scrubber. The results showed that the active packaging system increased the shelf life of bananas in all the MAP types studied with delayed ripening, degreening, and softening during ripening of bananas.

Incorporation of active substances in packaging films was also reported in bananas. Chitosan/PVOH blended with anti-browning oxalic acid coating was shown to minimize the peel browning of "Williams" banana with a reduction of the cell membrane degrading and the browning enzyme activities, provide a smooth surface and maintain long term shelf life of bananas at room temperature.

Banana coated with sodium alginate/carboxymethyl cellulose film forming solutions containing cinnamon essential oil (CEO; 5, 10, and 15 g/l) as antimicrobial agent was studied by Han et al. (2018). They found that the appearance of bananas coated with sodium alginate/carboxymethyl cellulose containing 5 and 10 g/l of CEO was much better than the uncoated and the control bananas. However, bananas coated with sodium alginate/carboxymethyl cellulose containing 15 g/l of CEO deteriorated quicker than the control due to increased oxygen permeability. Coating with suitable formulation prevented moisture loss and reduced the respiration rate which consequently extended the postharvest life of bananas with no decay.

Intelligent Packaging

With increased consumer concerns about food quality and safety, innovative intelligent packaging has increasingly received attention in the past decade. Intelligent packaging can provide information related to the quality and history of the products for all supply chain parties, including manufacturers, retailers, and consumers. It can be used to ensure quality and safety of the products for the users. Furthermore, intelligent packaging has become a significant tool for tracking and tracing throughout the supply chain.

There are three main technologies in intelligent packaging: indicators, sensors, and data carriers. Indicators aim to provide information to consumers about the packaged food quality. Sensors are used to detect, quantify, and signal the particular matter in foods. Data carriers store and transmit information for traceability of the packaged products (Kerry et al. 2006). Data carriers are not considered an intelligent packaging in some references as they do not respond and provide information related to the kinetic changes of food quality.

The major intelligent packaging systems for food applications are presented in Table 5.3. These include quality indicators, gas concentration indicators, TTIs, shock indicators, biosensors, and gas sensors. The most important data carriers in the food packaging industry are barcodes and RFID (radio frequency identification) tags. RFIDs are used to enhance communication efficiency through supply chains for traceability, counterfeit protection, and product identification. Recently, RFIDs have been integrated with sensors to enhance performance of intelligent packaging systems, for example, providing location-specific information and temperature managed traceability systems (Abad et al. 2009). Furthermore, nanocomponents are integrated in ultra-thin polymer substrates for RFID chips with biosensors for detecting foodborne pathogens or sensing the moisture or temperature of a product (Nachay 2007). Intelligent packaging systems are developed in numerous forms, for example labels, tags, and dot inks, to serve various applications.

Table 5.3 Intelligent packaging systems and their principles.

Systems	Principles
Indicators	Indicate the presence, absence or concentration of substance, or the reaction of substances and inform by color changes
Time–temperature indicators	Monitor time–temperature history and provide information relating to quality, safety, or shelf life of foods
Freshness/ripeness indicators	Monitor components based on quality attributes of food products and provide information relating to product quality, microbial growth or chemical changes in foods
Gas indicator	Monitor gas changes inside the package or detect the occurrence of leakages
Shock indicator	Response of mechanical shock to visually or physically change
Sensors	Detect, record, and transmit information regarding:
Chemical sensors	Chemicals or gases
Biosensors	Biological analytes (e.g., enzyme, microbe, or nucleic acid)
Gas sensors	Gaseous analytes (e.g., oxygen, carbon dioxide, water vapor, ethanol, organic acids)
Date carriers	
RFIDs	Data transmission using radio waves

Conclusion

This chapter presented the functions of packaging to enhance the quality, safety, marketing and consumer acceptance of fresh and processed bananas. Packaging plays an important role in the value chains from farm to table. Standardized common footprints of shipping containers are applied to improve the logistics and display efficiencies, which are important features of modern trade. Innovative packaging technologies are used to maintain the quality of fresh and processed bananas, including edible films and coatings, MAP, and active and intelligent packaging. Material innovation is a significant challenge for the banana industry, for example, the development of high gas permeable films for MAP and active packaging materials with antimicrobial, ethylene absorbing, oxygen absorbing, and carbon dioxide emitting/absorbing properties. Intelligent packaging systems are developed into various forms and integrated with advanced technologies to serve various applications for improving quality and safety, providing information, and tracing and managing the value chains of fresh and processed bananas.

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6

Ripe Banana Processing, Products, and Nutrition

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Introduction

Banana (*Musa* sp.) is the second largest produced fruit after citrus, contributing about 16% of the world's total fruit production. India is the largest producer of banana, contributing 27% of the world's banana production (FAO 2019). As a major staple fruit, banana represents the eighth top-starchy source in the world and its per capita consumption is estimated at about 0.5 kg/day in Latin America and over 1 kg/day in Eastern Africa. Besides being a main source of carbohydrates for over 500 million inhabitants of tropical countries (Aurore et al. 2009), banana is also of major economic significance, as this fruit contributes a considerable portion of the annual income for the small stakeholders (Bello-Pérez et al. 2012; Zhang et al. 2005).

There are more than 1000 varieties of banana produced and consumed in the world, among which three common species of Musa (*Musa cavendishii*, *Musa paradisiaca*, and *Musa sapientum*) are widely grown. *M. cavendishii*, known as dessert banana, is sweeter and less starchy than *M. paradisiaca*, while *M. sapientum*, known as true banana, is usually eaten raw when fully mature (Mohapatra et al. 2010).

Dessert bananas, at the fully ripe stage, are mostly eaten raw or used in a variety of desserts (Gibert et al. 2009). Cooking bananas, which are consumed at different stages of maturity, are mostly consumed in the cooked form. Consumers often prefer one variety over the other, based on the cooking method and consumption preference. Bello-Pérez et al. (2012) noted that the literature lacks information on the textural behavior of banana products during thermal processing, and also on hot textural characteristics linked to consumer perception of texture and mouthfeel. This chapter focuses on ripe banana processing technologies, processed products, and nutritional profile. The processing of dried banana products and green bananas are covered separately in Chapters 7 and 8, respectively.

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Processing Technologies

Harvesting of bananas is usually done in the pre-climacteric phase when they reach full mature green stage. The green matured fruits are processed as such or ripened and processed further into traditional or industrial scale products. Depending on end-use, the ripening can be controlled with the use of chemicals to be accelerated (for example by using ethephon) or delayed (for example by using nitrous oxide, salicylic acid, and 1-methylcyclopropane). Bananas are susceptible to chilling injury; various researchers have suggested that mature green bananas can be stored at 13 °C for 3–4 weeks without any symptom of chilling injury (Dauthy 1995). González-Aguilar et al. (2010) reported that a variety of postharvest stress-type treatments and interventions have been developed to preserve fruit quality (Figure 6.1), with many of these treatments also applicable to banana processing.

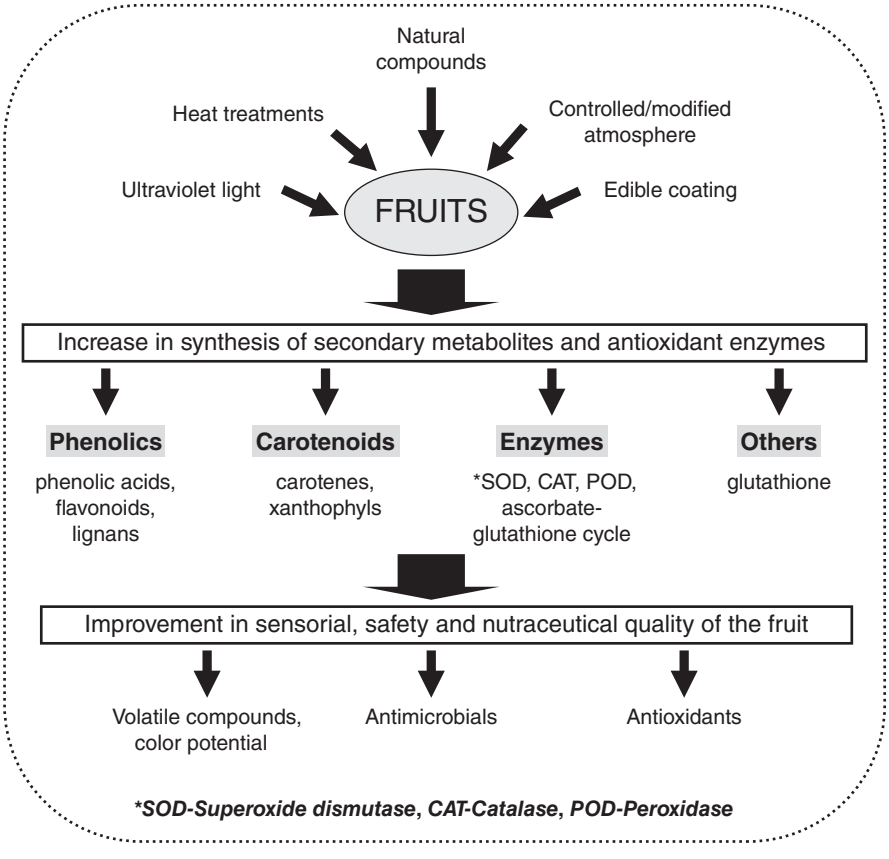

Figure 6.1 Controlled postharvest stress-type applied to tropical fruits which induces the synthesis of secondary metabolites and an antioxidant enzyme system increasing their sensorial, safety and nutraceutical quality. Source: González-Aguilar et al. (2010). Reproduced with permission of Elsevier.

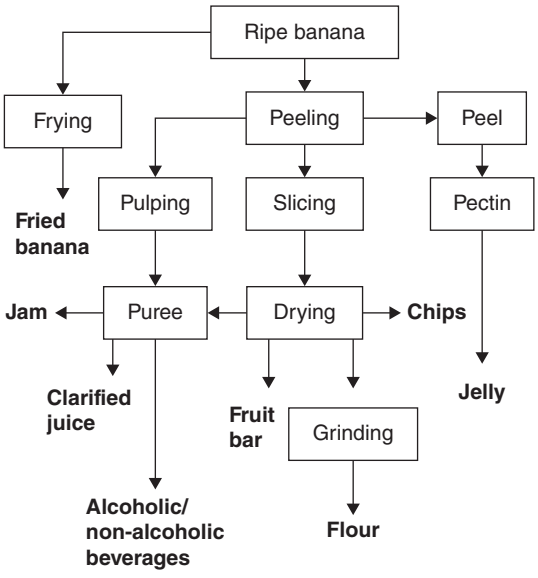

Figure 6.2 Various products obtained from processing ripe bananas. Source: Adapted from Mohapatra et al. (2011).

Most bananas are consumed raw and less than 5% are processed. Prior to processing, bananas are cleaned, dewaxed, disinfested and peeled either manually or mechanically. In most cases, manual peeling is preferred in the case of green bananas as the pectin has not yet degraded and separated from the endocarp. In comparison, it is easier to peel ripe bananas, which is done by passing the bananas through two steel rolls to split and separate the peel from pulp (Mohapatra et al. 2011). The various products obtained from processing ripe bananas are presented in Figure 6.2.

The banana processing technologies other than green banana processing and dried banana products are discussed in this chapter, covering both traditional and industrial-scale processes.

Ripe Banana Products

Pulp, puree, and juice account for the major processed products from ripe dessert bananas. A variety of diverse end-products are processed using pulp, puree, or juice as a base. It is noted that other products, except for baby foods, are not processed on a scale similar to pulp, puree, or juice.

Banana Pulp and Puree

Banana pulp/puree is prepared by crushing ripe bananas, with or without water and preserving by one of the following three methods: canning aseptically, acidification followed by normal or hot-fill canning, or quick freezing. A typical process of banana puree production is shown in Figure 6.3. The puree thus obtained is used in bakery products, baby foods,

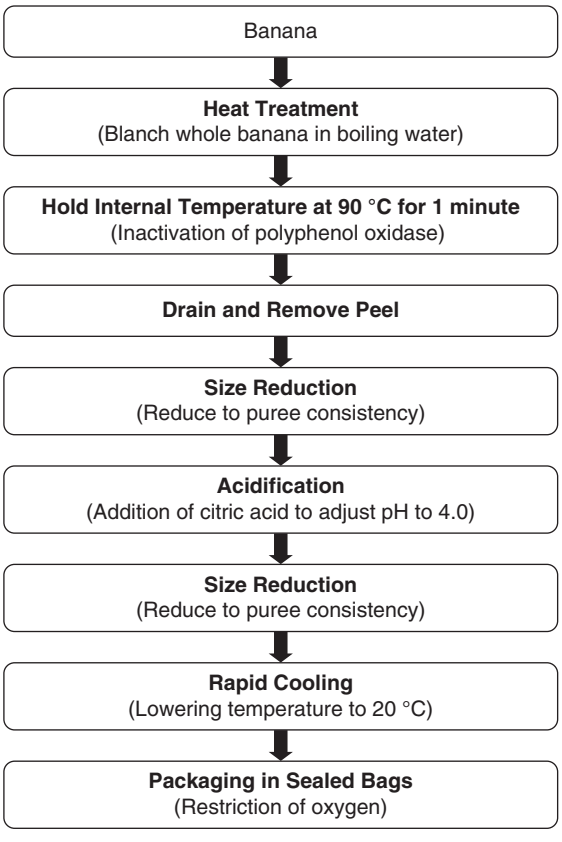

Figure 6.3 Detailed process flow diagram of banana puree processing. Source: Yap et al. (2017). Reproduced with permission of Elsevier.

smoothie production, juice processing or processed into dried powder. Further, it can also be added to mixed juices to provide body to the beverage in addition to acting as a source of sugar and as a filler. Adding banana can also supplement potassium in mixed fruit juices and smoothies. Products containing banana pulp get easily discolored during processing and storage due to the enzymatic browning of phenolic compounds by polyphenol oxidase activity. The use of anti-browning agents such as sodium metabisulfite and ascorbic acid can be used to reduce or inactivate the browning enzymes. Thermal processing is often applied to ensure microbial as well as enzymatic inactivation in banana pulp processing (Mohapatra et al. 2011). From the consumers' perspective, color or appearance of a food product is the single most important factor among all other quality attributes. If the color of a product, such as banana puree, is not acceptable or attractive, the consumer is less likely to purchase it regardless of its excellent texture, flavor, taste, or other quality attributes.

Aseptic canning is widely applied to process the bulk of the world's fruit purees. Peeled, ripe fruits are conveyed to a pump which forces them through a plate with ¼-in. holes, then into a homogenizer. The homogenized product goes through a centrifugal de-aerator, and into a receiving tank with 29-in. vacuum, where the removal of air helps prevent discoloration by oxidation. The puree is then passed through a series of scraped surface heat exchangers where it is sterilized by steam, partially cooled, and finally brought to filling

temperature. The sterilized puree is then packaged aseptically into steam-sterilized cans or polyethylene bags followed by seaming or sealing (Dauthy 1995).

Banana Juice

Juice is one of the major processed products from bananas. Juice extraction is achieved by mechanical press and/or by enzyme application using pectinolytic action of pectinase and polygalactouronase (Lee et al. 2006). Quality issues associated with banana juice processing primarily include browning caused by polyphenol oxidase and peroxidase enzyme activity, high tannin content, and loss of ascorbic acid during thermal processing. Banana varieties having low peroxidase activity such as *Berangan* and *Red Macabu* are preferred by the banana processors for being less susceptible to browning and chilling injury during handling and transportation (Yousaf et al. 2006). Novel processing technologies, such as high pressure processing (HPP), pulsed electric field (PEF), or ohmic heating may be applied to manage browning in processed banana products.

Other banana juice quality issues are linked to challenges in obtaining clear juice from banana due to the pectin settling, action of polyphenolic compounds and bonding of proteins to form haze, foam and cloudiness apart from browning of the juice, all leading to reduced consumer acceptability (Mohapatra et al. 2011). Commercially, a number of enzyme treatments are applied to obtain clarified juice, such as amylase reaction for starch hydrolysis, pectinase activity for depectinization, followed by fining (or refining) using bentonite and gelatin for removal of polyphenol compounds. The final clarified product is thus obtained by removal of residues through microfiltration (Lee et al. 2006, 2007). Other methods to obtain clarification of banana juice are esterification, application of lime, thermal treatment, centrifugation, ultrafiltration, and homogenization (Sims et al. 1994). A detailed banana juice extraction and refining process is shown in Figure 6.4.

Browning due to ascorbic acid losses can be controlled by dipping bananas into sodium metabisulfite or ascorbic acid solution prior to thermal treatment. Banana juice thus produced is further utilized to make value-added fermented and unfermented beverages. The clarified juice can be added to fruit blends as a natural source of sugar. This is prominently done by deionizing the banana juice to obtain a de-flavored clarified banana juice product, suitable for increasing the sweetness of the fruit juice blend without adding banana flavor to the formulation. De-flavored juice is obtained from ripe bananas through homogenization of the pulp, enzyme treatment, deaeration of the volatile flavoring compounds, and condensation of the volatiles (Sole 1993). When processing banana using high temperatures, precaution has to be taken as the flavoring components such as amyl acetate, amyl propionate, and eugenol are heat-sensitive (Boudhrioua et al. 2003).

Small-scale extraction and processing of banana juice involves manually working the pulp and this process has also been mechanized to some extent. Banana pulp is mixed with grass/straw and agitated manually or mechanically until the juice is released. Improvements to this traditional process have included replacement of grass with polyethylene strips and the pulp/polyethylene blend being mixed using a dough mixer until juice separation (Bello-Pérez et al. 2012). Juice yields of 54–80% from peeled fruit pulp have been reported depending on the banana variety used (Kyamuhangire et al. 2002).

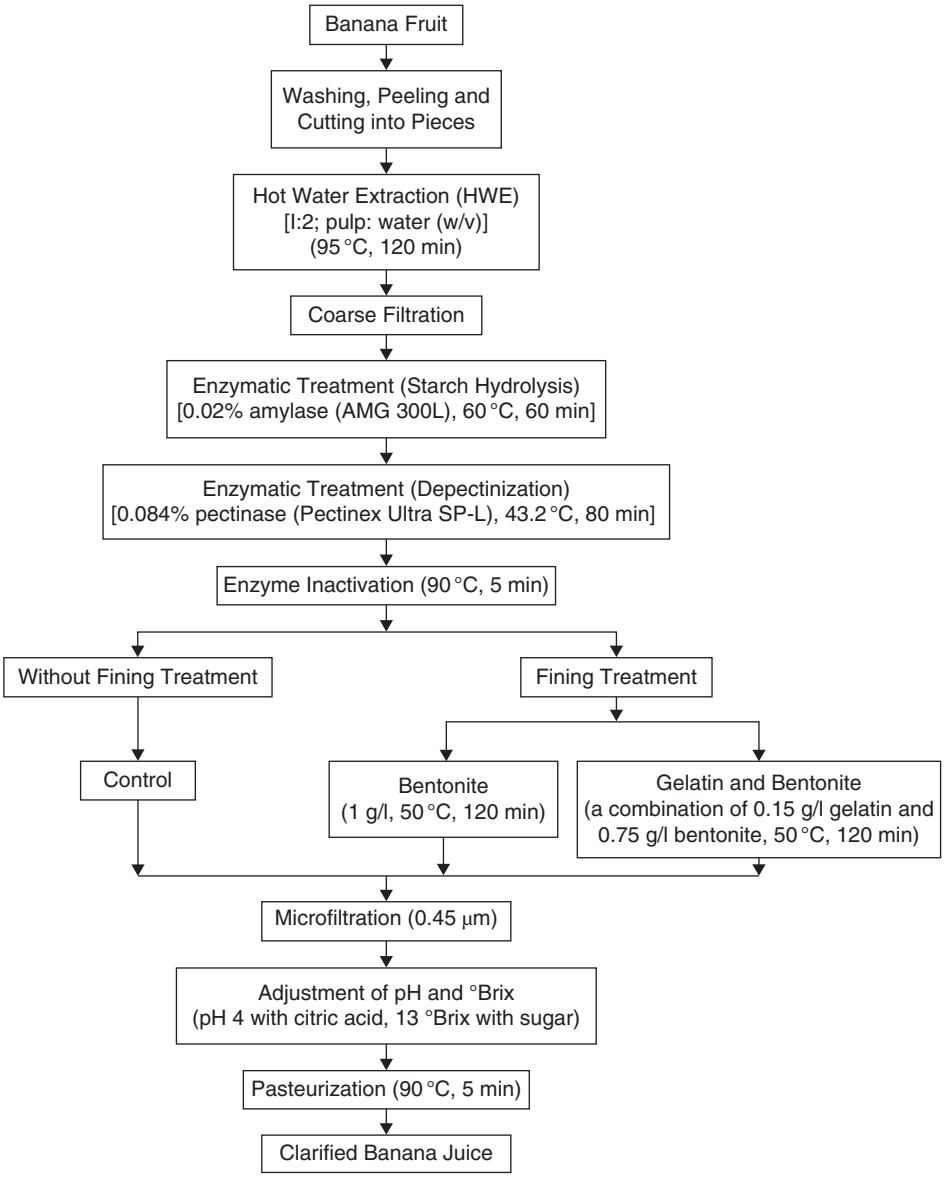

Figure 6.4 A typical flow chart for processing clarified banana juice. Source: Lee et al. (2007). Reproduced with permission of Elsevier.

The commercial process to extract banana juice typically involves hot water, which results in maximizing juice yield and optimizing color and flavor (Bello-Pérez et al. 2012; McLellan 1996). Bananas are peeled and sliced, followed by mixing in hot water, which, besides inactivation of enzymes, breaks down the pulp and facilitates efficient extraction of juice (Luh and Woodroof 1975). The raw extracted banana juice is turbid, viscous, and grayish in color. Starch and pectin are the primary contributors to juice turbidity and viscosity, and enzymatic treatment that degrades the pectin is commonly used for the clarification of banana juice (Kyamuhangire et al. 2002; Lee et al. 2006). To improve quality, the banana

juice extraction process was optimized using response surface methodology by Lee et al. (2007). It was demonstrated that the different variables (extraction time and temperature) for hot-water extraction of banana juice significantly affect the juice yield, total soluble solids, aroma, and taste of the juice.

Sagu et al. (2014) developed a process to extract banana juice using a commercial pectinase enzyme at relatively lower temperature and used response surface methodology to optimize the process parameters. The temperature of incubation (30–60 °C), time of reaction (20–120 minutes) and concentration of pectinase (0.01–0.05% v/w) were the independent variables, whereas, viscosity, clarity, alcohol insoluble solids, total polyphenol, and protein concentration were the responses. Their results showed a significant reduction of alcohol insoluble solids (Figure 6.5) and viscosity, which was dependent on the reaction time and pectinase concentration and reduction of polyphenol and protein concentration with temperature. Further, depectinization kinetics were also studied at optimum temperature and variation of kinetic constants with enzyme dose. A first-order rate equation was fitted to depectinization kinetics and the rate constant was found to vary linearly with enzyme concentration.

Yousaf et al. (2010) investigated the effect of inulin and oligofructose fortified clarified banana juice during 8-week storage at 4, 25, and 35 °C. Changes in selected physicochemical characteristics (pH, total soluble solids, titratable acidity, sucrose, reducing sugars, and turbidity), microbial count and sensory quality were evaluated. No differences were observed for pH and titratable acidity for all the stored juice samples. However, increase in turbidity was observed in all the juice samples, whereas juice samples stored at 35 °C recorded the highest increases. No microbial growth was observed for any of the juice samples stored at the three temperatures. Sensory results for taste, flavor and odor revealed no difference until week 7 of storage; however, the overall acceptability of the juice stored at 4 °C was rated highest as compared with juice samples stored at 25 and 35 °C.

The feasibility of high pressure homogenization (HPH) for the production of banana juices was studied by Calligaris et al. (2012), using prototype equipment working up to 400 MPa and a lab-scale homogenizer working up to 150 MPa. Temperature, microbial load, pectate lyase activity, color, and viscosity of the homogenized samples at increasing pressure

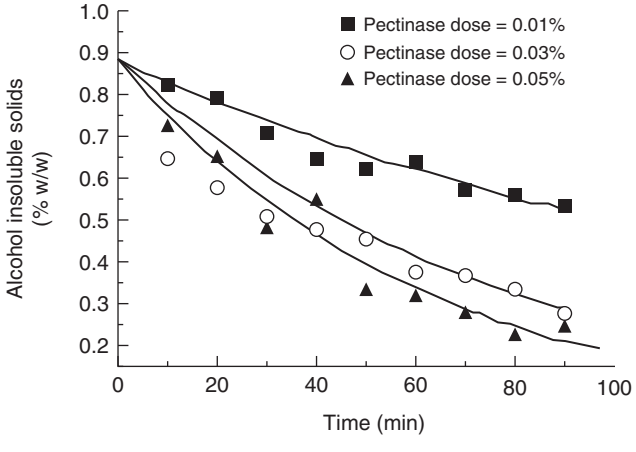

Figure 6.5 Effect of pectinase concentration (v/w) and treatment time on alcohol insoluble solids of banana pulp at 33 °C. Source: Sagu et al. (2014). Reproduced with permission of Elsevier.

were evaluated. It was shown that pressures higher than 200 MPa were needed to obtain 4-log reduction of total mesophilic bacteria and pectate lyase inactivation. It was suggested that HPH treatments could be a reliable technological alternative to conventional heat treatments for the production of value-added fruit juices.

Fresh-Cut Banana

Fresh-cut products have been one of the fastest growing segments of the food industry (Ma et al. 2017). Fresh-cut or minimally processed products are defined as any fresh fruit or vegetable or any combination thereof that has been physically altered from its original form but remains in a fresh state (Laurila and Ahvenainen 2002). However, the fresh-cut products undergo color degradation, resulting from the action of mainly two enzymes, polyphenol oxidase and peroxidase. In addition to visible color changes, these enzymes impair not only the other sensory properties, hence, the marketability of the product, but often lower its nutritive value as well (Vamos-Vigyazo 1981; Pilizota and Sapers 2004).

Banana fruit in the fresh-cut form has not been researched and developed to a scale similar to that of melons or some other fruits marketed in this form. Limited studies are available on the processing and quality aspects of fresh-cut bananas (Vilas-Boas and Kader 2006; Bico et al. 2009), these researchers explored the effect of edible coatings and/or controlled atmosphere on the physicochemical properties and the microbiological quality. Bello-Pérez et al. (2012) reported that major applications of fresh-cut bananas are in the food-service sector, mostly in selected fruit salads or as a garnish on desserts.

Canned Banana Slices

Canning is typically not a method of choice for the commercial processing of bananas. Any canning of banana reported in the literature has been mainly for experimental purposes only (Bello-Pérez et al. 2012). Karthiayani and Devadas (2007) processed three banana varieties (*Poovan*, *Rasthali*, and *Red Banana*) for canning quality evaluation. Bananas were peeled, sliced (10 mm thickness) and filled into 301 × 205 cans followed by the addition of 20, 25, or 30 °Brix sugar and jaggery (non-centrifuged cane sugar) syrup. The cans were exhausted in hot water bath for 8 minutes, immediately seamed, and thermally processed at 121 °C for 25 minutes. The textural analysis showed that *Rasthali* offered more resistance to cutting, penetration and compression followed by *Poovan*. *Red Banana* in 30 °Brix syrup after 135-day storage exhibited the poorest texture as it disintegrated during compression.

Dauthy (1995) reported that best-quality slices are obtained from fruit at an early stage of ripeness. The slices are processed in a syrup of 25 °Brix with pH about 4.2, and in some processes calcium chloride (0.2%) or calcium lactate (0.5%) are added as firming agents.

Banana-Based Baby Foods

Traditionally, infant cereal prepared from rice was considered the most common first food for infants. However, banana and banana products (juice and puree) have become an important part of commercially available baby foods since the mid-1980s (Bucheli and Read 2006; Fox et al. 2004). A list of commercially available banana-based baby foods is presented in

Box 6.1. Typically, baby foods are prepared using non-GMO fruit, with no added artificial flavors or color. In recent years, organically grown and processed fruits have been used on an increasing scale in baby foods, especially, in the developed countries. Bananas are also convenient to use, i.e., easy and quick incorporation, for home preparation of nutritious baby foods.

Box 6.1 A Sampling of Banana-Based Baby Food Products

- Applesauce with bananas
- Apple-banana juice
- Banana juice with low-fat yogurt
- Orange-apple-banana juice
- Bananas, strained
- Banana apple dessert
- Banana yogurt dessert
- Banana with mixed berries
- Bananas with apples and pears, strained
- Banana pudding
- Bananas and pineapple
- Bananas and strawberry
- Bananas and orange
- Fruit cookie
- Mixed cereal with applesauce and bananas
- Mixed cereal with bananas (dry, instant)
- Oatmeal with applesauce and bananas
- Oatmeal cereal with bananas (dry, instant)
- Plums, bananas, and rice, strained
- Rice cereal with applesauce and bananas
- Rice cereal with bananas (dry, instant)

Source: USDA (2019).

Intermediate-Moisture Banana Products

A method for producing an intermediate-moisture banana product for sale in flexible laminate pouches was reported by Dauthy (1995). Banana slices were blanched and equilibrated in a solution containing glycerol (42.5%), sucrose (14.85%), potassium sorbate (0.45%), and potassium metabisulfite (0.2%) at 90 °C for 3 minutes to give a moisture content of 30.2% (Dauthy 1995).

Optimal environmental conditions and adequate packaging materials can be used to guarantee high quality of intermediate-moisture banana products through shelf life, as reported by Yan et al. (2008). These researchers investigated the influence of environmental conditions on quality parameters of intermediate-moisture content (IMC) banana and identify the critical quality parameters during storage. IMC banana samples were placed in air-tight containers and stored according to a two-level full factorial design with four factors, i.e., storage temperature, relative humidity, light level, and air composition in the container. It was found that temperature and relative humidity were the most influential environment factors for color quality (Hunter L values), browning index, rehydration capacity, and overall acceptance for IMC banana. Moisture content and water activity were the critical instrumental quality parameters of IMC banana during storage.

Unfermented Banana Beverages

In a typical process to obtain an unfermented banana beverage, peeled ripe fruit is cut into pieces, blanched for two minutes in steam, pulped and pectinolytic enzyme added at a concentration of 2 g enzyme per kilogram of pulp, then held at 60–65 °C and 2.7–5.5 pH for 30 minutes (Dauthy 1995).

In a simpler method, lime is used to eliminate pectin. Calcium oxide (0.5%) is added to the pulp and after holding for 15 minutes, this is neutralized giving a yield of up to 88% of a clear, attractive juice. In another process banana pulp is acidified, and steam-blanched in a 28-in Hg vacuum which ensures disintegration and enzyme inactivation. The pulp is then conveyed to a screw press, and the resulting puree diluted (1:3) with water, and the pH adjusted to 4.2–4.3 by further addition of citric acid, which yields an attractive drink when this is centrifuged and sweetened (Dauthy 1995).

Banana juice which is low in protein can also be fortified with other protein source such as whey protein concentrate, to be consumed as unfermented fortified beverage. Banana pectin on esterification has the ability to improve the functional properties of whey protein by the improved pectin–protein bonding and can be stabilized by ultra-high temperature (UHT) treatment (Koffi 2003).

Yadav et al. (2010) explored the feasibility of developing a whey-based banana herbal beverage, with added mint (*Mentha arvensis*) extract up to 4%. The storage stability of the beverage was studied at 7 °C for 20 days. The sensory scores and overall acceptability of the beverage improved with a corresponding increase in mint extract from 0 to 2%. The higher levels of mint extract (3 or 4%) decreased the sensory quality of the beverage significantly. Acidity and reducing sugars increased during storage while pH experienced a decrease. The overall acceptability of the beverage was not desirable after 15 days of refrigerated storage. They indicated that besides excellent sensory and nutritional properties of mint extract, its addition could potentially enhance the therapeutic, prophylactic and antibacterial properties of whey-based banana beverage. Koffi et al. (2005) also evaluated the storage stability and sensorial characteristics of a beverage made by blending whey and banana juice. The product was sour, sweet and smooth, and the classic banana flavor was not detected.

Fermented Beverages

Fermented beverages such as beer and wine are industrially produced from banana, though at a smaller scale than conventional products. The clarified banana juice, which is rich in sugar and minerals with low acidity, is suitable substrate for fermentation (Mohapatra et al. 2011). It can be used as adjunct in beer making for improving the volume of ethanol production in case of all malt-wort beer; which results in a dark colored beer, probably due to the activity of browning enzymes (Carvalho et al. 2009). Bananas having high astringency that are not consumed by cooking, could be used for making beer (Karamura and Pickersgill 1999). The juice obtained by crushing and straining peeled ripe banana is mixed with water and crushed sorghum and allowed to ferment for up to 72 hours, which results in a light beer with low alcohol (2–5%). On the other hand, pure banana juice produces a strong alcoholic (11–15%) beer (Davies 1993). For wine production, the application of enzymes like pectinase and α-amylase to the banana pulp degrades the pectin and contributes to starch saccharification and liquefaction, respectively, making it desirable for fermentation of wine (Cheirsilp and Umsakul 2008). Since banana is cheaper than other fruit substrates for wine, it can be successfully used as an alternative in banana growing regions.

Banana Pectin for Jam and Jelly

Ripe banana contains significant amounts of pectin in the peel (21.3%) and to a lesser extent in the pulp (Emaga et al. 2008). Ultrasonication has been applied for extraction of pectin from apple pomace (Bhaskaracharya et al. 2009), and a similar procedure may be suitable for the extraction of pectin from banana peel and pulp. Pectin has uses in mixed fruit or banana jam and jelly preparations. A small amount of banana jam is made commercially by boiling equal quantities of fruit and sugar together with water and lemon juice, lime juice or citric acid, until setting point is reached at ~67 °Brix (Dauthy 1995).

Indigenous Banana Products

Table 6.1 presents a summary of some indigenous products made from banana fruit and its plant parts in different parts of the world. In Africa, diverse dishes using banana and plantain are prepared, e.g., in Uganda, banana is mixed with peanuts and spices, and the blend is wrapped in banana leaf and cooked by steaming; this dish is named *Matooke*. This product is widely used for weaning foods owing to its high fiber content and desirable viscosity

Table 6.1 New and indigenous products from banana.

Product	Country	Characteristics
Empanada	Ecuador, Colombia	Unripe banana, cooking bananas and plantain
Matooke	Uganda	Banana is mixed with peanuts and spices, the blend is wrapped in banana leaf and cooked by stewing
Fufu	Nigeria	Plantain and cassava are mixed
Plantain tarts	Jamaica	Ripe banana pulp mixed with bakery ingredients
Ketchup	Philippines	Banana pulp mixed with gums and spices
Chips and cake	Cameroon	Banana and plantain pulp mixed with flavors and bakery products
Stem juice	India	Green part of the stem peeled and its white inner portion cut into small pieces; pieces mechanically crushed to obtain juice
Tonto, Lubisi	Uganda	Pulp is mashed and the juice is fermented naturally
Spirit (with ~24% alcohol)	India	Banana juice blended with coarse sorghum flour and inoculated with *Saccharomyces cerevisae*
Spaghetti	Mexico	Unripe banana flour is blended with durum wheat flour. Another methods uses banana starch isolated from unripe bananas and blended with durum wheat flour
Bread	Mexico	Unripe banana flour is blended with bakery ingredients

Source: Adapted from Bello-Pérez et al. (2012).

(Bello-Pérez et al. 2012; Bukusuba et al. 2008). In Nigeria, plantain and cassava are mixed to make *Fufu*. In Jamaica, plantain *Tarts* are produced as small business that provides a good source of income. In the Philippines, bananas are used to produce a ketchup-type product, with a similar consistency and texture. Roasted unripe bananas are also used as coffee substitute in some countries (Bello-Pérez et al. 2012). Banana pulp is mashed and diluted to obtain a juice that can be fermented naturally to make traditional beer in Uganda, called *Tonto* and *Lubisi* that has a low alcohol content of 2% (Mwesigye and Okurut 1995). Banana stem juice was investigated by Singh et al. (2007) for its potential to control hypoglycemia. The results showed the presence of hyperglycemic effect in stem juice and the possibility of its antidiabetic potential in patients with type-2 diabetes.

Novel Processing Technologies

The consumer demand for fresh-like minimally processed foods has increased in recent years. To fulfill these requirements, various novel technologies are being developed by researchers worldwide that are capable of providing safe, high quality food. The success of such technologies is somewhat mixed with respect to large-scale commercialization. Some of the novel non-thermal technologies include high pressure processing (HPP), pulsed electric field (PEF), pulsed light application, irradiation, and ultrasonication (discussed in detail in Chapter 9). Among these technologies, HPP has emerged as the most promising one and is discussed briefly here.

HPP technology involves application of hydrostatic pressure in the range of 100–900 MPa that is instantaneously and uniformly distributed throughout the packaged or non-packaged food product (with or without thermal treatment), which renders the food shelf stable due to inactivation of enzymes (Terefe et al. 2014) and destruction of microorganisms (Knorr et al. 2011). In addition to increasing the product shelf life, HPP enhances food quality in terms of better retention of nutrients, minimal changes in appearance and desirable texture than conventional processing methods (Oey et al. 2008). Although there is a slight increase in temperature during pressurization, that rise is insufficient to degrade the nutritional compounds present within the food (Deliza et al. 2005).

The effect of HPP on low molecular weight food components such as flavoring agents, pigments, vitamins, etc. is minimal as covalent bonds are not affected by the pressure (San Martin et al. 2002). Pressure-treated foods have sensory properties similar to fresh products (Oey et al. 2008), which is a major advantage in fruit pulp or juice processing as it fulfills the consumer demand for healthy, nutritious and natural products. HPP of fruit pulps and juices produces foods of high quality, with greater safety, and increased shelf life (Rastogi et al. 2007). Being fluid in nature, the transmission of pressure happens uniformly in fruit pulps and juices following the isostatic rule, unlike in the thermal treatment. It finally leads to a shorter processing time as the pressure treatment is independent of the product's size and geometry (Rastogi et al. 2007).

Industrial application of high pressure to fruit pulps and juices restricts the pressure range from 400 to 800 MPa for optimum processing, as this range of pressure induces reversible and irreversible changes in several micro- or macromolecules in the medium (Heinz and Buckow 2010). Pasteurization and sterilization of fruit pulp and juice products are achieved

by the combination of high pressure with mild heat treatment, as pressure alone is not sufficient to destroy foodborne pathogens. When combined with pressure, the process temperature varies from 10 to 40 °C for the pasteurization (Deliza et al. 2005) and 40 to 90 °C for the sterilization (Barba et al. 2012).

HPP, when coupled with other treatments such as blanching, freezing, dehydration, and frying, has yielded better results in terms of shelf stability compared with the conventional processed products (Rastogi et al. 2007; Ramirez et al. 2009). Since HPP can be applied to a range of products from solid to liquid, the processed banana products can have suitable use for HPP and pressure-assisted processing for shelf-stable products. This has also been shown by a number of researchers who have worked on the processing of banana products using HPP alone or in combination with other technologies (Verma et al. 2014; Li et al. 2015; Xu et al. 2016).

Hurdle Technology

The consumer demand for fresh and minimally altered foods has increased in recent years, which has prompted researchers to use hurdle technology integrating basic principles of food preservation with thermal and non-thermal technologies for superior quality foods with longer shelf life while retaining high quality compared with their conventionally preserved/processed counterparts. The quality and shelf life of foods is majorly affected by microbial contamination and enzymatic changes faced during any postharvest processing chain of fruits. These issues can be managed with intelligent combination of various technologies at sub-intensity levels to create hurdles for the quality deteriorating factors, thus preserving quality and providing safe to consume foods with long shelf life. Similar techniques can be used to preserve and process banana puree, juice and fresh banana slices (Cullen et al. 2012).

Nutritional Profile

The nutritional profile of raw banana and selected banana products (nectar, fried and baked banana) is shown in Table 6.2; the nutritional values shown are those reported by the USDA (2019). Some differences can be anticipated in the composition of raw banana and banana products in other parts of the world, primarily due to different climatic and soil conditions, agricultural practices, postharvest handling and processing techniques, and so on. Additionally, varietal and ripeness differences can also contribute to variations in the composition of raw and finished products. For example, Aurore et al. (2009) reported higher protein and carbohydrate content in the unripe fruit than in its ripe state, with higher carbohydrate level in plantain than in the sweet or dessert banana.

A medium banana (118 g), provides 105 kcal of energy and 422 mg of potassium, whereas a large banana (136 g) provides 121 kcal of energy and 487 mg of potassium. Raw bananas available in North American markets are generally of the large size, in contrast, small size bananas are more common in most Asian countries. The potassium content (mg/100 g) of bananas (358) is significantly higher than that of some other commonly consumed fruits,

Table 6.2 Nutritional profile of raw bananas and selected processed products (per 100 g).

	Unit	Raw	Nectar	Fried, ripe	Baked	Chips
Proximate, Energy, and Sugars						
Water	g	74.91	81.17	67.58	64.93	4.3
Energy	kcal	89	70	147	127	519
Protein	g	1.09	0.38	1.14	1.22	2.3
Total lipid (fat)	g	0.33	0.12	6.41	0.38	33.6
Carbohydrate, by difference	g	22.84	17.99	23.99	32.55	58.4
Fiber, total dietary	g	2.6	0.9	2.7	2.9	7.7
Sugars, total	g	12.23	14.26	12.85	20.49	35.34
Minerals[1]						
Calcium	mg	5	4	5	6	18
Magnesium	mg	27	10	28	30	76
Phosphorus	mg	22	8	23	25	56
Potassium	mg	358	126	338	361	536
Sodium	mg	1	2	1	1	6
Vitamins[2]						
Vitamin C, total ascorbic acid	mg	8.7	3	6.4	9.6	6.3
Niacin	mg	0.665	0.233	0.629	0.665	0.71
Folate, total	µg	20	7	11	14	14
Choline, total	mg	9.8	3.4	10.3	11.1	21.3
Vitamin A, RAE	µg	3	1	2	3	4
Carotene, beta	µg	26	9	20	24	34
Carotene, alpha	µg	25	9	20	23	32
Lutein + zeaxanthin	µg	22	8	17	21	46
Vitamin K (phylloquinone)	µg	0.5	0.2	7.7	0.6	1.3

[1]For all products: iron, zinc, and copper = <1 mg, selenium = 0.4–1.0 µg.
[2]For all products: thiamin, riboflavin, vitamin B6, and vitamin E = <0.1 mg.
Source: USDA Nutrient Database (USDA 2019).

e.g., apples (107), apricots (232), grapes (191), mangoes (168), oranges (200), peaches (190), pineapples (109), and strawberries (153) (USDA 2019). The significantly high potassium and low sodium contents in banana are optimum for people suffering from hypertension and on a low-sodium diet (Appel et al. 1997). Among processed products, fried and dried banana slices have high energy values due to oil uptake during frying as well as water removal during frying and drying.

Banana, especially at the unripe stage, is considered the richest non-processed food source of resistant starch (RS) (Bello-Pérez et al. 2012). RS is not digested in the human small intestine and has a reduced caloric content, with its physiological effects comparable

with dietary fiber (Delcour and Eerlingen 1996). Therefore, RS has been proposed by many researchers as a nutraceutical ingredient to control obesity and overweight, which is one of the most serious public health problem worldwide (Hendrich 2010). Banana is also considered as a source of energy for athletes, as researchers have found its potential benefits for sports applications. In this regard, banana is reported to prevent muscular contractions in athletes since it contains vitamins and minerals (Qamar and Shaikh 2018). Further, a number of therapeutic activities have been reported in banana, such as antidiarrheal, antiulcerative, antimicrobial, antioxidant, hypoglycemic, wound healing, antilithiatic, and anticancer activities (Qamar and Shaikh 2018).

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7

Processing of Dehydrated Banana Products

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Introduction

The mature fruit of bananas *(Musa spp.)* is commonly consumed as a fresh product. This fresh fruit has a very limited shelf life and undergoes rapid deterioration based on physiological and microbial processes. Thus, banana has frequently been preserved by a range of cost-effective dehydration techniques. Preservation is achieved by cutting the peeled fruit into transverse slices to increase the surface area required for rapid removal of moisture during the dehydration procedure. The reduced moisture content and lowered water activity of the dehydrated products provide control of microbial pathogens and spoilage organisms. Dehydrated banana products are produced from a wide range of cultivars; however, the proper stage of harvest and ripening should assure that each possesses relatively high sugar contents and characteristic profile of aromatic compounds with the absence of bitterness and astringency.

The United States Department of Agriculture (USDA) has published useful guidelines used to describe the "degrees of ripeness" of banana. The commonly used terminology (green, turning yellow, and ripe) based on peel color characteristics is delineated on a seven-point scale as presented in Table 7.1. The use of the proper stage of banana ripeness will have a profound impact on final product quality attributes.

Commercial Dehydrated Banana Products

A wide array of shelf stable dehydrated banana products is commercially available. These products can be classified as: slices (trail mix, breakfast cereals, snacks) and banana meal/powder (food ingredients, baked products). These are commonly produced within the region of agricultural production and provided to global markets as value-added products. The regional processing and packaging avoids the cost of shipment of high moisture fresh weight bananas and dramatically improves the shelf life and security of the product. Processed and bulk packaged products are economically shipped in bulk totes and suitable for subsequent retail packaging. Dehydrated banana products may be composed of intact slices or milled powders. Slices are commonly used for direct consumption as

Handbook of Banana Production, Postharvest Science, Processing Technology, and Nutrition, First Edition.
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Table 7.1 USDA description of different stages of banana ripeness.

Green	1. Green
	2. Light green, breaking slightly toward yellow
Turning yellow	3. Yellowish-green, more green than yellow
	4. Greenish yellow, more yellow than green
Ripe	5. Yellow with green tips
	6. Yellow
	7. Yellow, flecked with brown

Source: USDA-AMS (2004).

trail mix blends with other fruits or nuts, breakfast cereals, or as snack foods. Banana meal/powder is typically used as a food ingredient highly suitable for baked products or in a myriad of formulated foods (pudding mixes, fruit purees, or beverages).

Dehydration Principles and Processes

The dehydration of foods has been a primary means of preservation from antiquity. The earliest methods of drying included exposure of foods to direct sun light to accelerate moisture evaporation from the product surface. This technique is particularly well suited to arid climates and in fact accounts for much of today's dehydrated banana production.

The processes and mechanisms of food dehydration have been thoroughly studied and are generally well understood. The principles of water activity are directly associated with the viability of both pathogenic and storage microbial organisms (Barbosa-Canovas et al. 2007; Labuza 1980). Microbial control of pathogenic organisms is paramount to the safety of a wholesome food supply; however, nonpathogenic spoilage organisms can result in loss of product quality stability and significant economic losses as well.

The physics of heat and mass transfer of water occurring during the drying process is, in part, due to the vapor pressure deficit (VPD) developed between the product and the surrounding environment. Much work has been conducted by food engineers to understand and optimize the drying process (Karim and Hawlader 2005; Hadrich and Kechaou 2009; Jannot et al. 2004). The moisture removal is a surface phenomenon and factors that enhance the physical conditions at the product interface have a substantial impact on the rate of dehydration. Increased product surface area is readily achieved through cutting, slicing and dicing of product and greater VPD achieved through elevated temperatures, decreased humidity of the air, and the volume and rate of air flow across the product surface.

Dehydration of foods demonstrates two distinct phases based on the rate of moisture loss. These phases are termed: (i) "constant rate" and (ii) "falling rate". Each phase is shown within an idealized drying curve presented in Figure 7.1. The constant rate drying results from moisture at the surface being transported directly to the low humidity air at a constant rate; however, as dehydration proceeds moisture within the product is transported to the product surface as vapor and this migration by diffusion occurs at a

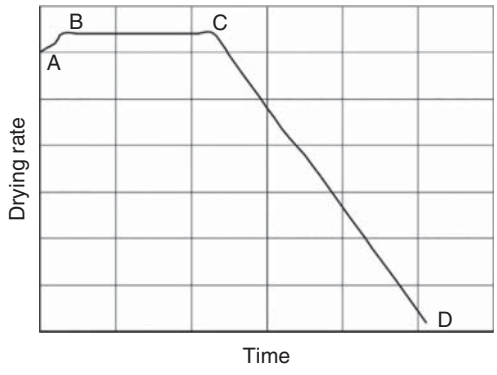

Figure 7.1 Typical drying rate curve for plant-based foods. Source: Ahmed (2018). Reproduced with permission of John Wiley and Sons.

diminishing rate (Karel 1975). The drying curve in Figure 7.1 shows discrete zones as follows:

Zone A–B (preheating period): This is observed while wet food material is exposed to hot air; initially only a minor change in moisture content occurs. The drying rate is almost zero in this zone.

Zone B–C (constant rate period): The mass of water starts to evaporate from the surface in equal intervals of time and the drying rate remains constant during this period. Material temperature is constant as well in this zone.

Zone C–D (falling rate period): During this zone, it takes more time for internal moisture to move to the surface, and evaporation of water is no longer constant with time. Thus, the drying rate declines.

Thus, the rate of moisture diffusion from within the product mass to the surface is of great importance to moisture loss (Katekawa and Silva 2006). On account of the importance of this phenomenon to commercial success, much research to measure and control the diffusivity of banana tissue has been undertaken. Moisture diffusion in sliced bananas varies with slice thickness and shape. It is generally observed that diffusion is dependent on the square of the slice thickness. Fernando et al. (2011) developed a mathematical model to characterize this behavior for the lateral thickness of the slice. However, further work is required to estimate the various dimensional diffusion (axial and radial) components.

Thuwapanichayanan et al. (2011) reported the effective moisture diffusivity and various quality attributes (shrinkage, color, texture, and microstructure) of banana slices during drying. Bananas were prepared as 3 mm thick slices, submerged in ascorbic acid solution and dried at four temperatures (70, 80, 90, and 100 °C). The effective diffusivity was shown to decrease markedly with moisture content during the first falling rate period and changed slightly in the second falling rate period.

Demirel and Turhan (2003) evaluated the air-drying behavior of banana slices. Various pretreatments improved color characteristics. These researchers demonstrated that moisture diffusivity increased between 40 °C and 60 °C, and decreased at 70 °C in the pretreated samples. This decrease was likely attributed to case hardening and starch gelatinization above 60 °C.

Banana Dehydration Processes and Equipment

Preparation of Bananas

Whole bananas of desired maturity are typically peeled prior to further cutting or processing. Special attention to rapid enzymatic browning must be paid prior to cross-cut or longitudinal slicing or pureeing. Hot water blanching or steam blanketing is commonly used to control undesirable discoloration. Properly prepared feedstock, specific for the dehydration method employed, is essential for final product acceptability. Rapid and sanitary handling of slices or puree is paramount.

Banana Slices and Dehydrated Chips

Numerous physical and biological factors influence the quality and integrity of dehydrated banana chips. The maturity and postharvest handling and storage have a fundamental impact on textural properties of final products (Nguyen and Price 2007). Inappropriate harvest criteria (color, solids, and composition) or extended postharvest holding may result in immature or senescent fruit that will possess suboptimal processing characteristics. Physical processing of cross cut slices requires uniform cutting equipment with sharp knives and consistent cut slice thickness. Improper cutting results in torn surfaces that will greatly influence appearance and heat and mass transfer (Van Arsdel et al. 1973; Demirel and Turhan 2003).

Banana Puree

Commuted banana pulp is prepared by heating peeled fruit and passing it through a hammer mill or finishing mill of a designated sieve size. This near homogeneous product is readily available for subsequent processing. Prepared banana puree may be frozen or aseptically packaged as single strength whole puree. Banana solids as puree may be wet sieved to various particle sizes suitable for incorporation into infant foods and various formulated foods.

Banana Flour or Powders

Dehydrated banana solids may be further concentrated and dehydrated typically using a drum drier to yield flakes or sized powders. Additionally, purees may be spray dried to produce an array of fine powders suitable for a wide range of food formulations. This approach has been used very favorably for green stage bananas (Tribess et al. 2009) or when crop conditions result in "poor quality" fresh bananas.

Pretreatments to Enhance Product Quality

Selected pretreatments have been studied as a means to enhance the quality of banana products. These have been focused on stabilizing color (e.g., water and steam blanching, ascorbic acid dips) or as processing aids to functional properties (emulsifiers, proteins, starches, and gums). Pretreatments are commonly integrated into the process stream (Dandamrongrak et al. 2002). Prepared whole bananas are typically blanched in hot water prior to slicing. The blanch time and temperature have a profound effect on dehydrated slice crispness.

Researchers have utilized various ingredient adjuncts to improve the sensory characteristics of dehydrated banana products. Farahmandfar et al. (2017) applied pretreatments of 0.7% suspensions of quince seed, almond, and tragacanth gums as edible coatings to reduce quality degradation of banana during the drying process. Results of these pretreatment dips demonstrated that improved color stability and subsequent rehydration enhancement was achieved compared with untreated controls.

Dandamrongrak et al. (2002) evaluated various pretreatments for the dehydration of banana. Four pretreatments (blanching, chilling, freezing, and combined blanching and freezing) were applied to the bananas prior to drying in a thin-layer heat pump dehumidifier dryer (50 °C, air velocity 3.1 m/s, and relative humidity of the inlet air ranging from 10 to 35%). Freezing pretreatments increased the rate of drying, perhaps due to cellular disruption and fissuring of tissue. Chilling did not enhance the drying rate. Blanching resulted in greater water absorption during preparation and thus, tended to diminish the rate of moisture loss during drying. Moisture diffusivities of bananas were reported for the process (range $4.3–13.2 \times 10^{-10}$ m^2/s).

Jeet et al. (2015) conducted studies on the effects of blanching on the dehydration characteristics of unripe banana slices. Slices were blanched (range 50–80 °C) and dehydrated at 50, 60, and 80 °C in a tray dryer with air velocity of 2–2.50 m/s. Results indicated that combined pretreatment of blanching and subsequent dehydration could be used to produce high quality dried banana slices or as a preparation process for milled banana flour. Rodrigues and Fernandes (2007) investigated the use of ultrasound as a pretreatment for dehydration of banana. Results demonstrated an increase in water diffusivity and greater than a 10% reduction in drying time.

Naknaen et al. (2016) reported the physicochemical properties and nutritional composition of foamed banana powders dehydrated by various drying methods. The foaming process of banana puree incorporated whey protein concentrate (5%) as a foaming agent and subsequent dehydration used hot air drying, vacuum drying, and freeze-drying. All the foamed banana powders contained higher total phenolic contents (TPCs), beta-carotene, thiamine, and riboflavin, as well as ascorbic acid, compared with the non-foamed (control) banana powder.

Traditional Solar Drying

Dehydration of foods by direct exposure to sunlight for preservation dates from antiquity and extends into modern agricultural and food processing practice. A diverse range of foods have been dried following preparation techniques (cutting, preheating, or sugaring and/or salting) and exposed directly to solar rays often with access to wind or circulating air currents. Although plant and animal products can be sun dried, plant products, particularly the fleshy fruits of bananas, can be successfully solar dried. Typically, it is important to provide large surface areas of exposure to facilitate moisture migration throughout the tissue and evaporation of moisture vapor from the surface. The development of a sufficient VPD between the food and the surrounding environment is essential to drive moisture from the product in a relatively short period of time. Low VPD will frequently result in quality deterioration or spoilage of the food due to delayed drying. Generally, the atmospheric relative humidity (% RH) should be less than 60% with temperatures above 30 °C recommended to

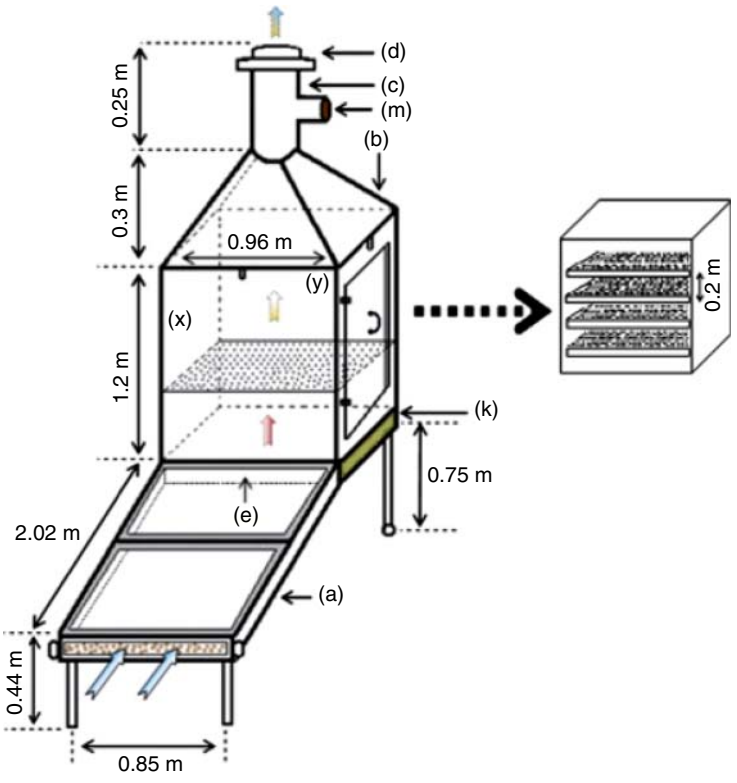

Figure 7.2 Prototype of indirect solar dryer: (a) solar collector; (b) drying unit; (c) chimney; (d) air extractor; (e) air entrance; (k) drying unit bottom side; (x) drying unit small side; (y) drying unit large side; and (m) air recycling pipe. Source: Dissa et al. (2009) Reproduced with permission of Elsevier.

achieve adequate drying rates. A typical solar dryer suitable for banana drying is shown is Figure 7.2.

The efficiency of solar drying is dramatically enhanced using a support rack or screens that enable air circulation. Reflective films or solar collecting metals aid heat distribution by both conduction and convection processes. Appropriate quality control during preparation procedures of the fresh banana slices, gentle handling and distribution during drying, and end-product handling and packaging are essential to achieve high quality marketable products.

Ekechukwu and Norton (1999) presented a comprehensive review of the various designs, details of construction and operational principles of the wide variety of practical designs of solar-energy drying systems. Two general classes of solar dryers included: (i) passive or natural-circulation solar-energy dryers; and (ii) active or forced-convection solar-energy dryers. This review highlighted appropriate applications. More recently, Amer et al. (2010) described a hybrid solar dryer designed and constructed using direct solar energy and a heat exchanger. The dryer consists of a solar collector, reflector, heat exchanger and drying chamber. The solar dryer was tested for drying ripe banana slices. The capacity of the dryer was rated to be about 30 kg of fresh banana slices (initial moisture content of 82%) to the

final moisture content of 18% (wb) during eight hours of sun light. These results compared with only 62% moisture content obtained using open sun-drying techniques. Improvements in the equipment used for solar drying have enabled more efficient banana throughput, higher quality end products (color, favor, texture), and improved sanitary controls. These developments have facilitated the entry of producers into global markets for dehydrated banana products.

Hot Air Drying (Cabinet, Tunnel)

All the fundamental principles of dehydration have been utilized to enhance the design and efficiencies of mechanical air-drying systems. Mechanical air-drying systems are well established in commercial practice of solid particulate products and consist of batch cabinet dryers and continuous tunnel dyers. The reader is referred to a series of excellent resources for these principles of dehydration (Van Arsdel et al. 1973; Demirel and Turhan 2003; Nguyen and Price 2007).

The drying of banana slices (transverse or longitudinal) is carried out on perforated trays or racked carts for batch dryers or continuous screen belts passing through an exhausted tunnel. The drying temperatures are maintained above 70 °C with high velocity air circulating through the carriers. The moisture vapor is exhausted from the cabinet or tunnel as the drying process continues. The resident time for drying the product will be highly dependent on the loading rate and the VPD achieved. Generally, fruit is dried to a moisture content of less than 20% (wb) within approximately 5 hours.

The more advanced tunnel dryers are commonly controlled by sequential zones that can be optimized for temperature, relative humidity and the rate of air flow. Such systems establish conditions that are highly suitable for economic energy use and high-quality product output.

Schematic diagrams of a continuous zone tunnel dryer and a multi-pass continuous dryer are presented in Figure 7.3.

Spray Drying

Spray drying is used to remove high volumes of moisture from fluid products to produce fine textured powders. Generally, a spray dryer consists of a large chamber (vertical or horizontal) with an atomizing spray nozzle that disperses the fluid into preheated air. Moisture is rapidly removed as the product descends in the chamber. Most commonly the spray dryer is configured as a vertical tower with the dispensing nozzle located at the apex of the chamber and the product dehydrates as it falls by gravity. High velocity air flow can be established as “counter current” or “co-current” dependent on product drying characteristics. A high pressure “timing pump” (homogenizer) is used to deliver product flow at a constant rate. The use of high solid banana purees that are preheated to inactivate enzymes and improve moisture transmission rates are readily spray dried into powders suitable as ingredients in diverse formulated foods.

The temperature and overall drying conditions dramatically influence the color, flavor, and rehydration capacity (hydration rate and water holding capacity) of the banana powders. These functional properties may dictate the processing parameters selected and their control.

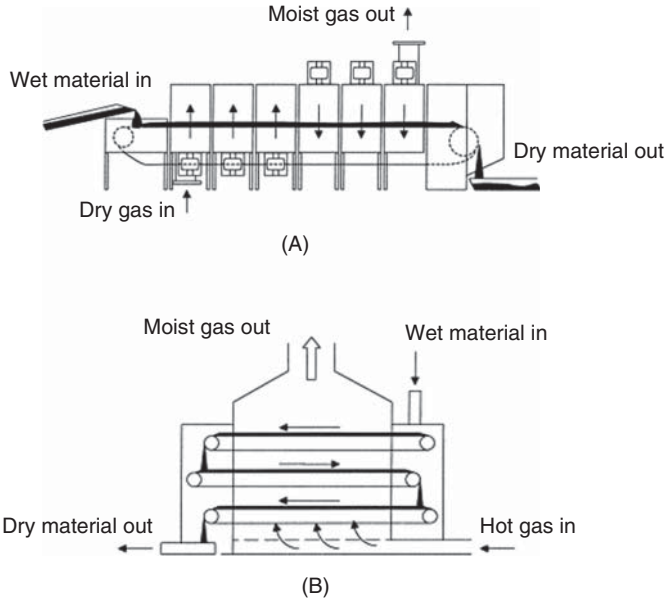

Figure 7.3 Continuous zone tunnel dryer (A) and multi-pass continuous dryer (B).

Wong et al. 2018 utilized enzymatic predigestion and addition of maltodextrins for the preparation of spray dried banana (*Musa acuminata*) powder. Pureed pulp was treated with pectolytic and cellulosic enzymes to increase liquefaction and decrease viscosity. Maltodextrin addition (10–50% w/w) to the mass was spray dried at different inlet temperatures (140–180 °C). The enzymatic liquefaction provided improved drying properties while temperature was optimized to reduce the stickiness during dehydration. Results indicated that the highest drying yield (>50%) was obtained at 150 °C with 30% (w/w) maltodextrin. The produced powder appeared to be suitable for formulation with various fruit-based products. Spray dried banana powders have potential as a readily rehydrated functional ingredient.

A typical configuration of a spray dryer used for fluid products is shown in Figure 7.4.

Drum Drying

Banana purees are commonly prepared as flakes or powders using drum drying technology. These dehydrated banana products are readily blended as a functional food ingredient. The basic design of the drum dryer is presented in Figure 7.5. Drum drying systems employ a series of counter rotating stainless steel cylinders that are heated internally with high-pressure steam. This configuration provides a large heating surface to which the liquid slurry is applied. The cylinders, which may range from 0.5 to 2.0 m in diameter, are placed in parallel with a gap termed the "nip" between them. The slurry is applied in a continuously filled "puddle" above the gap and applied to the drum surface as they rotate. Temperature, rotational speed (RPM) and product thickness/solids density are important control parameters that affect the final product quality and functionality. Dehydration occurs at the heating surface applied with a thin film of product. As the cylinders are rotated moisture is

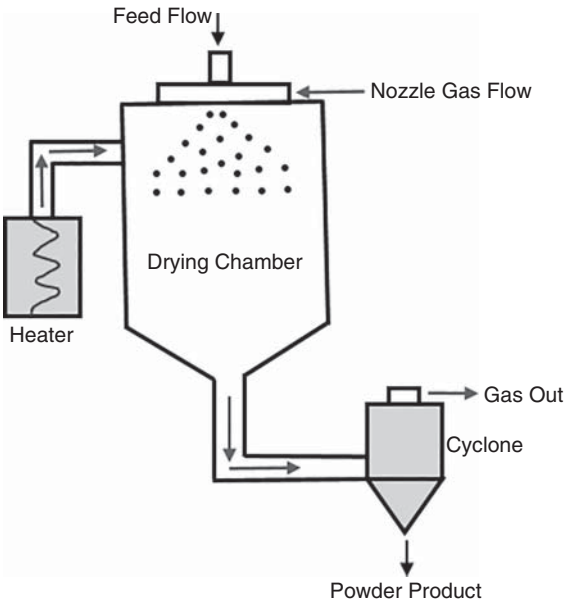

Figure 7.4 Schematic diagram of a typical spray dryer.

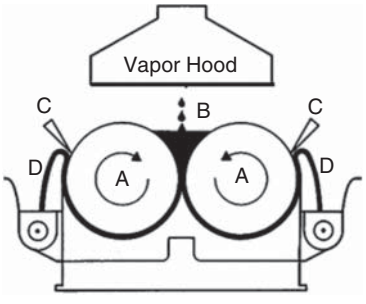

Figure 7.5 Schematic of the components of a drum dryer: A, steam-heated drums; B, product feed; C, scraper or "Doctor" blade; and D, dehydrated product. Source: Adapted from Occena et al. (1996).

driven off and exhausted as vapor. A scraper blade termed a "doctor blade" in contact with the surface removes the dehydrated product as a continuous sheet that can be milled to flakes. High solids content purees are commonly dried using drum dryers. Potatoes flakes, rice cereals, and a variety of food-based starches are successfully drum dried.

Freeze-Drying

Freeze-drying or lyophilization technology involves the principle of direct sublimation of frozen water (ice) to vapor without transition into the liquid water phase. This advanced and relatively expensive drying technology requires establishing the proper physical conditions (temperature and vacuum) to achieve the "critical collapse conditions" below the characteristic "triple point" of water where ice will sublime directly to vapor. These conditions are depicted in Figure 7.6. The batch equipment is expensive to construct and operate, thus most commercial applications are applied to high value products that achieve a highly competitive quality advantage (e.g., instant coffee). The process requires a prefrozen product to

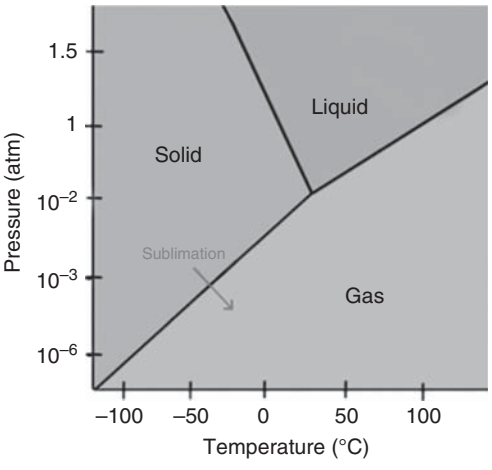

Figure 7.6 Generalized temperature and pressure conditions associated with water phases at the "triple point of water" (sublimation = solid to gas). Source: Anon. (2019).

be supported on a heating slab within a high vacuum chamber with adequate temperature control to drive the product moisture vapor to be deposited on condensing coils.

Freeze-drying systems may be supplemented with infrared (IR) or microwave heating to improve moisture removal. A major advantage of freeze-drying is in achieving a porous product with limited deformation which thus can be readily rehydrated.

The establishment of optimal freeze-drying generally requires mild product heating (typically by heating product support shelves) as a driving force for moisture sublimation. Controlled application of microwave energy can be used for this supplemental heating during the preliminary stages of drying. Jiang et al. (2014) studied changes of micro-structure and dielectric properties during microwave freeze-drying of banana chips. The dielectric properties were ε' (range 20.8–1.2) and ε'' (range 7.7–0.15). The cell size decreased as the dehydration process proceeded. The process temperature was readily controlled by microwave wattage and the overall process was accelerated.

Advanced Dehydration Technologies

Microwave energy, infrared (IR) heating, ultrasound and osmotic systems have been used discretely or in part to augment established drying processes.

Microwave Drying

Microwave energy has been used to heat food products and microwave ovens have been used extensively by consumers within the home. Microwaves are very long wavelength (1000 M) radiation that when exposed to moisture in food results in accelerated vibration of the dipolar water molecule resulting in thermal energy. Thus, this technique utilizes the water within the food and causes rapid heating throughout the mass. The energy is a function of the wattage applied by the system. Industrial microwave generators can apply relatively high energy directly to the product and result in moisture vaporization. The commercial use of microwave energy may be as the primary heating source for dehydration

of moist foods or perhaps more commonly and effectively to supplement and optimize conventional drying systems.

Ozturk et al. (2017) investigated the effects of initial moisture content and different drying methods on quality and dielectric properties of banana (*Musa cavendishii*). Dehydration using microwave energy (180, 270, 360 W) and microwave energy supplemented with IR radiation (600 W lamps) were compared. Increases in microwave power resulted in increased rate of drying and decreased processing time. Further, combining IR with microwave energy resulted in increases in moisture loss rate. Both experimental processes resulted in products of improved quality compared with the air-dried control.

Jiang et al. (2014) reported changes of microstructure and dielectric properties during microwave freeze-drying processing of banana chips. During the eight-hour process the highest drying temperature was 55 °C. The dielectric properties were ε' (range 20.80–1.20) and ε'' (range 7.74–0.15). Cell size decreased throughout the drying process as noted at the end of the falling rate phase (3–4 hours of drying). These researchers concluded that the end of the falling rate stage can be determined by these measures.

Maskan (2000) reported on the use of microwave energy in conjunction with conventional air drying of banana slices. Banana slices were dried using the following drying regimes: (i) convection (60 °C, air velocity 1.45 m/s); (ii) microwave (350, 490, and 700 W power); and (iii) convection followed by microwave (at 350 W, 4.3 mm thick sample) as a finish drying treatment. The moisture removal occurred during the falling rate drying period. Convection drying was longer than microwave. Further, drying rates increased with the higher wattage power level. Microwave finish drying reduced the convection drying time by greater than 60%. The use of microwave energy as a finish drying process resulted in dried banana slices that were lighter in color and possessed the highest rehydration value.

In an innovative study, Monteiro et al. (2016) applied a microwave multi-flash drying (MWMFD) process for the preparation of crisp bananas slices. A comprehensive study of various processing variables was designed to produce dried bananas with controlled microstructure and texture properties. The result of applying microwave heating coupled with vacuum pulses on the crispness of dried bananas was investigated. Slices were dehydrated by microwave vacuum drying (MWVD), a MWMFD process, and freeze-drying. Drying kinetics for both MWVD and MWMFD showed three distinctive drying phases (initial heating period, constant drying rate, and falling rate). Increased microwave power produced greater drying rates with no appreciable difference in product microstructures and texture. MWMFD resulted in dried fruits with larger pores and porosities 20–50% higher with increased crispness than those produced by MWVD. The results demonstrated that the potential to create dried-and-crisp bananas through application of successive heating and vacuum pulse cycles in a microwave field was superior compared with freeze-dried products.

Infrared Heating

Rastogi (2012) provided a review of recent trends and developments in IR heating in food processing. Clearly, IR heating offers advantages over conventional heating. These advantages include: (i) reduced heating time; (ii) uniform heating; (iii) reduced quality losses; and (iv) significant energy saving. IR heating can be integrated with thermal processing

operations such as blanching, convection air and freeze dehydration. Thus, combinations of IR heating with microwave heating and other common conductive and convective modes of heating are promising. Recent research has been reported on many novel and diverse uses of supplemental IR heating with much interest shown in dehydration of banana. Nimmol et al. (2007) reported improved color and crispy texture of banana chips with the use of low-pressure superheated stream and IR radiation applied at 80 °C. Pan et al. (2008 PDF) investigated the use of IR radiation in conjunction with freeze-drying of banana chips. This sequential process or an IR pretreatment resulted in longer drying times likely associated with tissue changes during the heating. These researchers included a pretreatment dip of ascorbic and citric acids which improved the color of the final product. Overall it was concluded that high quality banana chips could be prepared using this process.

Osmotic Dehydration Systems

This is an ancient method, which has received increased technical/commercial interest in recent years. Osmotic dehydration requires direct immersion of the product into a high-solids solution. The osmotic gradient between the product and the solution results in moisture migration from the product to reach an equilibrium. The principles of the osmotic gradient are illustrated in Figure 7.7.

The complexity of the cellular structure provides a semipermeable membrane which enables the transfer of water from the product into the osmotic solution. Various process variables affect the rate of diffusion. These include: (i) the temperature; (ii) the osmolality of the solution (solution concentration); (iii) the dimensions and surface area of the product; (iv) the mass ratio of material/solution; and (v) mechanical agitation to increase flux rate (Fernandes et al. 2006).

The physical and biological dynamics occurring during the osmotic dehydration process of banana slices has received intensified study in recent years (Chaguri et al. 2017; Mercali et al. 2012).

Torreggiani (1993) presented the basic principles of osmotic dehydration in fruit and vegetable processing. The "direct formulation" obtained through selective incorporation of solutes enables balancing water loss and solids uptake to yield specific functional properties of fruit and vegetables suitable for food formulations.

Farhaninejad et al. (2017) studied osmotic dehydration of banana slices using sonication. The process was optimized using response surface methodology (RSM) for various treatment (mechanical agitation, indirect and direct sonication) effects on product

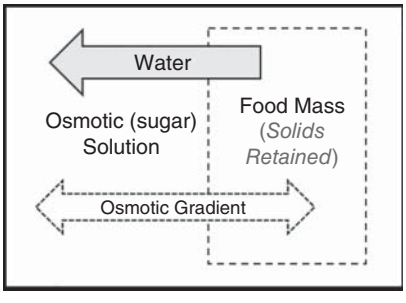

Figure 7.7 Illustration of osmotic dehydration principle.

microstructure. The direct sonication in sucrose demonstrated superior performance that was attributed to the creation of microchannels and disconnection between cavities. Ultrasound application during osmotic diffusion led to increased porosity compared with the control.

Almeida et al. (2015) reported the mass transfers and retention of phenolic compounds, condensed tannins and antioxidant activity of osmotically dehydrated banana slices. The variables were temperature (30, 40, and 50 °C) and sucrose solution concentration (45, 55, and 65% w/w). The analyses of slices were performed after 60 and 180 minutes of processing. Water loss and reductions in retention of phenolic compounds and antioxidant activity with increasing temperature were observed. Solids gains were noted with increased sucrose concentration. Osmotic dehydration reduced moisture content while retaining the native antioxidant activity of the banana.

Sankat et al. (1996) osmotically treated ripe banana slabs (10 mm thick) in sucrose solutions (35, 50, and 65 °Brix) for 36 hours. As the sugar content of the banana slabs increased through the osmotic treatment, drying rates fell. The moisture diffusivity was significantly lowered as the moisture content dropped in drying and with increased levels of sugar. Osmotically pretreated and subsequently air dried banana slabs possessed desirable color and texture compared with the fresh banana.

Osmotic dehydration was applied to facilitate the enrichment of banana with *Lactobacillus rhamnosus*. This research utilized a double emulsion system and a pulsed vacuum infusion to improve the probiotic properties of the fruit. The combination of a typical osmotic gradient (sucrose range 40–60%) and vacuum impregnation (50 bar, 10–20 minutes) increased the rate of water loss, solids gain and retention of viable cells at the tissue surface. Scanning electron microscopy (SEM) demonstrated encapsulated probiotic cells adhered to the surface of banana samples. This study demonstrated that double emulsions can be used to impregnate probiotics in plant-based foods (Huerta-Vera et al. 2017).

Quality Attributes of Dehydrated Banana Products

Carbohydrates (Sugars, Starch, Fiber)

The physiological stage of fruit ripeness dramatically influences the carbohydrate content and shifts among carbohydrate fractions of banana tissue. Changes in various carbohydrate fractions (starch, sucrose, and reducing sugars) at selected stages of banana ripeness are presented in Figure 7.8. The reduction of total starch content with concomitant increases in sucrose and reducing sugars with increased ripeness are evident. These shifts in total sugar at the expense of starch are indicative of fruit possessing greater sweetness and reactivity to browning and general tissue softening.

Tribess et al. (2009) reported the effects of dehydration methods on the content of resistant starch of green banana. Differences in the content of resistant starch were achieved with different air-drying procedures. Higher drying temperatures (52 versus 55 °C) produced more resistant starch. Further work on green banana flour reported by Bezerra et al. (2013) characterized the physiochemical properties of starch obtained from a sprouted bed dryer.

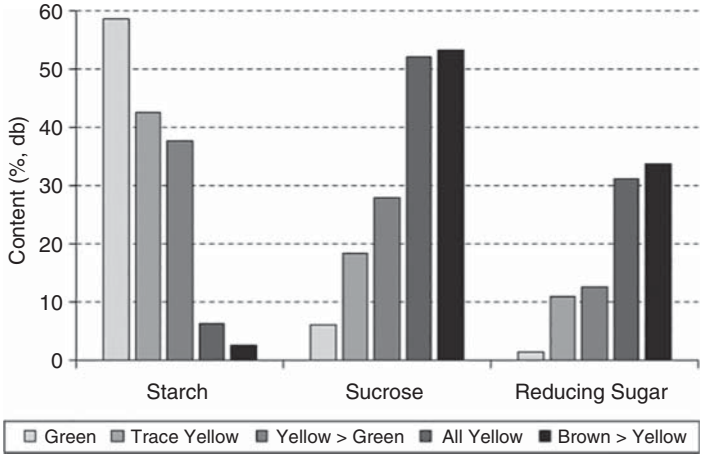

Figure 7.8 Changes in the carbohydrate fractions at selected stages of banana ripeness. Source: Adapted from Lii et al. (1982) and Zhang et al. (2005).

Katekawa and Silva (2007) reported the association of glass transition and product shrinkage during the drying of banana. Although this is a complex relationship, as made clear by the authors, the influence of temperature was significant with higher temperatures, above the glass transition temperature, inducing a higher extent of shrinkage.

Color (Browning)

The color and appearance of banana products are a primary quality attribute readily discerned by consumers. Fresh bananas contain high levels of phenolic compounds and high activity of polyphenol oxidase. This classic enzymatic browning reaction results in very rapid browning of banana tissue during handling and preparation (Nguyen and Price 2007). Peeling and cutting operations will enable rapid onset of browning, if unchecked. Pretreatments have been used to mitigate this reaction (Chaisakdanugull et al. 2007). These include using steam or water blanching, frying in oil, or use of ascorbic acid dips and the application of sucrose on the exposed surface. High temperature drying conditions will also limit enzymatic browning. However, during dehydration, particularly in the later stages, Maillard browning will readily occur. This reaction produces both discoloration and distinctive flavor and aroma.

Romano et al. (2010) monitored color changes of banana during drying using a laser backscattering (670 nm, 3 mW) technique. Pre-drying treatments are frequently employed to preserve fruit color and appearance. The experiments were conducted at drying air temperature of 63 °C with selected pretreatments: (i) chilling; (ii) soaking in ascorbic/citric acid; and (iii) dipping in distilled water. An untreated sample was used as a control. The relative laser area was used as an indicator for light absorption into the tissue. Results established a linear relationship between relative laser area and moisture content. The pretreatments showed significant differences of lightness (L* values) during drying. Treatment with ascorbic acid gave the best prediction of the moisture content using this technique; however, color degradation did not negatively impact absorption at 670 nm wavelength.

Chua et al. (2001) observed that by the use of changing drying air temperature it was possible to significantly reduce the drying time of bananas and produce improved product color.

Color and sorption characteristics of osmotically treated and air-dried banana were studied during air drying at 70 °C. Osmotic pretreatment prevented color damage and resulted in a shift in sorption isotherm with decreased sorption capacity of dehydrated products (Krokida et al. 2000). The color parameters lightness, redness, and yellowness were studied, using a Hunter Lab color meter. A first-order kinetic model was fitted to the experimental data adequately for color parameters, while osmotic data for treated and air-dried products were fitted to the GAB model. Untreated banana showed an extensive browning, which was demonstrated as a significant drop in the lightness and an increase in redness and yellowness. Osmotically pretreated samples did not brown as much as the untreated samples and the lightness decreased only slightly while the redness and yellowness values increased slightly. Osmotic pretreatment resulted in a shift in sorption isotherm for both treatments. Osmotic dehydration prevented color damage and decreased the sorption capacity of dehydrated products.

Texture and Microstructure

Textural characteristics of dehydrated banana chips are greatly impacted by preparation and processing procedures. The hardness and crispness attributes are highly associated with consumer acceptance. The microstructure of dehydrated banana tissue is influenced by the process used. Figure 7.9 illustrates the impact of IR radiation as a pretreatment prior to freeze-drying. Note an increase in porosity and apparent decrease in bulk density for the IR-treated sample. These changes dramatically influence the textural properties of the dehydrated banana slice.

Generally, a high-quality chip is described as "firm and crispy" and, of course, possessing desirable color and flavor. Process variables each have direct impact on final product quality. Thus, product moisture content, thermal processes (blanching and frying) and dehydration methodology (particularly temperature and air flow which readily affect the rate of drying

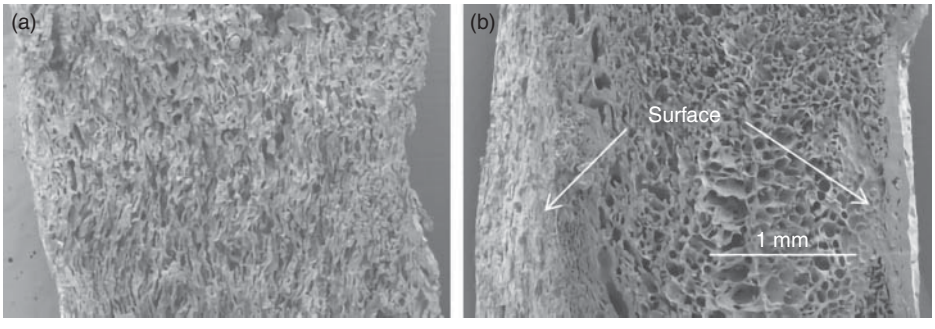

Figure 7.9 Scanning electron micrograph of cross section of dried banana slices with no acid treatment under different drying methods: (a) regular freeze-dried; and (b) IR pre-dehydration, 20% weight reduction before freeze-drying. Source: Pan et al. (2008). Reproduced with permission of Elsevier.

and final moisture level achieved) have been studied (Demirel and Turhan 2003; Fernandes et al. 2006; Katekawa and Silva 2006; Romano et al. 2010). Much research has been directed to understanding the interactions of these processes to yield optimized quality attributes.

The structure of freeze-dried banana is compared in macro-photographic images of cross-cut slices and scanning electron micrographs (50× magnification) in Figure 7.10. The use of MWVD and MWMFD applied at selected energy levels (400, 700, or 1000 W) during the freeze-drying process are presented for both laboratory and commercial samples. Note the differential porosity of tissue among these treatments. Under the conditions of these processes, results demonstrated that it is feasible to create dried-and-crisp banana by applying successive cycles of heating and vacuum pulses in a microwave field. Production of dried-and-crisp banana slices using the MWMFD process was more effective than using MWVD. Clearly, microwave treatments were most efficient, given very short drying times, compared with freeze-drying times.

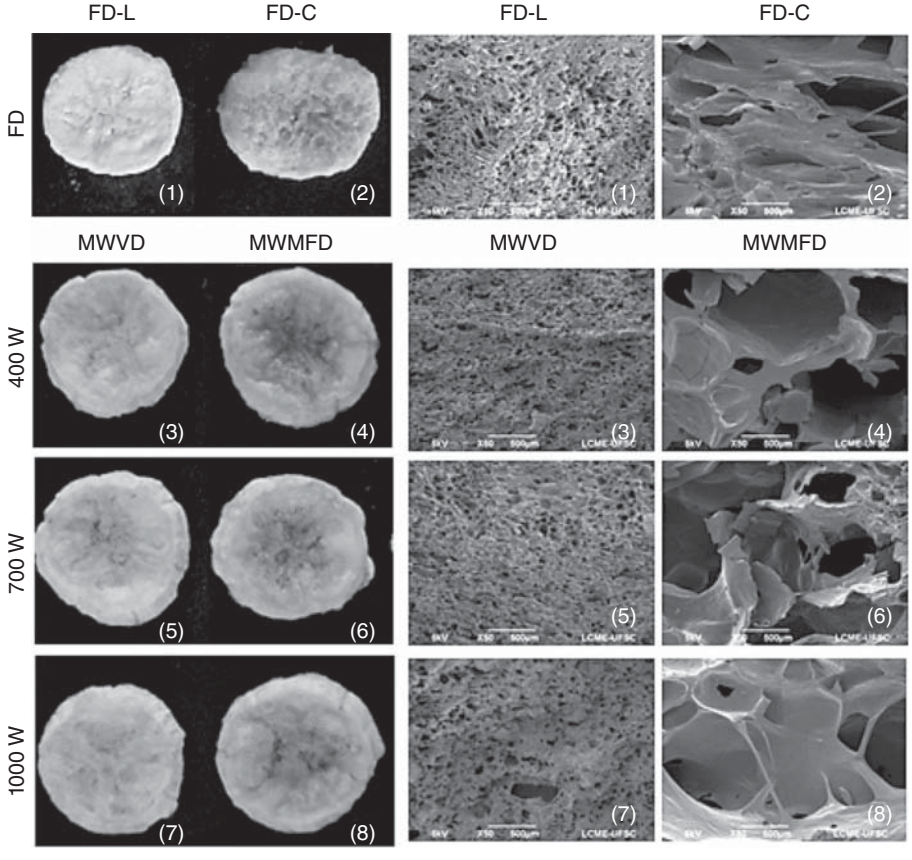

Figure 7.10 Photographs of dried bananas and scanning electron micrographs of fractures of dried bananas (magnification ×50): (1) FD-L; (2) FD-C; (3) MWVD-400 W; (4) MWMFD-400 W; (5) MWVD-700 W; (6) MWMFD-700 W; (7) MWVD-1000 W; and (8) MWMFD-1000 W. C, commercial; FD, freeze-drying; L, laboratory; MWMFD, microwave multi-flash drying; and MWVD, microwave vacuum drying. Source: Monteiro et al. (2016). Reproduced with permission of Elsevier.

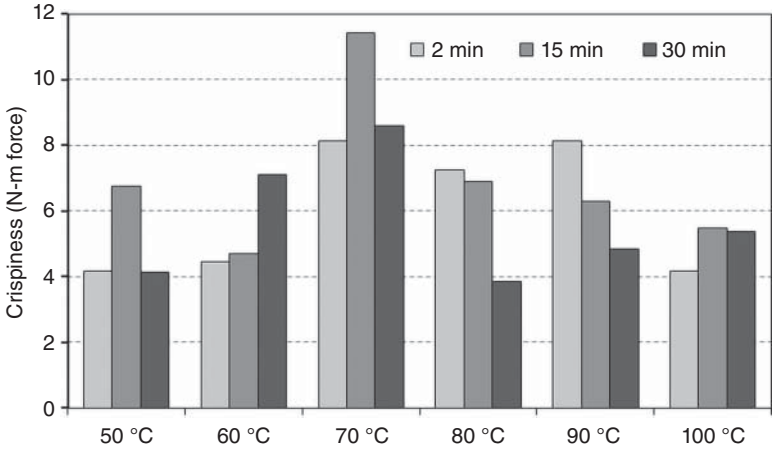

Figure 7.11 Effect of blanching temperature and time on the crispiness of dried banana chips. Source: Adapted from Jackson et al. (1996).

Jackson et al. (1996) blanched whole green bananas in water at different temperatures for 2, 15, and 30 minutes and demonstrated optimized blanch conditions using RSM to be 67 °C for 22 minutes for enhanced crispness of fried and dehydrated slices (Figure 7.11).

Raikham et al. (2013) reported the optimum conditions of fluidized bed puffing for producing crispy banana. High-temperature short-time processing conditions were employed. Puffing temperature and puffing time significantly affected the shrinkage, hardness, crispiness and color of the dried product. Higher puffing temperature and longer puffing time resulted in less shrinkage, better texture, and a darker brown color. Results indicated that an intermediate moisture content (26% db), puffing temperature of 163 °C, and puffing time of one minute were effective to produce puffed banana products using a fluidized bed technique.

Porciuncula et al. (2016) studied the potential of various processes designed to enhance the structure and texture of dehydrated banana. Emphasis was focused on the microstructure and texture of multi-flash drying of banana. Results showed that processing conditions clearly influence the porous structure of dehydrated banana. Product density, porosity, and shrinkage variation among various processes (conductive multi-flash drying process, conductive multi-flash drying combined with classical vacuum drying, convective drying in an oven, and vacuum drying) influenced textural properties.

Flavor Compounds

The natural aromatic flavor compounds prevalent in bananas have been extensively studied (Boudhrioua et al. 2003; Facundo et al. 2013; Marriott and Palmer 1980). Flavor attributes of bananas vary widely by variety and fruit maturity; however, predominate compounds include isoamyl alcohol, isoamyl acetate, butyl acetate, and elemicin, a phenylpropene. Table 7.2 shows the major volatile compounds in dehydrated banana as a result of different drying methods.

Table 7.2 Principal component analysis of major volatile compounds in banana dehydrated using different methods.

	Fraction (%)		
Compounds	**Freeze drying**	**Vacuum belt drying**	**Air drying**
3-Methylbutyl acetate	7.32	3.12	0.74
Butanoic acid 3-methylbutyl ester	0.59	0.31	0.28
3-Methylbutanoic acid 3-methylbutyl ester	16.11	19.3	22.39
Isoamyl butyrate	15.83	13.69	14.75
Butanoic acid 1-methylhexyl ester	7.45	6.85	5.87
Hexyl isovalerate	3.23	3.29	3.2
2-Heptanol acetate	3.54	2.34	1.67
Isobutyl isoval ester	4.51	1.6	3.23
Eugenol	0.45	1.23	0.76
Elemicin	—	0.67	1.26

Source: Wang et al. (2007). Reproduced with permission of Elsevier.

Boudhrioua et al. (2003) characterized the compounds associated with banana flavor and aroma. Further, they accessed changes in aromatic components of banana during ripening and air-drying. Fresh and dried bananas were extracted by solid-phase microextraction (SPME) and analyzed by gas chromatography (GC). The aromatic changes of Cavendish banana were then studied during ripening and drying. The entraining of aromatic compounds by water vapor was the main mechanism of loss during the preliminary phases of drying. Some compounds strongly decreased during drying (particularly isoamyls). Data suggest that Maillard reaction products were subsequently developed during extended drying at 80 °C. Process temperature and final moisture content of dehydrated slices dramatically impact compounds contributing to the final flavor and aroma profiles. Thus, final product flavor and aroma are clearly attributed to raw banana sources (banana type, maturity/ripeness, and handling/preparation stages) and to changes that occur during the dehydration process (losses and thermal synthesis of compounds).

Saha et al. (2018) used headspace gas chromatography mass spectrometry to measure changes in selected volatile flavor compounds in fresh banana during low temperature heat pump drying. The mechanisms for flavor and aroma losses were viewed to be complex. Ester and aldehyde levels reduced quickly during the early stages of drying. High molecular weight compounds, such as elemicine and eugenol, were not significantly affected during drying. It was observed that selective diffusion and volatility affected the degree of flavor retention in banana. It was concluded that retention of the important and abundant isoamyl and isobutyl acetates depends on rapid surface drying (at higher air temperatures) to remove water and seal the surface and thus retain volatiles within the banana slices.

Packaging and Shelf Life

Dehydrated banana slices must be properly handled and packaged to assure adequate high-quality shelf life. The generalized mode of quality deterioration is associated with sensory degradation of color and flavor, and the loss of characteristic crispness. Dehydrated products require packaging appropriate for the environmental conditions encountered during shipping and marketing. Environmental storage temperature and relative humidity are critical factors affecting shelf life. High quality shelf life of dehydrated banana slices is dramatically enhanced by maintaining reduced storage temperature (range 15–20 °C) and low relative humidity (range 5–10%). Packaging materials must be selected to provide adequate barrier properties to assure minimum moisture vapor transmission (MVT) and low oxygen permeability. Lipid oxidation and the development of stale off-flavors will develop in the presence of excessive oxygen. This condition is highly acerbated in oil fried chips.

Selected studies have been directed to assess effects of storage and packaging conditions on the quality degradation of dehydrated banana products, e.g., slices (Bellary et al. 2017) and powders (Mishra et al. 2016).

Bellary et al. (2017) reported the effect of storage conditions and packaging materials on the quality of raw banana slices. A moisture sorption study was conducted for the developed products in selected packaging materials: (i) polypropylene (PP); (ii) polyethylene terephthalate (PET)/low-density polyethylene terephthalate (LDPE); and (iii) metallized PET/LDPE. Fruit was held under ambient and accelerated storage conditions for 90 days. Results indicated that physical, chemical, and sensory quality attributes required an effective MVT barrier to achieve suitable shelf life.

Noor and Augustin (1984) studied the effectiveness of antioxidants on the storage stability of banana chips. Butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT) were compared for improving the stability of banana chips fried at 190 °C and stored at 65 or 25 °C with an untreated control. It was found that frying oil that contained either antioxidant resulted in more stable chips than chips fried without antioxidants. BHT was more effective than BHA in prolonging the shelf life of banana chips.

Yan et al. (2008) reported quality stability of intermediate moisture content banana. Optimal environmental conditions and adequate packaging materials can be used to guarantee high quality products through shelf life. Storage condition factors considered were temperature, relative humidity, light level, and package atmosphere composition. Objective and sensory measures were conducted throughout storage. Results indicated that temperature and relative humidity were the most critical environmental factors for retention of color and acceptability.

Summary

Dehydration processing provides a very economical and commercial value-added means to produce banana slices. Food safety, advanced quality control systems, and expanded efforts

for extending the shelf life have been undertaken to position dehydrated banana slices in world-wide commerce. Differentiated high-quality banana products can be designed using processes that range from simple solar drying to highly advanced technologies. Direct sun and solar drying processes are very common in tropical areas suitable for banana production. A significant portion of the total world production is achieved using this appropriate technology. The standard forced air drying of banana is well documented and follows simple kinetic principles common to general food dehydration. Valuable efficiencies of scale and throughput are readily achieved in properly designed tunnel drying systems. Process conditions have been modified to yield improved consumer acceptance. Bright color and crisp texture are the primary attributes that influence consumer appeal for dehydrated banana slices. Efficiency of processes and the specification for end products can dictate the use of supplemental processes (e.g., ultrasound and microwave energy or IR radiation). Advances in the modification and selective application of osmotic technologies have resulted in numerous options for specialty banana slices. Although freeze-drying produces exceptionally high-quality product, it is very energy intensive and generally not required for most acceptable product applications.

Packaging and handling systems are essential for safe and economical distribution of banana slices. The increased complexity of food industry supply chains requires advances in packaging films and package design to assure competitiveness. Further, work to optimize the primary dehydration methodologies that result in superior products that meet the specialty needs of ever increasingly sophisticated chefs, product developers and end users (consumers) is warranted. Selective modifications in banana composition through postharvest handling controls and pretreatments (e.g., enzymatic digests) should be sought to enhance digestibility. Also, assessing overall consumer acceptance of highly specialized forms of dehydrated banana slices should be considered. The need to appropriately inform end users of the many nutritional and functional values of bananas is warranted. The enlightened view that high quality banana slices are a vital ingredient and contribute to the flavor, texture, and consistency of many complex entrées provides an opportunity for the banana industry.

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8

Green Banana Processing, Products and Functional Properties

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Introduction

Banana (Musa spp. L.) is one of the most appealing fruits in the world. It belongs to the order Zingiberales and genus *Musa*. The fruits are an elongated, cylindrical, and curved shape with the skin color ranging from green to yellow. Bananas are mostly produced in Asia, South America, and Africa. The fruit is rich in vitamins and minerals, in particular, vitamins B and C, potassium, and calcium. Because of the health benefits, the consumption of banana has increased significantly in the developed countries. Although the major market share of bananas is based on the trade of the ripe fruit for both local consumption and international trade, the unripe or green bananas (GBs), also known as plantains, are a significant nutritional source for the people in many regions of the world. According to the FAO, the production of plantains and related products reached 39.24 MMT (million metric tons) in 2017 (FAO 2019).

Although bananas and plantains are among the top fruit crops, limited industrial products are made from these. The most common banana products are puree, juices, and chips. Despite the high production, about 20% of the average produce is wasted due to the perishable nature of the fruits and also rejected fruits are disposed of improperly. The loss is severe in Brazil. According to the Brazilian Banana Producers Association, 40% of production is lost because of lack of coordination from farming to marketing (Izidoro et al. 2007). The rate of plantain postharvest losses varies among countries, and depend upon the organization of production, handling of fruits, and modes of consumption. The losses can be minimized by the processing of rejected fruits and the utilization of green banana pulp, which contains 70–80% starch on a dry weight basis (Izidoro et al. 2011). To utilize the waste and to make proper utilization of fruits, some alternative technologies or approaches are required.

Green bananas are great source of resistant starches (RSs) (47–57% dry basis), in particular, type II (RS2). RS2 is packed tightly in a radial pattern, and this compact structure limits the accessibility of digestive enzymes and accounts for its resistant nature (Almeida 2009). In addition to RS, unripe banana (UB) flour contains 28% available starch, 7.2% dietary fiber, 0.96% sucrose, and 0.85% reducing sugars (Fuentes-Zaragoza et al. 2010). In the food industry, green banana flour (GBF) has been utilized in the development of many food products including cereal bars, cookies, crackers, noodles, and pasta. GBF and starches have

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attracted significant attention from nutritionists and health professionals because of their positive effect on human health since they increase the intake of unavailable carbohydrates, which may reduce the risk of non-communicable diseases (Giuntini et al. 2015; Sardá et al. 2016). Therefore, the consumption of unripe GBF is helpful in maintaining human health and reduces postharvest losses of the fruits.

This chapter reviews the processing and utilization of green banana into flour and starch, and their effect on human health. It is to be noted that both green banana (GB) and unripe banana (UB) terms are used interchangeably in this chapter to maintain the source information.

Preservation of Green Banana into Flour and Starch

Drying

Drying is one of best preservation techniques to remove excess water from the fresh produce. The most common drying methods for plantains are sun drying and hot air drying. However, reports are available on drying in a spouted bed, freeze-drying, and spray drying. During the process, both heat and mass transfer occur simultaneously. Two different mechanisms carry over the drying process: movement of water from inside the material to the surface; and evaporation of surface water to the surrounding environment. The leading parameters that influence the drying operations are temperature, air velocity, humidity, thickness, and dimension of the sample. The drying methods have a direct impact on the quality of the product. The drying kinetics and mathematical modeling of green banana have been reported in the literature.

The hot air drying was employed for green banana slices (4 mm) using a tray dryer (Tribess et al. 2009). The total drying time was about six hours with variable air temperatures (52–58 °C) and air velocity (0.6–1.4 m/s) at various temperature–air velocity combinations. After dehydration, the slices were ground to a powder with a particle size of 250 μm. Hatami et al. (2017) dried thin green banana slices (2.6 mm) in an indirect forced solar dryer at air mass flow rates of 0.016, 0.041, and 0.082 kg/s. The dryer comprised of a solar collector for heating air, a drying chamber, a rotator AC current fan located at the top of the chamber for air suction and formation of forced convection in airflow, and an exit duct for conducting the humidified air into the atmosphere. The variation in drying rate versus moisture ratio showed two distinct falling drying rates. During the first stage, the volume change of the product is higher than the evaporated water volume. Furthermore, more volume change occurred as the air mass flow rate increased. In the subsequent phase initiated from the critical moisture content, where the evaporated water volume equals the volume change of the product, and the air mass flow rate showed no significant effect on volume change in this stage. The shrinkage factor of the samples was less than one during drying indicating non-isotropic shrinkage with contraction of inner voids. Furthermore, product shrinkage $[(1 - V/V_0)]$ showed two descending drying steps in which the volume change was more than the evaporated water volume in the first step and equal to that in the second step. The dimensionless evaporated water volume $[(V_{evap}/V_0)]$ with respect to the dimensionless volume $[(\Delta V/V_0)]$ difference of the product also revealed that two

steps of volume change existed during drying separated at critical moisture ratio 0.23. The changes of area and volume were only related to the product moisture content and were independent of the air mass flow rate, and air temperature.

Bezerraa et al. (2013) produced GBF by drying in a conical spouted bed dryer with continuous feeding. The dryer made up of a conical base with an internal angle of 60° and an inlet orifice diameter of 50 mm. A cylindrical column ($D \times H = 200\,\text{mm} \times 300\,\text{mm}$) was connected to the conical base of the dryer. The upper part of the equipment was composed of another cone and a cyclone. The operation started with the introduction of inert polyethylene pellets ($D = 3.60\,\text{mm}$; density of $905.23\,\text{kg}\,\text{m}^{-3}$ and sphericity of 0.850) into the equipment. Spouting started when the air was injected at the base of the bed, and the spout was established when the inlet air was heated to the desired temperature. The working temperatures were set to 80 and 90 °C, and drying airflow rate was at 50 m^3/h. The green banana paste was fed to the drying chamber, at a rate of 3.91 ml/min, into the annular sliding layer from both sides by a peristaltic pump. The dried powders were separated from the outlet air in a cyclone and a bag filter. Results indicated that the flour with peel had the highest viscosity values, however, flour with and without peel showed a high tendency to retrogradation. The swelling power and solubility were similar for all flour samples, with low solubility under cold and high solubility under hot conditions. The starch granules diameter varied from 70 to 110 μ, with flattened and elongated morphology. The sorption isotherms of unpeeled and peeled banana flour exhibited type II and III, respectively, and the BET model delivered the best fit to the data, obtaining values for the monolayer adsorption of 5.78 and 4.34, respectively, and desorption of 4.85 and 4.14, respectively.

To improve the water migration rate during drying of unripe banana, La Fuente et al. (2017) employed two pretreatment methods, namely ultrasound (US) and pulsed vacuum (PV). The ultrasonication was carried out at 154 W and 25 kHz for 20 minutes prior to hot air-drying while the PV was maintained at 50 kPa in a vacuum-convective drier at ambient temperature for 60 minutes. Experiments were carried out in various combinations of pretreatment methods and drying. Experiments were conducted following various combinations: (i) US for 20 minutes + air-drying at 50 °C; (ii) US for 20 minutes + PV for 60 minutes + air-drying at 50 °C; (iii) US for 25 minutes + air-drying at 60 °C; and (iv) US for 25 minutes + PV for 60 minutes + air-drying at 60 °C. Experimental drying curves of banana slices exhibited no constant rate period for the drying of banana, and the complete drying took place in the falling rate period with two falling rates. Among various mathematical models, the best fit was obtained between the experimental data and the predictive values from the Midilli model (Midilli et al. 2002), with four parameters as shown in Table 8.1. Furthermore, the drying temperature strongly influenced the drying kinetics, i.e. the higher the temperature, the higher the value of D_{eff} obtained, mainly related to the first falling rate, as expected.

$$\frac{X - X_e}{X_0 - X_e} = a \exp(-kt^n) + bt \tag{8.1}$$

Where X_0, X and X_e are the zero time, at time t, and the equilibrium moisture content, respectively, and, a, k and b are fitting parameters. The pretreatment of green banana did not help the moisture migration and the drying rate. Increases in water effective diffusivity,

Table 8.1 Midilli model parameters for drying kinetics of unripe banana slices using various pretreatments prior to drying.

Pretreatment	Drying temperature (°C)	Time (min)	k (min^{-1})	n (–)	a (–)	b (min^{-1})
Control	50	–	0.003	1.066	0.989	0.002
	60	–	0.006	1.026	1.008	0.003
Ultrasound	50	20	0.009	0.960	1.108	0.004
	60	25	0.008	1.010	1.142	0.004
Ultrasound + pulsed vacuum	50	20 + 60	0.005	0.996	0.989	0.003
	60	25 + 60	0.005	1.061	1.088	0.004

Source: Adapted from La Fuente et al. (2017).

at the two falling rate periods, were observed due to the application of US, whereas the combined technique of US + PV did not improve the water migration, at both air-drying temperatures. The results revealed drying time savings of 28 and 18% at 50 and 60 °C, respectively.

One of the major limitations of GBF for consideration as an important food ingredient is its unpleasant astringency taste, which is produced by soluble tannin forming insoluble complexes with salivary proteins (Bravo 1998). Furthermore, products formulated with GBF were found to possess an unpleasant astringency flavor due to the soluble condensed tannins or proanthocyanidins. To improve the flavor in GBF, Liao and Hung (2015) adopted the astringency removal method as described by Simoons (1990) for other fruits. The green banana fruits were immersed in 10% limewater at room temperature for four days. De-astringent green banana fruits were peeled, cut into 2-cm slices and immediately dipped in a 0.3% citric acid solution for five minutes. The fruit slices were dried at 30 °C for 24 hours in a low-temperature desiccant dryer, which consisted of a honeycomb-type desiccant wheel dehumidifier and an air-cooled chiller. The dried slices were ground into powder, passed through 60 mesh sieve and stored in a sealed plastic bag. Astringency removal efficiency was evaluated by measuring the amount of soluble condensed tannins, expressed as mg catechin equivalents (CE) (9.04 mg CE/g extract) (Liao and Hung 2015). The soluble condensed tannin content (9.04 mg CE/g extract) of flour obtained from green banana fruit submitted to a previous limewater de-astringent treatment was significantly ($p < 0.05$) reduced by 42.6% compared with that (15.76 mg CE/g extract) of the non-treated control group, suggesting that limewater treatment improved the palatability of the flours by efficiently reducing their unpleasant astringency flavor.

Osmotic dehydration effects on the kinetics and some quality attributes of green banana slices at 25 °C with glycerol, sorbitol, and a mixture of both at concentrations varying from 40 to 60 g/100 g for up to six hours were described (Chaguri et al. 2017). A simplified Fick's equation was employed to estimate a pseudo-diffusion water coefficient by considering a banana slice as an infinite slab with negligible radial diffusion. The three-component diagram showed that the first pseudo-equilibrium was achieved, and the water pseudo-diffusion coefficient showed higher values with glycerol solutions. A modified Peleg's model was employed to obtain the maximum water loss. The following changes in green banana physical-chemical properties were observed: moisture content

from 1.25 to 0.19 kg/kg dry basis; soluble solute content from 5.4 to 16.9 °Brix; the total color difference from 2.7 to 15.8; and the maximum biaxial extensional viscosity from 0.63 to 1.53 MPa s. Moreover, the obtained low chroma difference values suggest that the osmotically drying process may be a suitable technique to preserve the final color of green banana slices.

Ultrasonic wave propagation and spray drying were employed to produce green banana starch (GBS) (Izidoro et al. 2011). Green banana samples were cut into cubes, blended in 1% bisulfite solution (1:2 w/v) followed by filtering through sieves of 35, 48, 100, 150, and 200 mesh. The solution obtained after passing through 200 mesh was centrifuged. The supernatant was removed, and the decanted mass was divided into four portions namely: a conventional oven, a spray dryer, a conventional oven with ultrasound treatment, and a spray dryer with ultrasound treatment. The results indicated high RS content, which was reduced by ultrasound treatment and also by spray drying. Both techniques increased the solubility, swelling power, and water absorption capacity.

Agglomerated Green Banana Flour

Mechanically dried unripe banana flours (UBFs) are fine and cohesive particles, however, they show a low dispersibility and solubility in water, at ambient temperature. The dispersion of GBF in hot water was avoided because of the heat sensitivity of RS above the gelatinization temperature. The best way to improve the flowability of UBF is the agglomeration process, where the particle sizes improve significantly. Rayo et al. (2015) studied the production of instant UBF by agglomeration in a pulsed fluidized bed (PFB) with a view to produce granules with higher dispersion in cold water for human consumption. GBF was submitted to an agglomeration process using a PFB at pulsation frequency of 10 Hz and air inlet temperature of 95 °C, which resulted in a process yield of about 88% and a moisture of agglomerated flour of 2.61 g/100 g (db). An aqueous solution of sodium alginate (5 g/100 g) was used as a binder. The process conditions were flow rate of 3.0 ml/min, temperature of 95 °C, pressure of 100 kPa, air velocity of 1.2 m/s and time of 50 minutes. Agglomerated UBF was obtained with reduced moisture content, increased mean particle diameter, high flowability and porosity with irregular shape (Table 8.2). Agglomerated flour presented a RS content of 53.95 ± 0.22 g/100 g in comparison with 57.49 ± 0.43 g/100 g (db) for the original content, indicating that the agglomeration process did not affect the functional properties of GBF and increased particle wettability properly for use in liquid preparations.

Influence of Processing on Green Banana Resistant Starch

The steps for the isolation of RS from green banana are shown in Figure 8.1. Bello-Pérez et al. (1998) produced unripe banana starch from the macerated pulp. The homogenate was consecutively sieved through selected sieve screens number 50- and 100-mesh followed by centrifugation. The white-starch sediments were drying in a convection oven at 40 °C for 48 hours, ground and passed through a 100-mesh sieve. The produced starch exhibited a water holding capacity (WHC) of 4.2 g/g dry sample at 25 °C, and the value increased

Table 8.2 A comparison of physical properties between unripe banana flour and agglomerated unripe banana flour.

Physical properties	UBF	Agglomerated UBF
X_w (g/100 g)	3.97	2.61
ρ_b (kg/m^3)	515	329
ρ_{tap} (kg/m^3)	652	403
ρ_P (kg/m^3)	1452	1330
ε_t (−)	0.70	0.73
CI (%)	21	18.3
HR (−)	1.27	1.22
d_{FLODEX} (mm)	26	9
h_{FLODEX} (mm)	38	33
α_{FLODEX} (°)	68	54
$\alpha_{freefall}$ (°)	37	34
t_w (s)	>748	<314

a) UBF, unripe banana flour; X_w, moisture content; ρ_b, bulk density; ρ_{tap}, tapped density; ρ_P, particle density; ε_t, total porosity; CI, Carr index; HR, Hausner ratio; d_{FLODEX}, flowability by hole size diameter; h_{FLODEX}, remaining height; α_{FLODEX}, angle of repose by FLODEX; $\alpha_{freefall}$, angle of repose by freefall; and t_w, wetting time.
Source: Adapted from Rayo et al. (2015).

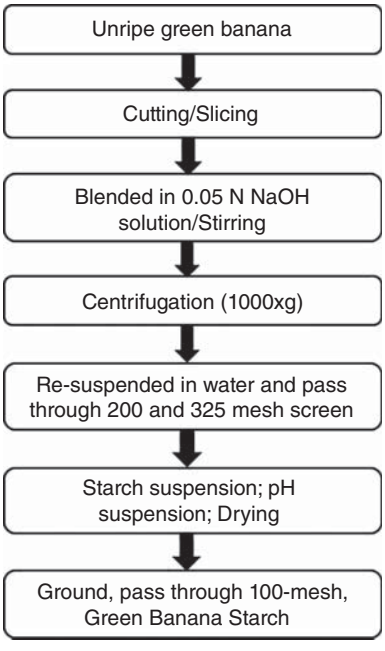

Figure 8.1 Flow diagram for green banana starch preparation.

abruptly to 11.1 and 31.1 g/g dry sample when the temperature increased from 25 to 60 and 90 °C, respectively. Amylose solubilized during starch gelatinization of banana starch at high temperature, which contributed to the swelling of starch granules.

Influence of drying condition on RS contents of GBF indicated that the highest amount of RS was obtained at 55 °C at the maximum air velocity (Table 8.3) (Tribess et al. 2009). The RS contents were significantly ($p < 0.05$) influenced by the combination of drying conditions and it can be observed that at a drying temperature of 55 °C and lower air velocity the RS contents decreased. This could happen because of the higher drying time and consequently partial disorganization of the crystalline structure of starch. However, at higher drying temperature with the same air velocity (0.6 m/s), the flour yielded a higher amount of RS content. At the conditions of lower temperature and lower air velocity, it was required to expose the banana slices for a longer time in order to reach the equilibrium humidity, diminishing the RS content. ANOVA indicated that no significant differences were observed on RS content of flours produced at constant air velocity and variable drying temperatures, whereas at constant air temperature the air velocity influenced the RS content significantly.

Extrusion involves processing starchy food materials under high temperature, pressure, and shear forces, which results in significant changes in physicochemical, rheological, and functional properties of the material. Extrusion of flour affects polyphenolic compounds and their antioxidant activity, depending on the type of material and extrusion process variables (e.g. feed rate, moisture content, screw configuration and speed, die geometry, temperature, and time). The UBF was extruded through a co-rotating twin-screw extruder with constant barrel temperature and the effect of extrusion process variables, i.e. feed moisture (FM, 20 and 50%), screw speed (SS, 200 and 400 rpm), and storing of the extruded flours at 4 °C for 24 hours on the functional properties were evaluated (Sarawong et al. 2014). Extrusion cooking at higher FM and lower SS improved the amylose content. The banana starch was extruded keeping the temperature, SS and moisture content as independent variables to obtain extrudates with functional and digestibility characteristics (González-Soto et al. 2007). The amylose content was 37.4% with high RS content in the ungelatinized sample, which dropped significantly when banana starch was gelatinized (1.9%). A higher RS content in the extrudate over the gelatinized native starch indicated that the extrusion

Table 8.3 Effect of drying conditions on resistant starch and gelatinization of green banana starch contents.

Temperature (°C)	Air velocity (m/s)	Resistant starch (g/100 g, db)	Gelatinization peak temperature (°C)	Process enthalpy (J/g)
Drying conditions				
55	1.4	58.5	68.44	10.28
55	1.0	56.0	68.20	9.04
55	0.6	43.8	68.54	11.10
58	0.6	45.3	68.63	9.25
52	0.6	40.9	67.95	11.63

Source: Tribess et al. (2009). Reproduced with permission of Elsevier.

process increased RS content of native starch due to starch depolymerization and during cooling of extrudates those linear chains form an arrangement which cannot be hydrolyzed by α-amylase. The response surface showed that water absorption index (WAI) values were high when the temperature, moisture content, and SS were also high; water solubility values were not affected by SS, and both temperature and moisture content had a quadratic effect. Cylindrical structures were observed in powders where RS was present and as RS level increased the cylinders became coarser.

Aparicio-Saguilán et al. (2005) prepared RS enriched powder from native and lintnerized (prolonged acid/heat treatment) banana starches by consecutive autoclaving/cooling treatments. The autoclaved samples had higher RS content than their parental counterparts, however the lintnerization process allowed development of higher RS proportions (19%, db). The autoclaved samples (RS-enriched products) showed similar swelling values ($a = 0.05$) at the temperatures assessed. These RS-rich products exhibited a lower solubility in water than the corresponding raw materials. The peak temperatures of the thermal transition were 155.5 and 145.87 °C for native autoclaved and lintnerized autoclaved starch, respectively. These values indicate that RS products have a marked thermal stability. The pasting behavior of the RS products was less pronounced than that of the raw counterparts. Hence, their potential use as processed food ingredients should not impact the final product viscosity. These RS-enriched products appear suitable for the formulation of functional foods.

Functional Properties of Green Banana Flour/Starch

Size reduction is one of the important unit operations in the food industry. The ground particles improve the water solubility, powder dispersion, wettability, bulk density and tapped density, water and oil holding capacity (OHC), the release of enzymes, and functional properties by exposing the large surface area during processing. Size reduction and particle size distribution of milled grains showed a significant difference in the nutritional profiles, especially ash, protein, and starch contents (Ahmed 2014). Influence of particle size on some physical, chemical and functional properties of UBF has been reported (Savlak et al. 2016). The flour samples were separated into selected particle fractions of <212, 212–315, 316–500, and 501–700 μm, and characterized for their functional properties. Particle size significantly influenced visual color, WAI and oil absorption capacity (Table 8.4). The color a* and b* values decreased by increasing the particle size and only the finest particles (<212 μm) were significantly different from other size fractions ($p < 0.01$). The particle size significantly influenced the WAI and OHC, which increased by increasing particle size.

Sardá et al. (2016) compared some important compositional parameters of UBF so that industries could set quality indexes for the UBF for product development. The wide variation recorded in the ash content, and the values ranged from 0.28 to 5.87%. The ash content in standard UBF and standard peel UBF was 2.45 and 4.27%, respectively. The protein analysis showed 3.72% for standard UBF and 5.51% for standard peel UBF and ranged between 4.01% and 5.79% for the commercial UBFs, except for two, which showed much lower results (0.64 and 0.00%, respectively). The lipid content varied between 0.04% and 2.07%. The total starch (TS) content of all the samples was higher than 60.0%, except for two

Table 8.4 Physicochemical and antioxidant properties of green banana flour as influenced by the particle size.

Particle size (μm)	Color a* value	Color b* value	Bulk density (kg/m^3)	Tapped density (kg/m^3)	WSI (g soluble flour/g dry flour)	WAI (g water/g dry flour)	OHC (g oil/g dry flour)	Total phenolic (mg GAE/g flour)	FRAP value (Fe(II) mmol/g flour)	DPPH scavenging capacity (% inhibition)	DPPH scavenging capacity (mg TE[1]/g flour)
<212	1.83	11.81	252	660	0.074	2.92	1.80	0.23	27.91	11.37	2.63
212–315	2.29	13.37	146	538	0.078	3.58	3.68	0.31	36.83	13.45	2.99
316–500	2.31	13.73	163	573	0.075	3.70	3.55	0.19	23.15	8.70	1.74
501–700	2.23	13.47	192	588	0.091	4.60	3.12	0.27	32.37	12.00	2.82

[1]Trolox equivalent.

Source: Adapted from Savlak et al. (2016).

where very high values were recorded (92%). The results indicated that three of the tested samples contained >40% RS content and samples showed a lower content, with two having less than 10% RS and over 80% TS. According to principal component analysis (PCA) and light microscopy identification, the main parameters for the characterization of commercial UBFs are the RS, dietary fiber, lipid and ash contents.

The color of green unripe banana is crucial for its commercial success and acceptability to consumers. Pretreatment of unripe banana slices by dipping into organic acid solutions have been a common practice to prevent enzymatic browning, biochemical and microbial activities of GBF. Anyasi et al. (2015) used ascorbic, citric and lactic acid at concentrations of 10, 15, and 20 g/l for pretreatment of green banana pulp, and thereafter, vacuum dried at a temperature of 70 °C for 12 hours. A higher lightness value, L*, and a lower redness value, a*, were obtained for the lactic acid treated GBF. These observations can be attributed to the anti-browning effects of organic acid pretreatment. However, organic acid pretreatment had little effect on the WHC and OHC.

The nutritional composition and functional properties of banana flour obtained from commercially available varieties were analyzed in order to find a possible utilization as ingredients in processed food (da Mota et al. 2000). The obtained flour was a white powder with finer particles. However, it turned brown because of the activity of the phenolic compounds during the storage period. Microscopic investigation showed a great number of starch granules, which displayed birefringence with polarized light. The amylose contents of banana flours were about 21% total starch.

Thermal treatments changed the WHC, swelling volume (SV) and freeze-thaw stability (FTS) of the native banana flour (Cahyana et al. 2019). Heat-moisture treatment (HMT) dropped the SV to the lowest level of 11.51 ml/g compared with that of the native flour which was 15.23 ml/g. However, only the solubility of annealing (ANN)-treated flour was significantly changed. The native starch compact granule surface remained unchanged with ANN but changed to a more porous surface with HMT and dual retrogradation (DR), thereby increasing the digestibility.

The functional properties of isolated starches from four banana cultivars grown in India revealed that the amylose content has a significant role in controlling physicochemical

properties of starches, and it was involved in the make-up of an amorphous fraction in the starch granules (Reddy et al. 2015). The percentage of amylose showed significant difference among different banana cultivars, and the values ranged between 23.10% and 32.05%. The swelling power of banana starch from different cultivars was directly correlated to an increase in temperature. While comparing starches from diverse varieties of bananas, Agama-Acevedo et al. (2015) found that the RS was the main fraction in the uncooked banana starches. Morado variety showed the highest amount of slowly digestible starch (SDS) and the lowest RS content. Banana starch cooked samples contained significant amounts of SDS and RS. Molecular weight and gyration radius of the four banana starches ranged from 2.88×10^8 to 3.14×10^8 g/mol and 286 to 302 nm, respectively. The chain-length distributions of banana amylopectin showed that B1chains (DP 13–24) were the main fraction, and a significant amount of long chains (DP $\geq$ 37) were present, too. The information generated from this study can be useful to determine banana varieties for starch isolation with specific functionality.

Rheology

Rheological characteristics of banana flour/starch in water dispersion provide information on flow behavior, gelatinization and mixing characteristics. The gels produced from ultrasonicated and spray dried GBF exhibited non-Newtonian shear-thinning behavior with a flow behavior index less than unity (Izidoro et al. 2011). The US wave propagation reduced the yield stress and the consistency coefficient in starch gels. Oscillatory shear measurement exhibited the solid-like behavior of all gels ($G' > G''$) in the studied frequency range. Furthermore, employment of the Cox–Merz rule confirmed the complex dynamic viscosity (η^*) was higher than the shear apparent viscosity (η) in all samples. The gelatinization temperature was mainly influenced by the drying technique and ultrasound treatment reduced the amount of energy required to gelatinize the starch.

Agama-Acevedo et al. (2015) compared banana starches from diverse varieties for their rheological properties. The banana starch pastes exhibited a shear-thinning behavior with a low hysteresis loop during two shear cycles (Figure 8.2). The starches displayed higher shear stress values during the second cycle than the first cycle, indicating re-ordering of the starch structure. The changes in the dynamic moduli, namely the elastic (G') and viscous (G'') modulus during oscillatory shear measurements are illustrated in Figure 8.2. The G' showed a low-frequency dependency ($G' \propto \omega^{0.07}$) while a relatively high-frequency dependency was observed for the G'' ($G'' \propto \omega^{0.35}$). The damping factor, tan δ, values ranged between 0.1 and 0.5, which indicated the formation of very weak gels.

Ahmed et al. (2020) compared the rheological behavior of tray-dried and freeze-dried banana flour dispersions (1:3 flour to water ratio) during nonisothermal heating (Figure 8.3). It was found that the peak complex viscosity was detected at 92 and 99 °C for tray-dried and freeze-dried samples, respectively. The freeze-dried sample additionally exhibited another small peak at 82 °C. These peaks are mostly associated with the starch gelatinization. The significant increase in the gelatinization peak temperatures could be attributed to the presence of a significant amount of RS content.

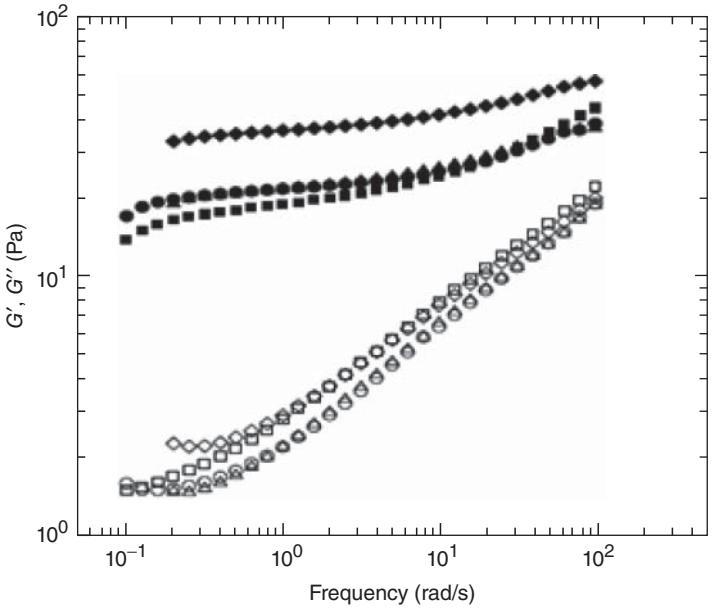

Figure 8.2 Viscoelastic behavior of banana starch pastes (4% w/v) at 25 °C from different varieties: Macho (circles), Morado (squares), Valery (diamonds), and Enano Gigante (triangles). *G′*, black symbols; and *G″*, white symbols. Source: Agama-Acevedo et al. (2015) Reproduced with permission of Elsevier.

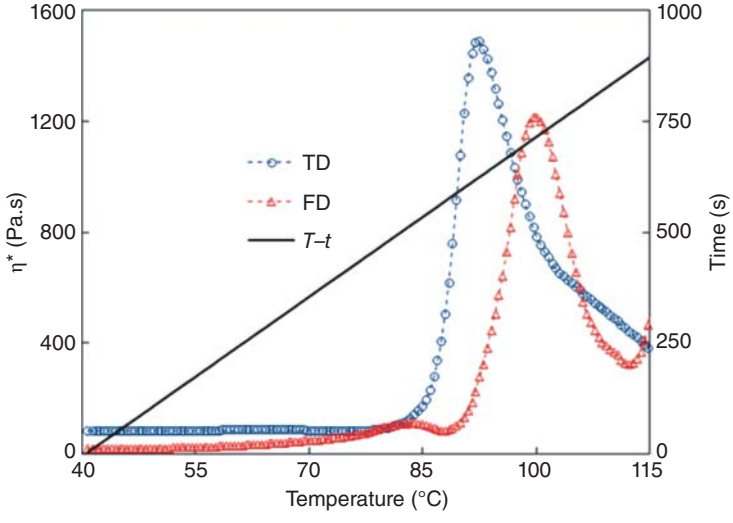

Figure 8.3 Nonisothermal heating of tray-dried (TD) and freeze-dried (FD) banana flour dispersions (1:3 flour to water ratio) at a heating rate of 5 °C/min. Source: Ahmed et al. (2020) Reproduced with permission of Elsevier.

Pasting Properties

Pasting refers to heating/cooling steps for a predefined residence time of starch–water dispersions at the vicinity of the gelatinization temperature at a constant shear rate. The starch granules undergo many changes during cooking and cooling steps, namely swelling, deformation, fragmentation, and solubilization, which provide information about the suitability of the starch for a specific purpose. The GBF samples exhibited a pronounced peak viscosity due to temperature increase, indicatory of homogeneous strength between granules, but without strong cohesion (da Mota et al. 2000). Pasting temperatures were, on average, 50 °C. The difference between the pasting temperature data and those obtained by differential scanning calorimetry (DSC) (62–72 °C) may be due to the nature of the phenomena that lead to measurements of pasting temperature, given by the Rapid Visco Analyzer (RVA), and temperature onset, by DSC (da Mota et al. 2000). Comparative RVA pasting curves of the flour and isolated starch indicated that a lower peak viscosity was observed for the starch followed by a slight viscosity increase and more stability during the holding period at 95 °C, showing that isolated starch granules are more resistant to mechanical fragmentation than whole flour.

A wide range of pasting temperatures for banana flour and starches has been reported in the literature. Agama-Acevedo et al. (2015) compared banana starches from diverse varieties (Macho, Morado, Valery, and Enano Gigante) and found the highest pasting temperature of 79 °C. Furthermore the breakdown and setback values did not differ significantly. The swelling pattern of the banana starches influenced their pasting profile. While comparing the pasting and gel texture of UBF produced from South Africa and India, Kongolo et al. (2017) and Reddy et al. (2015) found significant ($p < 0.05$) variation in the pasting parameters among cultivars. The pasting temperature and the peak viscosity of the South African UBFs varied from 67.6 to 71.1 °C and from 405 to 556 RVUs (rapid visco units), respectively. The breakdown viscosity, final viscosity, and setback viscosity ranged from 190 to 350, 213 to 333.4, and 46 to 997 RVU, respectively (Kongolo et al. 2017). For Indian cultivars, the peak viscosity ranged between 1108 cP and 1343 cP, which mostly relies on amylose leaching, swelling of granules, and ratio of amylose to amylopectin (Reddy et al. 2015). The hold viscosity of all cultivars varied from one another in the range of 1097–1340 RVU. The final viscosity of all samples ranged between 1358 RVU and 1779 RVU. The pasting parameters were influenced by the amylose and amylopectin complex content.

Bertolini et al. (2010) evaluated the pasting profiles of GBF obtained from pulp and peel. Pasting property data indicated that flours obtained from banana pulp showed higher peak and final viscosities than those of flour from banana peel because of the presence of higher fiber contents and lower starch contents in flours from banana peel than those from the banana pulp. Moreover, fibers would be competitive with starch in water absorption, resulting in lower apparent viscosity of flours obtained from banana peel. The peel-derived flour samples showed lower gelatinization enthalpy, and higher temperature of gelatinization than those from the pulp. Antioxidant treatment of fruits with citric acid did not change pasting profiles of flours from pulp, but resulted in slight increase in viscosity, suggesting that structure of starch could be modified by acidification (Figure 8.4).

Effect of cooking on pasting properties of UBF was investigated by Rodriguez-Damian et al. (2013). The cooking of UBF for five minutes did not change the pasting profile of that

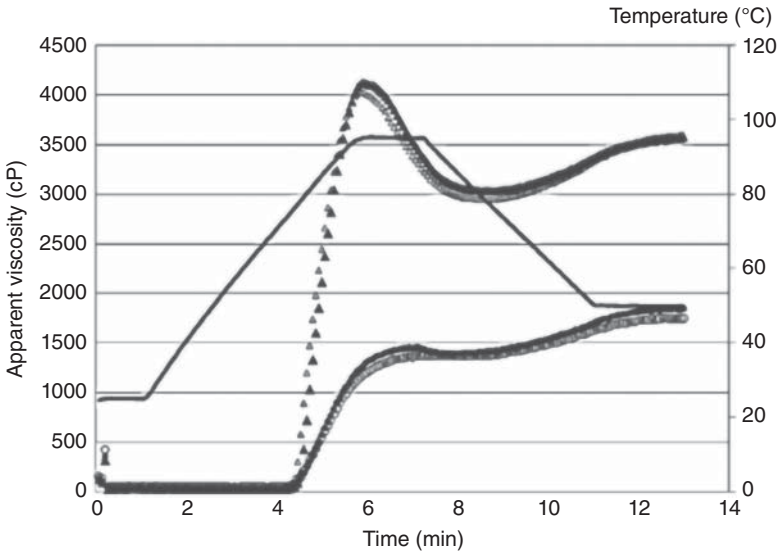

Figure 8.4 Pasting profiles of banana flours obtained from peel and pulp with and without citric acid treatment. Peel citric acid (○), peel control (●), pulp citric acid (Δ), pulp control (▲), temperature (—). Source: Bertolini et al. (2010). Reproduced with permission of John Wiley and Sons.

of the control sample. At the longest cooking time (15 and 25 minutes), the peak viscosity dropped because of swelling of some starch granules before the test, and they did not increase the viscosity. The sample cooked for 25 minutes showed a small breakdown and higher setback value; this pattern was due to the disorganization of starch components in the granule produced during the cooking. The RVA viscoamylogram of samples cooked plus HMT did not exhibit a characteristic pasting profile with low values of viscosity. The effect was significant for the sample that underwent cooking for the longest time. An increase in the pasting temperature was observed as well as a decrease in peak viscosity, but there was no breakdown or a trough viscosity. The changes in the pasting properties of the HMT starches are due to the associations among the chains in the amorphous region of the granule and the changes in crystallinity during hydrothermal treatment.

The cooked plus HMT + S (storage) samples showed effects of pasting properties lower than the samples cooked plus HMT; in the raw UBF there is no change in the peak viscosity, but in the UBF cooked for 5 and 25 minutes the peak viscosities and the setbacks decrease significantly. This is because during starch gelatinization, the granules imbibe water and swell, but the HMT causes reorganization of the components in the starch granule limiting the water absorption. Li et al. (2010) cited that the swelling capacity and solubility of water decrease after the HMT due to the fact that the rearrangement of molecular chains is strengthened, which restricted water being absorbed inside starch matrices and therefore the molecular structure is more rigid. Cahyana et al. (2019) found a remarkable increase in the pasting temperature of HMT-treated flour than that of ANN-treated flour, even though it had a similar increase in crystallinity. The hold, final and setback viscosities decreased when HMT and DR were applied but they increased when ANN was employed. The lowest

breakdown in HMT-banana flour suggested that the flour was the most stable to shear and heat treatment during the pasting process.

Thermal Properties of Green Bananas

GBF is rich in carbohydrates, in particular, starch content and quantifying its gelatinization is important to understand how it affects food processing and the functional properties of the flour. Influence of drying conditions on thermal properties of GBF was reported by Tribess et al. (2009). The DSC thermogram of tray-dried GBF exhibited a single endothermic transition and a flow of maximum heating at peak temperatures from 67.95 to 68.63 °C. It was observed that the drying temperature influenced the gelatinization peak temperature (T_p) significantly ($p < 0.05$). The enthalpy of gelatinization ranged from 9.04 to 11.63 J/g, which remained independent of employed temperature and air velocity. Ahmed et al. (2020) reported significantly higher values for the peak gelatinization temperature (T_p) as 82.48 and 83.39 °C for the tray-dried (TD) and freeze-dried (FD) green banana flour. The process enthalpy (E_a) values for the TD and the FD samples were 11.35 and 12.56 J/g, respectively.

The peak gelatinization temperature for UBF produced from some selected South African banana cultivars showed pasting temperature values in the range of 65–71.2 °C, and the process enthalpy values ranged from 5.42 to 10.12 J/g (Kongolo et al. 2017). No significant difference was found among the gelatinization temperatures of the different varieties. Thermal properties of UBFs indicated that the starch gelatinization temperatures of the UBFs were moderately correlated with the pasting temperature. A DSC thermogram of acid-treated (ascorbic, citric, and lactic acids) UBF showed a single endothermic transition at various pretreatment concentration (Anyasi et al. 2017). The onset temperature (T_o), peak temperature (T_p), and conclusion temperature (T_c) ranged from 49.82 to 65.59, 60.11 to 76.71, and 70.36 to 94.1 °C, respectively. The corresponding enthalpy of gelatinization varied from 2.61 to 32.24 J/g. Thermal properties of Indian cultivars showed significant difference among the four banana cultivars and it may be influenced by the starch extraction procedure, distribution of starch granules, and amylose/amylopectin complexes ($p \leq 0.05$) (Reddy et al. 2015).

The thermal stability and loss of volatile compounds of GBS were thoroughly investigated by thermogravimetric analysis (TGA) and it was found the mass loss happened in the multiple stages (Cordoba et al. 2018). Dehydration and loss of volatile compounds of starch were observed in the first mass loss. After a stability period, samples showed higher thermal stability against thermal degradation. During the second loss, depolymerization of starch chains occurred with the release of gaseous compounds formed from the composition of amylose and amylopectin. The second step was completed in temperatures close to the three samples (339–355 °C). After the third mass loss, the formation of ash was observed in starch samples, which were 0.46, 1.68, and 1.10%, respectively. The temperature ranges in which the loss occurred were 355–469 °C for sample (a) (Terra Plátano [AAB]) and between 339 °C and 462 °C for cultivar samples (b) (Caturra Cavendish [AAA]) and (c) (Prata Anã [AAB]). It was observed that cultivar samples (b) and (c) had an additional loss (fourth mass loss), related to the second stage of starch chain degradation, requiring a higher temperature for

the formation of ash (up to 504 °C). This might happen due to the presence of significant amount of resistant starch.

Thermal Diffusivity and Conductivity

Bananas are mostly exported to distant locations even to another continent, so transport of palletized bananas in containers requires proper temperature maintenance. At low temperature storage, particularly below 11 °C, bananas show chilling injury, and the fruits become smoky or dull yellow color after ripening. Therefore, thermal properties (e.g. thermal diffusivity and thermal conductivity) are important to predict the cooling rate and for optimal design of a cooling process. Erdogdu et al. (2014) studied thermal properties of green Cavendish bananas using an analytical solution of heat transfer for an infinite cylinder. Cooling chambers were used for the experiments, and the temperature changes of the bananas were monitored. The heat transfer coefficient varied between 5.34 W/m^2 K and 5.72 W/m^2 K with the measured diameters of the bananas being 40.33–30 mm. As expected for natural convection cooling conditions, rather low values for heat transfer coefficient were obtained. The thermal diffusivity and thermal conductivity values for the mature green Cavendish variety bananas were 1.442×10^{-7} m^2/s and 0.302 W/m K, respectively. Ikegwu and Ekwu (2009) reported the thermal diffusivity and the thermal conductivity of banana flesh as 1.50×10^{-7} m^2/s and 0.498 W/m K, respectively. While comparing the thermal properties of GBF produced by tray-drying and freeze-drying, Ahmed et al. (2020) found significant difference between the modes of drying. The thermal conductivity, thermal diffusivity and specific heat values for the tray-dried and the freeze-dried flour samples were: 0.183 and 0.118 W/m K; 0.272 and 0.151 mm^2/s; and 0.671 and 0.782 0.6875 MJ/m^3 K, respectively.

Microstructure

The structural change of GBF and GBS are mostly assessed by employing scanning electron microscopy (SEM) and X-ray diffraction (XRD). Overall, the starch derived from the green banana exhibits both B-type and C-type XRD profiles. The XRD pattern of GBSs from diverse varieties and different countries exhibited the B-type crystallinity pattern, with a slight difference in the crystallinity level (Agama-Acevedo et al. 2015; Reddy et al. 2015). SEM observation of Indian cultivars revealed that starch granules were oval, rod shaped, and irregular with smooth surfaces which may be affected by genetic variation (Reddy et al. 2015). The XRD of the Caturra Cavendish (AAA) and Prata Anã (AAB) exhibited C-type profile and the Terra Plátano (AAB) exhibited B-type profile and significantly higher relative crystallinity (Cordoba et al. 2018). SEM analysis and optical microscopy revealed that the granules have ellipsoidal and flattened shape. SEM micrographs of UBF obtained from commercial and noncommercial South African cultivars pretreated with acid solutions exhibited different shapes including oval, elongated, polygonal, and spherical for different cultivars (Anyasi et al. 2017).

Rodriguez-Damian et al. (2013) studied the XRD patterns of green banana flour with different treatments (cooking, cooking plus high-moisture treatment [HMT], and

cooking plus high-moisture treatment plus storage [HMT + S]). It was observed that the unblanched flour cooked for selected times exhibited a C-type diffraction pattern. The intensity of the peaks decreased with increasing cooking time because of modification of the crystallinity. When the raw banana flour was subjected to HMT, the 2θ peak at 17° was split into two peaks (17° and 18°), indicating that there is a polymorphic transformation of C-type to A-type. The sample cooked for 15 minutes plus HMT showed changes in relative intensity, a wider peak was observed at a 2θ value of 17°, and the split peak completely disappeared. These shifts in the XRD pattern influenced by HMT indicated a closer packing of the double helices.

Cahyana et al. (2019) employed HMT, DR and ANN to study the structural properties of GBS. The native banana starch showed an XRD pattern with a small peak at 5.51°, strong peaks at 15° and 16.95° with a shoulder around 17.8° and a broad peak at 22.98°, a feature characteristic of a B-type pattern. The diffractogram remained unchanged while ANN was applied to UBF confirming the retention of the crystal structure. However, the relative crystallinity improved from 31.9 to 35.5%. For the HMT process, the diffraction peak at 5.51° disappeared, while both strong peaks located at 15° and 22.98° still remained. Interestingly, an unresolved doublet peak appeared at a 2θ value of 16.95° and 17.8°, which corresponded to an A-type pattern. For DR treated samples, the peak located at a 2θ value of 5.51° disappeared, broadening the peak at 15° and lowering the intensity of the single peak at 16.95°. Additionally, a new peak appeared at 21.96° following the treatment. The presence of these peaks showed that DR changed the XRD pattern of the native banana starch to A + B type. The relative crystallinity was decreased to about 26%.

A major shift in crystalline type from B to A or A + B type following thermal treatment for UBF is an interesting observation. The B-polymorphic structure consists of hexagonal packing of double helices containing 36 water molecules inside each cell, and the structure is believed to be thermodynamically less stable compared with A-type polymorphs which contain about six water molecules inside the helices. The transformation of the starch structure as evidenced through the diffraction pattern of the unripe banana following thermal treatment could be linked to dehydration or to movement of a pair of double helices into the central channel, which thereafter triggered a disruption of the starch crystallites and/or change in crystal orientation (Gunaratne and Hoover 2002). The fact that ANN did not change the crystal type for banana starch showed that thermal energy at 50 °C is not adequate to trigger dehydration or movement of a pair of double helices (Cahyana et al. 2019).

The granule morphology of native and modified banana flour has been studied by (Cahyana et al. 2019), and is illustrated in Figure 8.5. The flour granule size of the native starch ranged from 10 to approximately 40 μM. The granules were compact with an elongated, oval shape. The granules exhibited a change when the granules were subjected to HMT or DR treatment whereas no pronounced change occurred when ANN was applied. HMT-treated granules resembled an amorphous mass with a cohesive structure and a less compact surface while DR-treated samples showed the presence of a similar cohesive structure with some holes on the surface. DR treatment resulted in much more aggregated granules with a more irregular granule surface than HMT treatment.

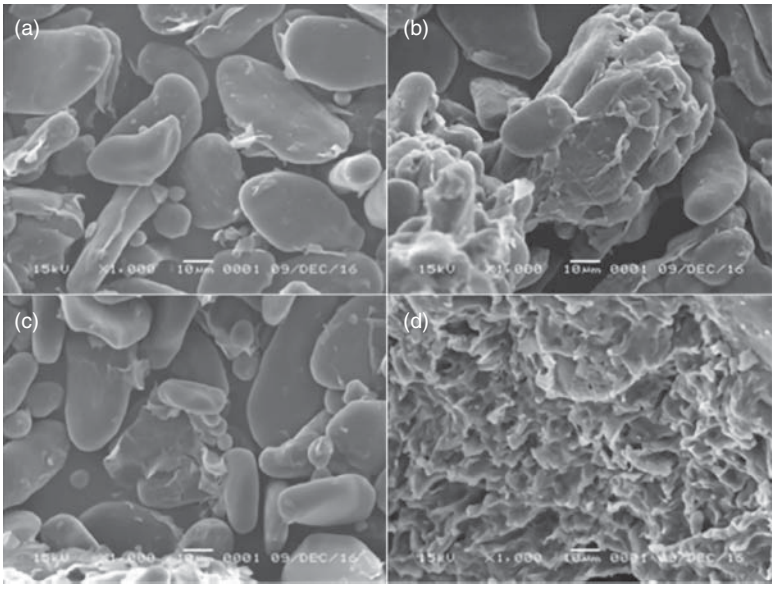

Figure 8.5 Influence of various treatments on the morphology of the banana starch granule in flour: (a) native; (b) heat-moisture treatment; (c) annealing; and (d) retrogradation. Source: Cahyana et al. (2019). Reproduced with permission of Elsevier.

Antioxidant Properties

Phytochemicals are attaining importance for their contribution to human health and their multiple biological effects including antioxidant, antimutagenic, anticarcinogenic, and cytoprotective activities, and for their therapeutic properties. Flour from unripe banana is especially rich in phytosterols. Bertolini et al. (2010) evaluated the phytosterol content of GBF obtained from pulp and peel. They detected major phytosterols (15.4–15.6 mg/100 g dry matter) in flour from banana peel, which included β-sitosterol, campesterol, and stigmasterol. While the treatment with citric acid resulted in a decrease in the total amount of phytosterols present in flour from peel samples, no change was observed in phytosterol contents of acidified and control samples from the pulp.

The antioxidant activity of GBF particle fractions were measured by two different methods (1,1-diphenyl-2-picrylhydrazyl [DPPH] and ferric reducing antioxidant power [FRAP]) and total polyphenol content (TPC); it was found that the TPC ranged between 0.19 and 0.31 mg GAE/g dry flour (Savlak et al. 2016). Effect of particle size on TPC was found to be statistically significant. FRAP values of flour varied between 23.15 and 36.83 mmol Fe(II)/g flour. Particles between 212 μm and 315 μm had the highest antioxidant activity (36.83 mmol Fe(II)/g dry flour) whereas particles between 316 μm and 500 μm had the lowest (23.15 mmol Fe(II)/g dry flour). DPPH radical scavenging activity of flour extracts was significantly influenced by particle size distribution and varied between 1.74 and 2.99 mg Trolox equivalent/g dry flour. DPPH inhibition was between 8.7% and 13.45%.

Effect of extrusion process variables (FM, 20% and 50%; SS, 200 and 400 RPM) and storing of the extruded flours at 4 °C for 24 hours on the antioxidant properties (FRAP, DPPH, and

ABTS.$^+$ assays) were evaluated through a co-rotating twin-screw extruder with constant barrel temperature (Sarawong et al. 2014). Varied FM and SS and their interaction had significant influences on the free, bound and total phenolic content. Increased FM within the same SS resulted in a significant decrease of total phenolics by 12.4–29.2% due to a significant decrease in free phenolics (17.5–42.8%) and bound phenolics (7.9–19.7%). Within the same FM, increasing SS, especially at lower FM, led to an increase in the antioxidant activity of total phenolics due to a significant increase in the antioxidant activity of free phenolics compared with a small increase in the bound phenolics. The increase in antioxidant activity with increased SS was probably due to the shorter residence times during extrusion. The extrusion cooking led to a significant decrease in total antioxidant capacities as compared with native flours, mostly due to a significant decrease in the antioxidant activities of the free phenolics, whereas the antioxidant activities of the bound phenolics were not or only slightly increased. The antioxidant capacities in free, bound and total phenolics showed a significant positive correlation with the content of free, bound and total phenolics measured by FRAP, ABTS.$^+$, and DPPH.

Digestibility of Starch

The application of native starch is restricted in the food industry due to its low thermal, shear and acid stability. To improve application, starch modification is required. Among the modifications, physical modifications such as HMT, ANN (a process used for high moisture foods [>65% w/w] at which the temperature is set below the onset of gelatinization but above the glass transition temperature, T_g), and DR followed by storing the gelatinized starch at a low temperature are mostly used to modify native starch properties. The cooking of starch-enriched food leads to gelatinization of the starch granules with the transformation of the crystalline structure to the amorphous state, improving starch digestibility. It is well-known that the temperature and water contents are the driving force for the gelatinization and for digestibility. Extensive literature is available on the digestibility of starch, which can be modulated by maintaining the water-temperature conditions in a processing operation.

Rodriguez-Damian et al. (2013) studied different treatments, namely, cooking (5, 15, and 25 minutes), cooking plus high-moisture treatment (HMT), and cooking plus high-moisture treatment plus storage (HMT + S), to increase the SDS and RS fractions. The longest cooking time decreased the RS content in the non-gelatinized samples; HMT and HMT + S increased the SDS level. These samples could be used in products without heat treatment during their preparation. The gelatinized samples presented a significant fraction of RS in comparison with the non-gelatinized, demonstrating that the samples can be used in products where cooking is necessary, conserving a high amount of indigestible carbohydrates. Cooking of the UBF at the longest times (15 and 25 minutes) increased the rapidly digestible starch (RDS) content and decreased the RS content because of the gelatinization of the starch, which decreased the RS content. However, up to 20% of RS is conserved in the cooked samples at the longest times. The HMT did not produce appreciable changes in RDS and RS values compared with the cooked counterpart, but the additional storage decreased RDS with a concomitant increase in SDS. The HMT and

storage treatment modified the starch digestibility in different ways. The reorganization of starch components during storage produced a structure that is slowly hydrolyzed by the digestive enzymes.

Cahyana et al. (2019) employed HMT, retrogradation (DR) and ANN to study digestibility of starch components of banana flour. The UBF was enriched with RDS, SDS, and RS. The native flour had RDS, SDS and RS contents of 5.84, 4.89, and 89.27% total starch, respectively. RS was predominantly present in the native form. Thermal treatment improved the RDS content to about 8–31%. HMT or DR increased the SDS content while no significant change in RS and SDS contents in the flour when subjected to ANN treatment was noticed. HMT-treated flour was more susceptible to hydrolysis as indicated by the increase in RDS and SDS contents compared with NBF and the sample subjected to ANN treatment. This trend was linked to the A-type crystallite in HMT-treated flour which was more vulnerable to hydrolysis than the B-type in NBF and ANN-treated flour.

Toro et al. (2016) worked to establish a relationship between the degree of starch gelatinization measured by DSC and *in vitro* digestibility (RDS and RS) for both a plantain pulp ("real food") and a plantain paste ("water-flour dispersion") at different degrees of starch gelatinization under controlled thermal conditions. They compared the degree of starch gelatinization (α) and *in vitro* digestibility between the pulp and the paste over the heating range of 65–100 °C and at a water content of 1.6 kg/kg (db). The gelatinization behavior of starch was identical at a temperature below 76 °C and at 100 °C, however, at 85 °C a significant mean relative difference was observed. For low α (0–0.4) and very high α ($\approx$1), the pieces of plantain and flour paste were not significantly different. At an intermediate degree of gelatinization, the starch swelling pressure may have lowered α as a result of the physical form in the homogenized pieces of plantain pulp, while some cellular integrity and larger estimated volume median diameter were recorded. Both Weibull and exponential models fitted well over temperature data and starch digestibility fractions over α. Contrary to the RDS fraction that remained lower in the pieces of pulp throughout the gelatinization process, the RS fraction was slightly higher for the pieces of plantain pulp. Although no explicit relationship was established between the intact pulp structure and ground flour state of plantain, the evaluation of the degree of starch gelatinization and digestibility of a plantain flour paste could be used to predict the gelatinization and digestibility behavior of plantain starch in intact pieces of pulp.

The influence of extrusion process variables (FM, 20% and 50%; SS, 200 and 400 RPM) and storing of the extruded GBF at 4 °C for 24 hours on the RS and digestibility were evaluated (Sarawong et al. 2014). Compared with native flour, the RS content of the extruded samples dropped drastically by 91.5–98.1%. FM significantly increased insoluble dietary fiber (IDF, by 26.1–28.0%) and total dietary fiber (TDF, by 17.4–18.7%) but not soluble dietary fiber (SDF).

Resistant starch 3 (RS3) is formed by starch gelatinization and subsequent retrogradation where a slow recrystallization of starch components occurs on cooling. Retrograded amylose is of specific interest regarding its thermal stability, and it has commercial interest because of its usefulness as a source of thermally stable RS for various food applications (Haralampu 2000). Retrogradation of amylose is the main mechanism for the formation of RS3 and the amount is strongly associated with the amylose content (Berry 1986). Studies regarding RS3 formation obtained directly from GBF are limited. Liao and Hung (2015)

produced RS3 from GBF, which is faster and less expensive than other plant sources due to no need to isolate the starch first. Furthermore, *in vitro* starch digestibility, the hydrolysis index (HI) and estimated glycemic index (eGI) of de-astringent GBF and its derived autoclaved/debranched powder were studied. Autoclaved/debranched green banana flour (ADGBF) was prepared by autoclaving and debranching GBF with different levels of pullulanase to induce the formation of RS3.

In vitro starch digestion kinetics and eGI were determined in accordance with the previous procedure described by Goni et al. (1997) with modification. Glucose content in the hydrolysates was measured by the dinitrosalicylic colorimetric method (Miller 1959). The amounts of starch digested at selected times (30, 60, 90, 120, and 180 minutes) were calculated by multiplying the amount of hydrolyzed glucose by a factor of 0.9. The percentage of starch hydrolysis was expressed as the percentage of total starch at the start of the digestion divided by the amount of starch digested at different times.

The hydrolysis curves (percentage of starch hydrolysis versus time) follow a first-order kinetic model (Goni et al. 1997):

$$C = C_{\infty}[1 - \exp(-kt)] \tag{8.2}$$

where C, C_{∞}, and k are the percentage of starch hydrolysis at time t, at 180 minutes, and the kinetic constant, respectively. The area under the curve (AUC) was calculated as the integral of the kinetic equation:

$$\mathrm{AUC} = C_{\infty}(t_{\mathrm{f}} - t_0) - \left(\frac{C_{\infty}}{k}\right)[1 - \exp(t_f - t_0)] \tag{8.3}$$

where t is the time (in minutes), t_{f} is the final time (180 minutes) and t_0 is the initial time (0 minute). The HI was calculated by dividing the AUC of the samples by that of a reference (white bread). The eGI values were obtained according to the equation of Goni et al. (1997):

$$\mathrm{eGI} = 39.71 + 0.549 \times \mathrm{HI} \tag{8.4}$$

The starch hydrolysis followed first-order reaction kinetics. The starch hydrolysis curves and the results of the *in vitro* starch digestion are shown in Figure 8.6 and Table 8.5, respectively. The *in vitro* starch hydrolysis profile showed a gradual increment in all tested samples with increasing time until a maximum plateau was attained. White bread, used as a reference food, underwent a higher starch hydrolysis during 30–180 minutes than studied samples. A 54.07% (C_{∞}) of digestion within 180 minutes was recorded for white bread, which was found to have nearly 50% digestion. The percentages of hydrolysis observed in GBF and ADGBF were lower than that obtained with white bread during 30–180 minutes. However, GBF underwent a slightly higher starch hydrolysis than ADGBF until 90 minutes; after this time, the parental flour generated slightly less percentage of hydrolysis. The equilibrium concentrations, the hydrolysis extent when the hydrolysis curve reached a plateau, were significantly higher in ADGBF (24.40%) than in GBF (19.44%). The kinetic constant (k) obtained from the curve fitting of the linearly transformed data using linear regression analysis reflects the reaction rate of the first-order kinetic model of starch hydrolysis; accordingly, the sample characterized by a higher k value liberates glucose faster from the digestible starch during α-amylase hydrolysis. The kinetic constant was lower in ADGBF ($0.0353\ \mathrm{min}^{-1}$) than in GBF ($0.0386\ \mathrm{min}^{-1}$), while white bread exhibited the lowest kinetic constant ($0.0210\ \mathrm{min}^{-1}$) in this study.

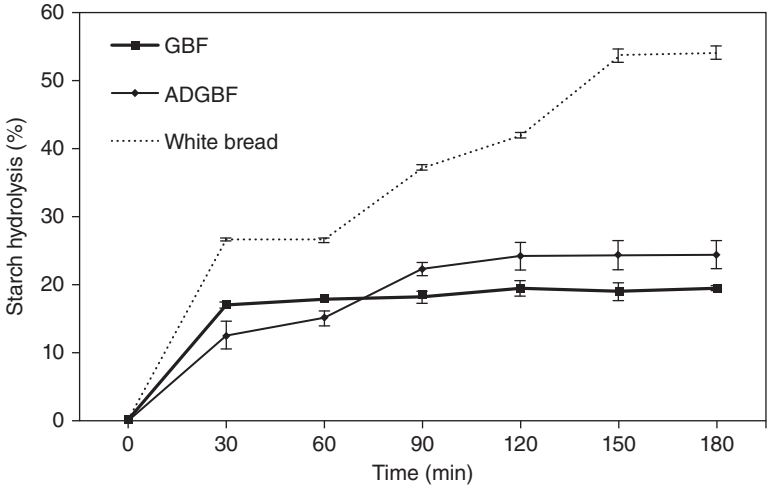

Figure 8.6 *In-vitro* starch hydrolysis in green banana flour (GBF) and autoclaved/debranched green banana flour (ADGBF). White bread is the standard sample for the experiment and the hydrolysis index is 100. Source: Liao and Hung (2015). Reproduced with permission of Elsevier.

Table 8.5 Model parameters, hydrolysis index and estimated glycemic index of green banana flour and autoclaved/debranched green banana flour.

Parameter	GBF	ADGBF
C_∞ (%)	19.44	24.40
k (min^{-1})	0.039	0.035
HI	19.67	28.63
eGI	50.51	55.43

GBF, green banana flour; ADGBF, autoclaved/debranched green banana flour; C_∞, equilibrium constant; k, kinetic constant; HI, hydrolysis index; eGI, estimated glycemic index.
Source: Liao and Hung (2015). Reproduced with permission of Elsevier.

From the results of C_∞ and k values, GBF was the most effective in hindering the *in vitro* hydrolysis of starch among the samples tested, whereas ADGBF showed slightly greater susceptibility to *in vitro* amylolysis than its parental counterpart. The present results demonstrated that the rate and extent of starch hydrolysis were different between GBF and ADGBF. The HI, a parameter obtained from dividing the AUC of the samples by that of a reference (white bread), was used to determine the eGI. The HI values of GBF and ADGBF were 19.67 and 28.63, respectively, while the *in vitro* eGI of GBF and ADGBF based on HI were 50.5 and 55.4, respectively (Table 8.5).

Srikaeo et al. (2011) studied the physicochemical properties and starch digestibility of UBF and compared it with two commercially available high-fiber-modified starches; the UBF was shown to contain 12.5% RS. DSC showed a single endothermic peak at 83 °C.

They calculated *in vitro* starch digestion and the glycemic index of unripe banana starch. The time-course of starch digestion of banana starch in the samples was determined using a rapid *in vitro* digestibility assay based on glucometry (Sopade and Gidley 2009). The ground sample was treated with artificial saliva containing porcine α-amylase followed by addition of pepsin, and incubation at 37 °C for 30 minutes. The digesta was neutralized with NaOH followed by the addition of pancreatin and amyloglucosidase. The mixture was incubated for four hours, during which the glucose concentration in the digesta was measured with a glucometer at specific periods. Digested starch per 100 g dry starch was calculated using the following equation:

$$\mathrm{DS} = \frac{0.9 \times G_{\mathrm{G}} \times 180 \times V}{W \times S[100 - M]} \tag{8.5}$$

where G_{G} is the glucometer reading (mM/l), V is the volume of digesta (ml), 180 is the molecular weight of glucose, W is the weight of sample (g), S is the starch content of sample (g per 100 g), M is the moisture content of a sample (g per 100 g sample), and 0.9 is the stoichiometric constant for starch from glucose contents.

The digestogram of UBF was modeled using a modified first-order kinetic model (Eq. (8.6)) as described by Mahasukhonthachat et al. (2010).

$$D_t = D_0 + D_{\infty-0}[1 - \exp(-Kt)] \tag{8.6}$$

where D_{t} (g per 100 g dry starch) is the digested starch at time t, D_0 is the digested starch at time $t = 0$, D_∞ is the digestion at infinite time ($D_0 + D_{\infty-0}$), and K is the rate constant (min^{-1}).

The glycemic indexes (GIs) of the samples (areas under the digestograms, $\mathrm{AUC}_{\mathrm{exp}}$) were computed with Eq. (8.3), which is the integral form of Eq. (8.7):

$$\mathrm{AUC}_{\mathrm{exp}} = \left[[D_\infty t] + \frac{D_{\infty-0}}{K}\exp(-Kt)\right]_{t_1}^{t_2} \tag{8.7}$$

The estimated model parameters are shown in Table 8.6. The sample exhibited high D_0 (gastric digestion), a measure of the very rapidly digested starch. From the data it can be concluded that the unripe banana appeared to be a potential valuable ingredient for low-GI

Table 8.6 *In vitro* unripe banana starch digestion parameters.

Parameter	Gastric–pancreatic	Pancreatic
D_0 (g/100 g dry starch)	47.1	–
D_∞ (g/100 g dry starch)	94.6	44.9
$K \times 10^{-3}$ (min^{-1})	2.8	2.3
$\mathrm{GI}_{\mathrm{H90}}$ (%)	85	48
$\mathrm{GI}_{\mathrm{HI}}$ (%)	101	53

D_0, digested starch at time $t = 0$; D_∞, digestion at infinite time ($D_0 + D_{\infty-0}$); GI, glycemic index; HI, hydrolysis index; and K, rate constant.
Source: Srikaeo et al. (2011). Reproduced with permission of John Wiley and Sons.

foods. The GI of foods depends upon various factors such as starch granule morphology, amylose to amylopectin ratio, molecular structure, and degree of branching in terms of steric hindrance and consequently mass transfer resistance.

The digestibility fractions of uncooked and gelatinized banana starches obtained by *in vitro* starch hydrolysis demonstrated that RDS, SDS, and RS values of uncooked banana starches ranged from 1.3 to 16.6%, 4.4 to 18.1%, and 88.0 to 92.0%, respectively (Agama-Acevedo et al. 2015). A marginal difference in the digestion property of the uncooked native banana starches can be attributed to the chain-length distribution, and the arrangement of these chains in the semicrystalline structure of amylopectin. When the native banana starches were cooked in a boiling water bath for 20 minutes before the Englyst test, the resistant digestion property was lost, with an increase in the RDS. Cooking induced a disorganization of the starch components in the semicrystalline structure of the native banana starches, indicating that the B-type polymorphism is critical for their resistant digestion property. Although the RDS content increased in the gelatinized samples, an important amount of SDS is retained in some samples. This issue opens the possibility to modify these banana starches with physical methods (i.e. hydrothermal treatments) to increase the SDS fraction. Additionally, the gelatinized banana starches exhibited a higher RS content.

Green Banana Waste Utilization

Agricultural practice generates a significant amount of waste rich in cellulose and its proper utilization could add value to this by-product. Plantain and banana harvest wastes are rich in starch, which has numerous applications in various industries including the paper, textile, pharmaceutical, food, and polymer industries. During processing of bananas, a huge amount of by-products is generated, including, peel, rachis, leaves and rhizome. These by-products can be an alternative source of natural bioactive compounds and value-added products (e.g. fibers) (Padam et al. 2014). The peel contains a large amount of cellulose (12%), which can be potentially appropriate as a reinforcing component in high-performance composite films (Tibolla et al. 2017). In addition, numerous products have been obtained from banana waste including cellulose microfibrils and cellulose nanofibers (CNFs).

The industrial plantain peel wastes in Columbia were utilized to produce starch using the wet extraction method (Hernández-Carmona et al. 2017). Starch extraction from plantain peel wastes has proven potential for waste use and processing into value-added products. Average starch yield was 29% (dry mass), while purity reached almost 70%.

Banana peels were transformed into value-added CNFs using a combination of chemical and mechanical treatments with different number of passages through the high-pressure homogenizer (0, 3, 5, and 7 passages) (Pelissari et al. 2017). New nanocomposites (NCs) were then fabricated from a mixed suspension of banana starch and CNFs and the effect of the addition of these nanofibers on the properties of the resulting NCs was investigated. The CNFs increased the T_g of the NC by establishing a strong intermolecular interaction between the starch and cellulose. The tensile strength of the nanocomposites improved significantly. Tibolla et al. (2019) prepared two different types of CNFs, CNF1 and CNF2,

by enzymatic hydrolysis of banana peel bran concentration (15 and 35%) at selected temperatures (35 and 55 °C) using xylanase (70 U/g). The length and diameters of CNF1 were 1490 and 3.7 nm and the corresponding values for CNF2 were 1545 and 8.8 nm, respectively. The aspect ratio of those nanofibers (length/diameter) were 405 and 170. Both CNFs were employed to develop unripe banana starch-based NC films. The cytotoxicity of CNFs was evaluated on a Caco-2 cell line, and it was found that CNFs were not cytotoxic at 50–2000 μg/ml. The developed NCs showed a complex structure with a remarkable improvement in mechanical and water barrier properties, opacity, and ultraviolet light barrier compared with the control film. CNFs can offer great potential as reinforcing material for starch-based NC films, producing a value-added food packaging from a waste material.

The thinner and finer webs (43.8 and 10.3 nm) of cellulose nanopapers (CNPs) were produced from the underutilized agro-waste of culinary banana (Musa ABB) peel using chemical treatment followed by high-intensity ultrasonication (Khawas et al. 2016). The high purity of cellulose in the developed CNP was verified by FTIR and ^{13}C-NMR of cellulose I. The diameter (43.8 nm) and length (1389.6 nm) of the CNF in CNP-UT revealed a lower aspect ratio (31.7) compared with CNP-T (51.9) which is made up of smaller diameter (10.3 nm) and length (536.1 nm). The developed CNP exhibited high crystallinity, thermal, mechanical and electrical stability, and has credible evidence for the production of bio-composites and may be considered as one of the potent renewable reinforcement agents for use in the food packaging industry.

Summary

Green bananas are consumed as a staple food in many parts of the world. On account of the excellent source of RS, the flour obtained from unripe banana has been considered for product development with considerable health benefits by increasing the non-digestible fraction. The drying process has minimal effect on the RS starch of GBF. The starch granules of GBSs were oval, rod shaped, and irregular with smooth surfaces and the XRD pattern exhibited the B-type crystallinity pattern. Flour contains a considerable amount of bioactive compounds for health promotion and thus phytochemical and *in vitro* studies have received much interest. GBF has a high viscosity and a high tendency toward retrogradation, which are features required for their use as thickeners. The banana wastes are rich in starch, which has numerous applications in various industries including the paper, textile, pharmaceutical, food, and polymer industries. During processing of bananas, a huge amount of waste is produced, which could be transformed into natural bioactive compounds and value-added products.

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9

Innovative Processing Technologies for Banana Products

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Introduction

Among fruits, bananas are the most consumed and produced worldwide. Bananas are eaten in the ripe stage, and about 90% of production is consumed in the production areas. A marginal proportion of ripe fruit is utilized for processing and storage. In this chapter, the focus is on the ripe fruit only. Ripe bananas can be processed into various products similar to those obtained from other fruits including juice, fruit drinks, puree, marmalade, jam, fermented drinks, flour, flakes, confectionery and ingredients for bakery, and frozen desserts.

Thermal processing (TP) is commonly employed for the processing of fruit products, and banana is not an exception. Banana-based beverages are processed by pasteurization to enhance the shelf life by inactivating the associated enzymes and pathogens. Drying is employed to remove the moisture and to produce dried slices, and further to banana flour. Although the conventional processing technologies improve the shelf life of fruit products, the sensory properties, bioactive compounds, and nutrients losses become significant for those products. As a result, consumers are looking for fresh-like products rather than cooked-flavor products produced by conventional processing technologies. A group of new technologies applied to food processing is known as "Novel or Emerging Technologies" where food products are either processed by non-thermal methods (e.g., high pressure processing [HPP], oscillating magnetic field, irradiation, ozonization) or are based on electrotechnologies (e.g., pulsed electric, radio frequency [RF] heating, microwave [MW] heating, infrared [IR] heating, Ohmic heating) to retain micronutrients and keep the sensory quality at the highest levels. Electrotechnology relies on conventional thermal mechanisms for achieving preservation and processing whereas, non-thermal processing technologies inactivate enzymes and microorganisms, and modify the functional properties of food without substantially increasing the product temperature.

Some of these novel technologies have gradually transferred from the laboratory to pilot scale, and a few of them have even been approved by regulatory agencies for use on an industrial scale. The major challenge for the commercialization of any novel technology is process validation and ensuring product safety. Among novel technologies, HPP has been approved for the pasteurization of specific products; its approval in the USA for use as a processing alternative in combination with thermal processing for sterilization has also been

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granted (NCFST 2009). The bottleneck of the novel technologies is the high capital expenditures. Furthermore, the novel technologies are mostly developed on either laboratory scale or pilot scale, and therefore, full-scale operational cost and the impact on the product are unknown, and quality risk remains a hurdle for the processors (Ahmed and Ozadali 2012).

This chapter describes the applications of some novel food processing technologies and their influence on ripe banana products. Furthermore, ripening, quality, shelf life, and safety of banana products as influenced by novel processing technologies are elucidated in detail.

High Pressure Processing

Pressure is an important thermodynamic parameter, which can intensely influence molecular systems. Over the past two decades, HPP has emerged as one of the promising non-thermal processing technologies of recent times. It has the potential to replace or complement conventional thermal processing by providing a balance between quality and safety. The HPP, or ultra high pressure (UHP) or high hydrostatic pressure (HHP), is defined as a process that employs pressure from 100 to 800 MPa to food products, with or without packaging. The time of exposure may vary from a few seconds to about 30 minutes and the temperatures maintained during pressure treatment may vary from subzero to above 100 °C. The process can extend the shelf life of foods by inactivating enzymes (e.g., pectin methylesterase, PME), spoilage organisms (e.g., yeasts, molds, and lactic acid bacteria), and enhance the safety of products by killing vegetative pathogens (e.g., *Escherichia coli* O157: H7, *Listeria monocytogenes,* and *Salmonella*). Contrary to thermal processing, HPP can preserve key food quality components (e.g., vitamins, flavor compounds, and pigments) effectively, which helps products processed in this manner keep qualities associated with fresh or unprocessed foods. Among fruit products, juices appear to be the most frequently investigated test samples.

HPP can be carried out in any type of hydraulic fluid including water, glycol-water solutions, castor oil, sodium benzoates and ethanol solutions (Balasubramaniam et al. 2008) but water is preferred because of its ease of operation and compatibility with food materials. Additionally, water is relatively incompressible, and it stores much less energy in its compressed state than gases (Earnshaw 1996). The high pressure (HP) chamber is filled with water and HP is generated by compression (direct or indirect) or by heating the pressure medium. Once the desired pressure is achieved, it is maintained at that level, and no additional energy has to be spent.

HP equipment is very specialized and expensive. Pressure vessels are constructed out of forged steel or reinforced with tensioned wire windings (Earnshaw 1996). Currently, laboratory, pilot plant and commercial scale HP equipment (batch, semi-continuous, continuous) are available for different food applications. A list of HP manufacturers is presented in Table 9.1. About 270 HP units at around 200 companies representing a total vessel volume of about 55,000 liters around the world were reported in commercial service (excluding lab-scale or pilot plant machines) in 2014 (Martin 2016). Industrially, HP operates discontinuously and can attain pressures of up to 800 MPa, although pressures exceeding 400 MPa

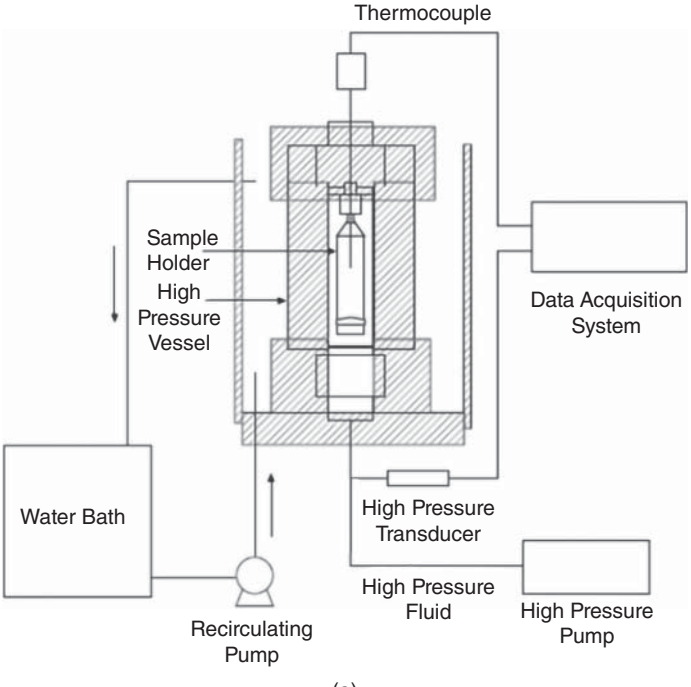
Table 9.1 List of major distributors and manufacturers of high pressure units.

Manufacturer/distributor	High pressure unit specifications
Laboratory scale	
Avure Technologies, USA	690 MPa; 1.5 l
Stansted Fluid Power Ltd, UK	400 MPa; 10 ml to 5 l; multi-vessel units
EPSI, Belgium	1000 MPa; 5 l
FLOW	600–1500 MPa; 1.5 l
ALSTHOM	400–700 MPa; 3–4 l; semi-continuous; and 600 MPa, 5 l
RESATO	800 MPa; multi-vessel units
Commercial/pilot scale	
Avure Technologies, USA	600 MPa; 35–687 l (largest diameter vessel available); production capacity, 5000 kg/h; wire winding technology and continuous operation
Hiperbaric, Spain	600 MPa; 55–525 l; largest diameter, 380 mm; production capacity, 3000 kg/h
Bao Tou KeFa High-pressure Technology Co., Ltd (China)	600 MPa; 30–200 l; single, quos (2 × 200 l, 2 × 300 l), quartos (4 × 200 l, 4 × 300 l); autofrettage technology
Multivac	600 MPa; 55–350 l; volume 900 l/h
ALSTHOM	500 MPa; 50–500 l
UHDE	700 MPa; 100 l; semi-continuous
Kobe Steel	400 MPa; 2 × 300 l
Stansted Fluid Power Ltd, UK	350 MPa; High pressure homogenizer
Elmhurst Research, Inc.	700 MPa

are not normally used for foods because they can bring about a reversible or irreversible disruption of inter- and intramolecular bonds (Knorr et al. 2006; Heinz and Buckow 2010).

Further, additional parameters are incorporated into the basic equipment to broaden the scope of the technology. Pressure-shift freezing is another form of use of HP technology. In Japan, the Meidi-ya Company is manufacturing jams, jellies and sauces using products pre-filled into flexible plastic containers, which are subsequently loaded into a vessel for pressure treatment. Other manufacturing configurations consist of either direct or indirect pressurization of pumpable foods or drinks and subsequent aseptic or clean packaging (Earnshaw 1996).

Schematic diagrams for HP processing for fruit products and laboratory-scale equipment are shown in Figure 9.1a and Figure 9.1b, respectively. Liquid foods can be compressed directly in a pressure vessel. The samples are packed in flexible packaging, and placed in the pressure vessel, which is then closed. The pressure transmitting medium is applied after the degassing of the vessel, and pressure is applied through a HP pump. The resulting volume change due to compression is about 4% at 100 MPa at room temperature and 15% at 600 MPa. The food remains under pressure for a specified treatment time, and then the chamber is decompressed, and the treated food is taken out.



(a)

(b)

Figure 9.1 (a) Schematic diagram of a high pressure operation. Source: Patazca et al. (2007). Reproduced with permission of Elsevier. (b) Laboratory scale high pressure unit. Source: Courtesy of Avure Technology, USA.

High pressures can be applied during the freezing of foods. There are two types of high pressure shift freezing (HPSF): (i) expansion occurs gradually; and (ii) expansion to atmospheric pressure occurs suddenly, thus achieving considerable supercooling at atmospheric pressure. HPSF is considered to be a less harmful freezing method for a cellular structure like fruit. Table 9.2 summarizes the influence of HP on the banana and banana-based products.

The quality characteristics of HP-treated (500 MPa/10 min) and thermally treated (90 °C/2 min) banana puree during 30 days of refrigerated storage were compared by Xu et al. (2016). The total aerobic bacteria and yeasts and molds counts of banana puree were drastically reduced from 3.80 and 3.10 CFU/g to 1 and 0.3 CFU/g by HP and thermal treatment, respectively. Most of the quality parameters, i.e., pH, titratable acidity, total soluble solids (TSS), lightness, and yellowness, total phenolic content (TPC), and antioxidant capacity remained unaffected by the treatment. During storage, color parameters of puree samples did not change whereas the percentage of TPC and ascorbic acid (AA) of HP-treated samples decreased drastically (75.85 and 55.09%) compared with thermally treated samples (96.30 and 68.09%). The loss of antioxidant capacity supported the loss of AA and TPC. The particle size distribution and apparent viscosity of banana puree was not influenced by the pressure treatment whereas thermal processing increased the number of smaller particles and viscosity after processing and in storage. The flavor as detected by volatiles was well preserved by both treatments although HP treatment had the edge over the thermal treatment.

Ly-Nguyen et al. (2003) assessed thermal–HP inactivation (at a moderate temperature, 30–76 °C, in combination with HP, 0.1–900 MPa) of banana PME in a model system at pH 7.0. The stable fraction remained inactivated and isobaric-isothermal inactivation followed a fractional-conversion model. At lower pressure (≤300–400 MPa) and higher temperature (≥64 °C), an antagonistic effect of pressure and heat was observed. Third-degree polynomial models were successfully employed to describe the heat–pressure dependence of the inactivation rate constants.

Hurtado et al. (2015) prepared "fresh-like" banana smoothies free of cooked-fruit flavors using HP treatment (350 MPa/10 °C/5 min) thermal processing (TP, 85 °C/7 min) and compared their stability and sensory acceptability for at least 14 days at 4 °C. The intensity of odor and flavor of banana decreased during the storage period and, mostly, the intensity of both remained higher in the HP smoothies than in the TP smoothies. The loss of fresh fruit flavor and reduced sliminess indicated a sensory deterioration of smoothies during storage. HP-treated smoothies retained the maximum amount of vitamin C, however, degraded significantly during storage. Most importantly, the HP smoothies were free of the off-odors and off-flavors, while the TP smoothies developed the persistent odor and flavor of cooked fruit, which explains their lower score for freshness. Moreover, the HP smoothies were scored as more acidic than the TP smoothies from day 14.

High Pressure Homogenization

High pressure homogenization (HPH) is an emerging technology, which has been used for food preservation with minimum sensory and nutritional loss (Franchi et al. 2011).

Table 9.2 Application of high pressure processing/homogenization for banana products.

Products	Process conditions	Major observations
Banana puree packed in LDPE bags[a]	500 MPa, 25–35 °C and 10 min	■ Microbial safety and stability of banana puree was achieved ■ No change in pH, acidity, TSS, lightness, yellowness, TPC, and antioxidant capacity but thermal pasteurization reduced redness and ascorbic acid ■ HPP had minimal negative effect on banana puree volatiles ■ HPP was an effective alternative pasteurization for preserving the quality of fresh-like banana puree
PME extracted from bananas[b]	0.1–900 MPa; 30–76 °C	■ Thermal–high pressure inactivation of PME extracted from bananas indicated the stable fraction was not inactivated and isobaric-isothermal inactivation followed a fractional-conversion model ■ At lower pressure (300–400 MPa) and higher temperature (>64 °C), an antagonistic effect of pressure and heat was observed
Banana juice, HPH[c]	150–400 MPa; juice temperature after homogenization and at the heat exchanger outlet, 46–100 °C	■ Pressures >200 MPa were required to achieve 4-log reduction of total mesophilic bacteria and pectate lyase inactivation ■ HPH produced brighter and less viscous banana juice ■ The homogenization design could play a critical role in determining the desired effects on product quality attributes ■ HPH treatments could be a reliable technological alternative to conventional heat treatments for added-value banana juice production
Banana juice, HPCD[d]	HPCD treatment of pulp at 20 MPa and mild heat (45, 50, 55, and 60 °C) for 30 min at atmospheric pressure	■ Residual polyphenol oxidase in the juice from HPCD-treated banana pulp was lower than that from mild heat-treated pulp ■ Color L* value and clarity of juice was higher than that of mild heat-treated banana pulp, however, a* value, b* value, viscosity, pectin and protein were lower compared with mild heat treatment ■ The particle size and zeta potential of juice from HPCD-treated pulp became smaller and more negative, and all their reduction increased with increasing treatment temperature ■ A slight decrease in the juice yield, pH, and total soluble solids of banana juice from HPCD-treated banana pulp was observed compared with juice from mild heat-treated banana pulp

HPCD, high pressure carbon dioxide; HPH, high pressure homogenization; HPP, high pressure processing; LDPE, low-density polyethylene; PME, pectin methylesterase; TPC, total phenolic content; TSS, total soluble solids.
Source: [a]Xu et al. (2016); [b]Ly-Nguyen et al. (2003); [c]Calligaris et al. (2012); [d]Yu et al. (2013).

The main principle of HPH is similar to the conventional homogenization employed in the dairy industry except for the pressure level, which is significantly higher (up to 400 MPa). HPH allows processing in continuous fluid foodstuffs and its great potential to inactivate pathogenic and spoilage microorganisms in fruit juices has been reported (Suárez-Jacobo et al. 2011; Velázquez-Estrada et al. 2011). Besides its ability to reduce the microbial activity, ultra HPH also minimizes the adverse effects of heat on food properties or constituents. The effects of HPH are a function of the level of pressure applied for the homogenization, the temperature of the enzyme during the process, the nature of enzyme studied, pH of homogenization and the presence/absence of substrate during homogenization (Tribst and Cristianini 2012a, 2012b).

Calligaris et al. (2012) examined the potential applicability of HPH for the production of banana juices using prototype equipment working up to 400 MPa and a lab-scale homogenizer working up to 150 MPa. It was observed that pressures higher than 200 MPa were required to achieve 4-log cycle reduction of total mesophilic bacteria and pectate lyase inactivation. HPH-treated banana juice was found to be brighter and less viscous than the untreated one. Furthermore, data indicated that HPH treatments could be a reliable technological alternative to conventional heat treatments for the production of value-added fruit juices. However, the design of homogenizer could play a critical role in affecting the product quality attributes.

High Pressure Carbon Dioxide

High pressure carbon dioxide (HPCD) is another novel non-thermal technology for pasteurization of food products by inactivating microorganisms and enzymes. The HPCD preservation technique has many advantages. Carbon dioxide used in this process is relatively inert, inexpensive, nontoxic, nonflammable, recyclable and readily available in high purity leaving no residue when removed after the process (Clifford and Williams 2000). Additionally, it is considered to be a GRAS (generally recognized as safe) solvent, which means it can be used in food products.

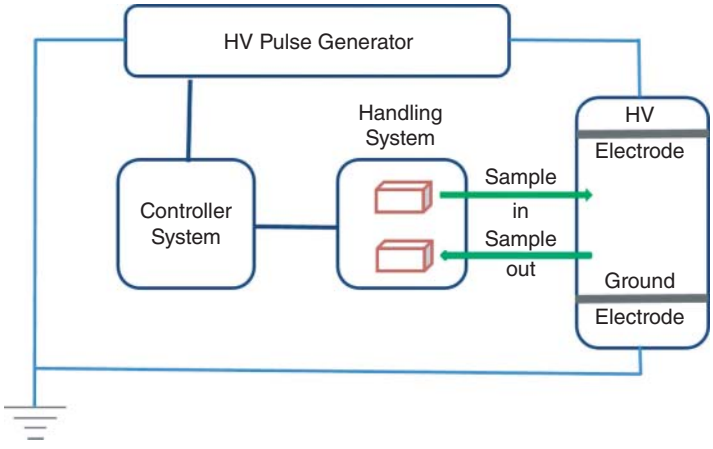
Yu et al. (2013) employed HPCD at 20 MPa and mild heat at atmospheric pressure to extract juice from banana pulp. The process temperatures were 45, 50, 55, and 60 °C, and the treatment time was 30 minutes. It was observed that the residual polyphenol oxidase (PPO) in the juice from HPCD-treated banana pulp was lower than the mild heat-treated banana pulp and its minimum value was 11.6% at 60 °C. The lightness and clarity of juice from HPCD-treated banana pulp was higher than that from mild heat-treated banana pulp; however, color a* and b* values, viscosity, pectin, and protein were lower. The particle size and zeta potential of juice from HPCD-treated banana pulp were finer and more negative. Moreover, a slight decrease in the juice yield, pH, and TSS of banana juice from HPCD-treated banana pulp was observed as compared with juice from mild heat-treated banana pulp.

Pulsed Electric Field Processing

The potential to commercialize the non-thermal pulsed electric field (PEF) technology or electroporation as a new method to preserve food products has received the attention of the

food industry, which wishes to satisfy consumers' demands for fresh-like products (Wouters et al. 2001). The PEF treatment or high intensity pulsed electric field is one of the most suitable techniques for fruit processing, which has emerged as a promising alternative to conventional pasteurization (Sizer and Balasubramaniam 1999; Toepfl et al. 2007). By permeabilizing cell membranes, PEF facilitated tissue softening and improved mass transfer, resulting in improved extraction. This process has been studied as a non-thermal treatment for food pasteurization (Eshtiaghi and Knorr 2002). However, the PEF technology is mostly suitable for liquid foods, e.g., fruit juice to increase their shelf life while maintaining the sensory attributes. The retention of vitamins, pigments and antioxidants adds a healthier, fresh-like and more appetizing product.

The PEF treatment of liquid foods is based on the application of high intensity electric field (typically 20–80 kV/cm) to the food product as it flows between two electrodes. Generally, PEF treatment systems consist of (i) a pulse generator, (ii) treatment chambers, (iii) a fluid-handling system, and (iv) monitoring systems (Rivas et al. 2006). A schematic diagram of the unit is illustrated in Figure 9.2a. The PEF treatment chamber uses two electrodes



(a)

(b)

(c)

Figure 9.2 (a) Schematic diagram of pulse electric field heating unit. (b) PEF SafeJuice System for juice processing. Source: Courtesy of Elea GmbH, Germany. (c) Co-field industrial continuous treatment chambers fitted with food grade stainless steel and nylon, plug-and-play, with high-voltage interlock. Source: Courtesy of Energy Pulse System, Portugal.

and delivers a high voltage to the food material. An industrial PEF system and continuous treatment chamber of fluid food are shown in Figure 9.2b and Figure 9.2c, respectively.

The design of the treatment chamber is one of the most important factors in the development of the PEF treatment for non-thermal pasteurization, as it should impart uniform electric field to foods with a minimum increase in temperature and the electrodes should be designed to minimize the effect of electrolysis (Toepfl et al. 2007). The PEF may be applied in the form of exponentially decaying, square wave, bipolar, or oscillatory pulses and at ambient, subambient, or slightly above ambient temperature. Duration of pulses is in seconds. The key variables involved in PEF are electric field strength (E), pulse duration or pulse width (τ), treatment time (t), pulse repetition rate (f), the waveform of the pulse, and treatment temperature. Huang and Wang (2009) reviewed various PEF designs for liquid food pasteurization.

In recent years, PEF treatment has received a great deal of attention for fruit processing. It is expected that application of PEF treatment would be less detrimental than heat treatment for plant tissue ingredients such as pigments, vitamins, and flavoring agents. Additionally, the process ensures product safety by inactivating microorganisms. Most of the research work on PEF treatment of fruit products is of the comparative type. Post-PEF products are regularly compared with high-temperature short-time (HTST) pasteurization to ensure the safety issue. PEF technology has been integrated with the aseptic processing and packaging technologies to process fruit products through a continuous flow processing line. A combination of mild heat treatment and PEF are found to be effective. Application of PEF is restricted to low electrical conductivity food products that can withstand high electric fields. It is also important that the product does not entrap bubbles. The particle size of the liquid food is an application limitation for this technology. Several theories have been proposed to explain microbial inactivation by PEF, and the most studied are electrical breakdown and electroporation (Weaver 1995).

Contrary to other juices, limited information is available on the application of PEF for banana juice. Walking-Ribeiro et al. (2008) used a combination of moderate heat and PEF as a potential alternative to thermal pasteurization of a smoothie based on banana, pineapple, and coconut milk using *E. coli* K12 as a test organism. The smoothie was heated to a selected temperature (25, 45 or 55 °C) over 60 seconds, and thereafter, cooled to 10 °C. PEF was applied at the electric field strengths of 24 and 34 kV/cm with specific energy inputs of 350, 500, and 650 kJ/l. A higher reduction in *E. coli* was achieved by increasing the temperature from 45 to 55 °C. By increasing the field strength in the stand-alone PEF treatment from 24 to 34 kV/cm, a higher number of *E. coli* cells were inactivated (2.8 vs. 4.2 $\log_{10}$ CFU/ml). An increase in heating temperature from 45 to 55 °C during a combined heat/PEF hurdle approach induced a further inactivation, i.e., 5.1 compared with 6.9 $\log_{10}$ CFU/ml, respectively, with the latter value comparable with the bacterial reduction of 6.3 $\log_{10}$ CFU/ml, achieved by thermal pasteurization (72 °C, 15 seconds).

Microwave Drying

MW heating refers to dielectric heating because of the polarization effects at a selected frequency band in a non-conductor. MWs are a part of the electromagnetic spectrum, which consists of frequencies from 300 to 3000 MHz. MW energy is delivered at a molecular

level, through molecular interaction with the electromagnetic field, in particular, through molecular friction resulting from dipole rotation of polar solvents and the conductive migration of dissolved ions (Oliveira and Franca 2002).

MW heating is very common as it is mostly used in the household for the warming of foods in the form of MW ovens. The technology exploited food industries for tempering frozen foods, cooking of solid foods, and also in continuous flow MW heating of fluids (Ahmed and Ozadali 2012). In the United States, the MW frequencies employed for the household and industries are regulated by the Federal Communication Commission. For household MW ovens, a frequency of 2450 MHz is assigned whereas 915 MHz is prescribed for industrial applications.

The heating of foods using MW depends on the generation of heat inside the food by the transformation of electromagnetic energy from the MWs into heat. Furthermore, MW heating differs widely from the conventional heating of foods in the following points: (i) ease of power on and off for the heating and degree of heating; (ii) it has very rapid heating dynamics without overheating the surface; (iii) it does not depend on the contact with hot surfaces or a hot medium or electrodes; (iv) the heating is very selective on materials used for the heating purpose; and (v) it is volumetric heating, thus theoretically more uniform in heating over conventional heating (Coronel et al. 2009). The non-uniform temperature gradient becomes the major limitation of MW heating. It is suggested that heating efficiency could be improved by following certain rules during heating including MW waveguide location, food composition, geometry and placement of food inside the oven (Geedipalli et al. 2007). An industrial MW dryer is shown in Figure 9.3.

Figure 9.3 An industrial microwave dryer (5–100 kW/915 MHz per module). Source: Courtesy of PÜSCHNER GMBH (Germany).

Dehydration of banana offers an excellent method of preservation by removing the moisture content and lowering the water activity, and further slowing down microbial growth, enzymatic activity, and chemical reaction. Different drying methods have been reported in the literature for banana including solar drying, tray drying, and osmotic/hot air drying. Drying of banana slices using a series of steps, convection (60 °C at 1.45 m/s)/MW (350, 490, and 700 W power)/convection/finishing by MW (at 350 W), was reported by Maskan (2000). The drying of banana slices took place in the falling rate period and the convection drying took the longest time. Higher drying rates were observed with higher power level. MW finish drying reduced the convection drying time by about 64.3%. The crisp banana slices can be produced by dehydration too. A comparative study of different drying strategies to produce dried bananas with controlled microstructure and texture properties was evaluated by Monteiro et al. (2016). They employed MW heating coupled with vacuum pulses for the work. Banana slices were dehydrated by microwave vacuum drying (MWVD), a microwave multi-flash drying (MWMFD), and freeze-drying.

Barba et al. (2014) compared the effects of the MW-assisted drying process against the convective air-assisted drying and found the MW drying process was more effective. In particular, the resulting samples were homogeneous in water content; the contents of reducing sugars were decreased significantly on drying with MWs. Further, the PPO was inactivated by the high temperature produced by the process and thus the polyphenol content remained practically the same as in the fresh product.

Öztürk et al. (2017) evaluated the effects of initial moisture content, different drying methods, and different MW power on the quality and dielectric properties of banana. They also aimed to examine the correlation between dielectric properties and MW and microwave-infrared combination (MW-IR) drying characteristics of banana. Samples with different initial moisture contents were dried by using different MW powers (180, 270, and 360 W). For combination drying of banana, the application parameters were adjusted to 360 W for MW power and 600 W for upper and lower halogen lamps (600 W). It was found that an increase in MW power increased the rate of drying and a decrease in processing time. Furthermore, the combination of IR and MW resulted in higher rates of moisture loss from the product. Dielectric properties of banana samples decreased with increasing MW power and initial moisture content. When MW and combination dried samples were compared with conventionally dried ones, products with lower final moisture content and higher quality could be produced with a time saving of approximately 98%.

Ultrasound

Ultrasound is sound waves, where the frequency surpasses the hearing limit of the human ear (~20 kHz). Ultrasound has been known for many years for its major applications in medical diagnostics, industrial processes, and inspections. The applications of ultrasound in food processing and quality control can be divided into low energy (low power, low intensity) and high energy (high power, high intensity), based on the frequency range. Low energy ultrasound (frequencies >100 kHz and intensities <1 W cm^2) can be employed for non-invasive analysis and monitoring of food materials during processing and storage to ensure high quality and safety whereas high energy ultrasound (frequencies 20–500 kHz

and intensities >1 W cm^2) has a disruptive impact on the physicochemical, mechanical and biochemical properties of foods (Awad et al. 2012). High energy systems are quite attractive for the food industry for controlling microstructure and modifying textural characteristics, and inactivation or acceleration of enzymatic activity to improve shelf life and quality of products. The propagation of ultrasound in a liquid produces bubble cavitation because of the pressure changes. The collapse of those microbubbles is responsible for an increase in temperature and pressure. Thus, the intense local energy and high pressure generate a localized pasteurization effect without causing a significant rise in macro-temperature (Jiménez-Sánchez et al. 2016). However, still, the technology remains at laboratory or pilot scale due to lack of efficient design of ultrasonic power systems.

Ultrasound has been identified as a potential technology to meet the U.S. Food and Drug Administration (FDA) requirement of a 5-log reduction in pertinent microorganisms found in fruit juices (Salleh-Mack and Roberts 2007). When high power ultrasound propagates in a liquid, cavitation bubbles are generated due to pressure changes. These microbubbles collapse violently in the succeeding compression cycles of a propagated sonic wave.

The effect of ultrasonic pretreatment before air-drying on the quality of bananas was examined by Fernandes and Rodrigues (2007). The water diffusivity in the air-drying process for bananas increased after the application of ultrasound and the overall drying time was reduced by 11% confirming an energy cost intensive. During the ultrasonic treatment, bananas lost sugar, so the ultrasonic pretreatment can be a promising process to produce dried fruits with low sugar content.

Bora et al. (2017) employed ultrasound and enzymatic pretreatment (cellulase and pectinase) in studying the yield and properties of banana juice. Ultrasonic pretreatment individually did not increase the yield of juice significantly. However, ultrasound in combination with the enzymes produced a maximum yield (89.40%) over the control (47.30%). The viscosity of the juice lowered with the addition of enzymes and with the application of ultrasound. Ultrasonication alone was found to be more effective than enzymatic treatment in improving the juice clarity.

Ionizing Radiation

Ionizing radiation has the potential for extending the shelf life of food commodities due to its capabilities to eliminate pathogens, disinfest fresh fruits as a postharvest quarantine treatment, delay ripening, and reduce or eliminate microorganisms. Ionizing radiation can be achieved using γ-rays (with Co-60 or Cs-137 radioisotope), electron beams, or X-rays, as specified in 21 CFR 179.26(a) for packaged food. The influence of radiation on food and packaging depends on the type of radiation and energy level, exposure time, composition, physical state, temperature and environment of the absorbing material. Chemical changes can occur via primary radiolysis effects, which occur as a result of the adsorption of the energy by the absorbing matter and can have biological consequences in the case where the target materials include living organisms. With proper application, irradiation can be an effective means of eliminating and reducing the microbial load and thus the foodborne diseases they induce, thereby improving the safety of many foods as well as extending their shelf life (Komolprasert 2007).

Expert groups of national and international organizations as well as many regulatory agencies have generally concluded that irradiated food is safe and wholesome, and that food irradiation at commonly used dosing levels does not present any enhanced toxicological, microbiological, or nutritional hazards to the food beyond those brought about by conventional food processing techniques. These experts have agreed that irradiation of food for microbial safety should be carried out under Good Manufacturing Practices (GMPs) and Good Irradiation Practices (GIPs). Subsequently, standards on various aspects of radiation processing have been developed and internationally accepted (Farrar et al. 1993).

The World Health Organization (WHO) considers ionizing radiation an important process for ensuring food safety (Diehl 1995). It can be a useful control measure in the production of several types of raw or minimally processed foods such as poultry, meat and meat products, fish, seafood, and fruits and vegetables (Molins et al. 2001). An increased interest in food irradiation for quality and microbiological safety was realized by several emerging studies on various food products, including irradiation of fruit juices (Fan et al. 2004). Irradiation is the process of exposing food to ionizing radiation in order to destroy food-poisoning bacteria such as *Salmonella*, *Campylobacter*, and *E. coli* and viruses, and for insect disinfestation in foods.

Thomas et al. (1971) studied γ-irradiation (20–40 krad) for inhibiting ripening in preclimacteric bananas without altering the fruit quality, and it was found that both fruit maturity at harvest and post-irradiation storage temperature markedly influence the response to irradiation. The ability of the banana fruit to withstand higher doses of γ-irradiation depends on the physiological status of the fruit at the time of irradiation. Doses above 50 krad resulted in severe skin discoloration and fruit splitting. Ionizing radiation under anoxia did not reduce the radiation injury significantly, which suggests that factors other than ozone formed during the radiation in air may contribute the radiation damage. Furthermore, it was reported that banana fruits on the climacteric could withstand a dosage up to 200 krad without effect on ripening rate.

Gloria and Adao (2013) employed a range of γ-irradiation doses (0, 1, 1.5, and 2 kGy) to green "Prata" bananas at the full three-quarter stage and stored at 16 °C and 85% relative humidity. Samples were collected at a regular interval and analyzed for peel color, pulp-to-peel ratio, and levels of starch, soluble sugars and bioactive amines. It was found that the starch degradation and formation of fructose and glucose followed first- and zero-order kinetics, respectively. Higher irradiation doses caused increased inhibitory effect on starch degradation and glucose formation. However, doses of 1.5 and 2.0 kGy caused browning of the peel, making the fruit unacceptable. Irradiation at 1.0 kGy was the most promising dose, as it did not affect peel color, the pulp-to-peel ratio or the levels of the amines spermidine, serotonin and putrescine. However, it slowed down starch degradation and the formation and accumulation of fructose and glucose, delaying the ripening of the fruit for seven days.

With the ability to modify wavelengths necessary to the photosynthetically active radiation spectrum of plant pigments, light-emitting diodes (LEDs) provide huge potential in horticultural lighting. Huang et al. (2018) employed LED-light irradiation to study the ripening and nutritional quality of postharvest banana fruit. Mature green bananas were treated daily with selected blue (464–474 nm), green (515–525 nm), and red (617–627 nm) LED lights for 8 days and compared with non-illuminated control. It was observed that the

blue LED lighting had the highest capability for the acceleration of ripening in bananas, followed by red and green. Under LED-light irradiation, faster peel de-greening and flesh softening, and increased ethylene production and respiration rate in bananas were noted during storage. Additionally, the accumulation of ascorbic acid, total phenols, and total sugars in banana fruit were improved by LED light exposure.

Other Novel Processing Technologies

Some other novel technologies have been explored in fruit processing, including ultraviolet (UV) light, pulse light technology, ultrafiltration, ozone treatment, and dense-phase carbon dioxide. Before discussing some of those technologies, it is worth mentioning that the use of some of the technologies such as radiation for food processing or packaging may not be allowed in some countries. It is highly advisable to check with the local regulatory agencies before considering any applications (Ahmed and Ozadali 2012). For instance, the FDA is responsible for regulating the use of irradiation in the treatment of food and food packaging in the US and countries exporting to the US (FDA 2005). This authority derives from the 1958 Food Additives Amendment to the Federal Food, Drug, and Cosmetic Act (FD&C Act) where Congress explicitly defined a source of radiation as a food additive (Section 201(s) of the FD&C Act). The 1958 Food Additives Amendment also provides that food is adulterated (that is, it cannot be marketed legally) if it has been irradiated, unless the irradiation is carried out in conformity with a regulation prescribing safe conditions of use (Section 403(a)(7) of the FD&C Act).

Ultraviolet Light

UV-light technology is a non-thermal, non-chemical, simple, and inexpensive approach applied in the food industry for disinfection. UV light is the electromagnetic radiation in the spectral region classified into four wavelength ranges: UV-A (315–400 nm), UV-B (280–315 nm), UV-C (200–280 nm), and Vacuum-UV (100–200 nm) (Krishnamurthy et al. 2008). The UV-C light treatment uses the radiation from the electromagnetic spectrum (200–280 nm) and a powerful surface germicidal method. It is safe to apply, but some simple precautions are necessary to avoid worker exposure to light and evacuate the generated ozone. It is also reported that both UV-B (280–315 nm) and UV-C (200–280 nm) treatments can enrich certain nutrients and nutraceutical compounds.

The UV radiant exposure must be at least 400 J/m^2 in all parts of the product to achieve microbial inactivation. The major governing factors in the process are the transmissivity of the product, the geometric configuration of the reactor, the power, wavelength and physical arrangement of the UV source(s), the product flow profile and the radiation path length. UV may be used in combination with other alternative process technologies, including various powerful oxidizing agents such as ozone and hydrogen peroxide (FDA 2000).

Alothman et al. (2009) evaluated the effect of ultraviolet (UV-C; 2.158 kJ/m^2) treatment on total phenol, flavonoid, and vitamin C content of fresh-cut banana. It was observed that the UV-C irradiation elevated levels of phenolic and flavonoid contents of banana after 10 minutes of treatment. However, UV-C treatment decreased the vitamin C content.

Ozone Treatment

Ozone is a triatomic allotrope of oxygen and decomposes readily to oxygen. It has a high oxidation potential of 2.07 V in alkaline solution over chlorine (1.36 V), and, therefore, it can be used as an effective antimicrobial agent. Furthermore, the decomposition of ozone to oxygen without producing toxic residues makes it an environmentally friendly sanitizer. A trace amount of ozone with a short contact time produces the desired antimicrobial effect. Excess ozone auto decomposes rapidly to produce oxygen and thus it leaves no residues in food. Such advantages make ozone attractive to the food industry and consequently it was declared as GRAS for use in food processing by the FDA in 1997 (Graham 1997).

De Alencar et al. (2013) studied the influence of ozone treatment (both dry and wet) on the physicochemical, microbiological and sensory qualities of banana. Ozone gas was produced employing an ozone generator based on dielectric barrier discharge (DBD). Bananas untreated with ozone were used as an experimental control. For the dry processing, the fruits were directly fumigated with ozone for 30 minutes. For the wet treatment, the water was first ozonized for 20 minutes followed by immersion of the fruit in the ozonized water for 10 minutes. In both treatments, the utilized gas concentration and flow were 0.36 mg/l and 1.5 l/min, respectively. The quality of the fruits was evaluated at different time intervals (0, 3, 6, 9, and 12 days). It was found that the fruits immersed in the ozonized water presented better quality, in reference to both the physicochemical and microbiological parameters, as well as having good sensory acceptability.

The effect of ozone treatment on total phenol, flavonoid, and vitamin C content of fresh-cut banana cv. "Pisang Mas" was investigated by Alothman et al. (2010). Total phenol and flavonoid contents of fresh-cut banana increased significantly by ozone treatment for up to 20 minutes, with a corresponding increase in ferric reducing antioxidant power (FRAP) and 1,1-diphenyl-2-picrylhydrazyl (DPPH) values. However, ozone treatment was shown to decrease the vitamin C significantly.

Microfiltration

Membrane processes have attracted attention from fruit juice processors because of the athermal separation process without any phase change. Also, the process produces additive-free juices, which have high quality and fresh-like taste. Juice clarification, stabilization, depectinization and concentration are typical steps in which membrane processes such as microfiltration , ultrafiltration , nanofiltration, and reverse osmosis have been successfully employed.

Microfiltration and ultrafiltration offer a quite competitive and attractive alternative compared with thermal processes that cause an irreversible change in the flavor profile, color degradation, and appearance of the cooked product (Cassano et al. 2006). Microfiltration is mostly used as a pretreatment for clarification of various juices. The use of ultrafiltration for the clarification of fruit juices has been employed for various fruit juices. Sagu et al. (2014a) extracted banana juice by pectinase treatment, and clarification of banana juice was carried out using centrifugation and hollow fiber microfiltration. A comparative study of these two processes was conducted with five parameters namely, viscosity, clarity, alcohol-insoluble solids (AIS), polyphenol, and protein in the clarified banana juice. Microfiltration showed

the best result in terms of viscosity, clarity, and AIS. The optimal values of these parameters were: viscosity, 1.22 mPa s; clarity, 93.1% T; and AIS, 0.24% w/w. Based on these physical and nutritional parameters of banana juice obtained, and considering operating parameters, microfiltration was found to be most suitable for primary clarification of banana juice.

Furthermore, Sagu et al. (2014b) employed cross flow ultrafiltration using a hollow fiber module under total recycle mode for banana juice clarification. Three surface-modified polysulfone-based membrane cartridges with molecular weight cut-offs 10, 27, and 44 kDa were used to identify the most suitable membrane. Results indicated that the membrane of molecular weight cut-off 27 kDa was suitable. The permeate flux depended strongly on the transmembrane pressure drop, but its variation on cross flow rate was insignificant. The clarified juice had high clarity and no pectineus materials, and it contained a significant amount of polyphenol and protein.

Machine Vision

Color is the first impression as a quality indicator for a consumer, and the acceptance or rejection of the banana fruit depends upon the accepted color of the peel. In the trade, there are seven stages practiced to evaluate ripening of banana, which relate to pigment changes in the peel of the banana: stage 1, green; stage 2, green, traces of yellow; stage 3, more green than yellow; stage 4, more yellow than green; stage 5, green tip and yellow; stage 6, all yellow; and stage 7, yellow, flecked with brown (Li et al. 1997). In the industry, the color of the fruit is compared with either a visual inspection or color chart or employing some instrument to assess its ripeness. However, all these tests have several limitations and processes are labor intensive.

In recent years, computer vision-based approaches have been proposed to assess the color of banana fruits during ripening stages for the quality inspection, which overcomes the deficiencies of visual and instrumental techniques and offer an objective measure for color and other physical factors. Many algorithms have also been developed based on the appearance of bananas and other quality factors. The system consists of standard illuminants, a digital camera for image acquisition, and computer software for image analysis.

A computer vision system was reported by Mendoza and Aguilera (2004) to identify the ripening stages of bananas based on color, development of brown spots, and image texture information. They counted nine features of appearance, namely, L*, a*, and b* values, brown area percentage, number of brown spots/cm^2, and homogeneity, contrast, correlation and entropy of image texture by capturing images for classification purposes. They showed selected images of one banana from stage 3 to the overripe stage with color change and development of spots. Results indicated that although there were variations in data for color and appearance, a simple classification technique is as good to identify the ripening stages of bananas as professional visual perception. Using L*, a*, and b* bands, brown area percentage and contrast it was possible to classify banana samples in their seven ripening stages with an accuracy of 98%. Computer vision shows promise for online prediction of ripening stages of bananas.

Hu et al. (2015) extended the earlier concept color vision by developing an automatic algorithm based on computer vision to determine three size indicators of banana, namely,

Figure 9.4 Typical computer vision system. Source: Zhang et al. (2018). Licensed under CC BY 4.0.

length, ventral straight length, and arc height, respectively. A typical computer vision system is shown in Figure 9.4. The automatic algorithm calculated these indicators by three steps, namely, (i) image pre-processing, (ii) the Five Points Method which is the core part of the automatic algorithm, and (iii) the Euclidean distances between two certain points. The three size indicators of 28 bananas with slightly curved, curved, and end-straight shape were determined using the manual method, the semi-automatic method, and automatic method, respectively. Results indicated that the automatic method was more precise with lower standard deviations and more accurate with a percent difference within 16 and 22% for the length and the ventral straight length, respectively. In conclusion, the automatic algorithm was acceptable for banana size determination.

Zhang et al. (2018) proposed a novel convolutional neural network architecture, which is designed specifically for the fine-grained classification intended to measure banana ripening stages. The proposed deep indicator integrates the capabilities of accurate fine-grained classification and non-invasive examination. It consists of fine-grained image features based on a data-driven mechanism and offers a deep indicator of banana ripening stage. The resulting indicator can help to differentiate the subtle differences among subordinate classes of bananas in ripening state. Experimental results from 17,312 images of bananas in different ripening stages demonstrated that the deep indicator achieved an accuracy significantly superior to state-of-the-art computer vision-based systems both in rough-

and fine-grained classification of ripening stages irrespective of whether the bananas had severe defects or not.

Conclusions

Banana fruit is mostly consumed as fresh, and a limited portion of the total production goes for processing. The ripening process can be delayed by a suitable novel technology. Considering conventional thermal pasteurization as the processing index, various novel technologies can be employed to produce banana products with desirable sensory and nutritional qualities. Among various available novel technologies, HPP and MW processing have huge potential for industrial applications to produce safe products. More research is required needed for full-scale commercialization of the novel technologies with respect to process optimization, packaging, and consumer acceptance.

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10

Value-Added Processing and Utilization of Banana By-Products

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Introduction

Banana is one of the most widely grown tropical fruit, cultivated in over 130 countries along the tropics and subtropics of Capricorn (Mohapatra et al. 2010). Banana produces a huge quantity of by-products or solid waste during harvest and postharvest operations. In order to get a clear picture of the by-products, one needs to know the different parts of the banana plant and their role in human nourishment.

The banana plant is tall and sturdy with large size leaves and a bunch of fruits (Figure 10.1). It is a large flowering herb which does not have a woody stem. Its trunk, called a pseudostem, is formed by spirally bound leaf sheaths. The stalk or petiole along with the blade or lamina is attached to the sheath. A new sheath, formed at the center of the pseudostem, is tubular in shape and its ends meet each other. However, as it grows older, the next sheath is formed in the center, and the edges of the old sheath are forced apart (Archibald 1949). Generally, a banana plant is 5 m tall but its height may vary from 3 to 7 m depending on variety and growing conditions. Leaves are spirally arranged and may grow to about 2.7 m long and 60 cm wide. At the maturity stage, a stem develops from the rhizome or corm, which moves inside the pseudostem and emerges at the top to produce an inflorescence. The banana fruits develop from the inflorescence in a large "hanging cluster", also known as a "bunch," comprising of 3–20 hands each bearing up to 20 fruits or "fingers." A commercial banana bunch weighs 30–50 kg whereas an individual fruit has an average weight of around 125 g (INIBAP 2000).

A banana plant produces only one bunch in its lifetime which leads to enormous waste generation first at the time of banana bunch harvesting, and secondly at the time of processing or consumption. The parts of the banana plant which turn into solid waste are the roots, suckers, rhizome, pseudostem, leaves, peduncle, rachis, and male bud. The main underground structure is the rhizome, also called the corm or bulb, which produces primary roots and suckers. Secondary and tertiary roots originate from the primary roots. After harvesting, the suckers are either used for producing new crop or discarded as waste. The pseudostem is formed by the spirally bound leaf sheaths. A thin true stem is present at the center of the pseudostem that develops into a peduncle, bunch, rachis, and male flower.

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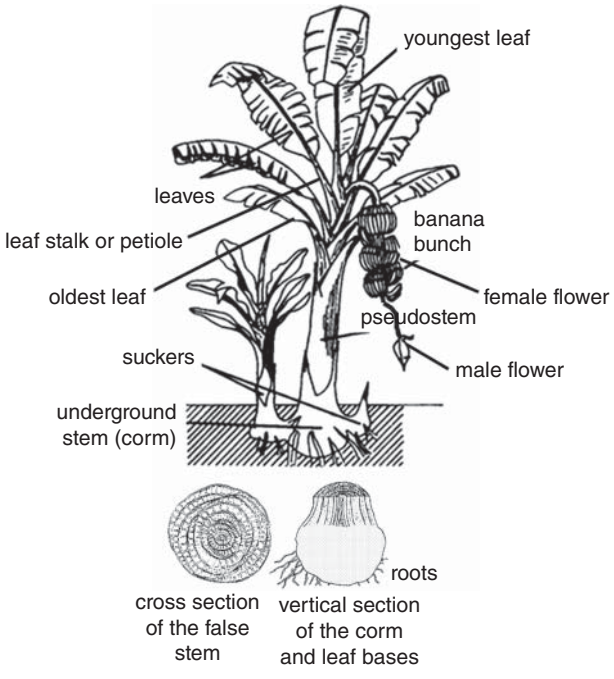

Figure 10.1 Parts of a banana plant at the time of harvesting. Source: FAO (2019a).

The leaf synthesizes food through photosynthesis and consists of three parts, i.e., sheath, petiole, and blade. The sheath is the part of the pseudostem that supports the petiole and blade. After harvesting, leaves become a part of the solid waste (ProMusa.org 2019).

The bunch is the main item of commerce and is separated by cutting the peduncle and rachis. The mature unripe bunch or hands are packed and sent to the fresh fruit market or food processing industry. Unripe bananas are used for making banana chips, flour, etc. The fruit is ripened with the help of growth regulators such as ethylene gas, ethephon solution, etc., and marketed as either fresh fruit or used for processing into various products such as juice, pulp, powder, jam, puree, etc. The peel is discarded as solid waste at the time of consumption or processing.

Quantity of Waste

The quantity of waste generated has been estimated from data on banana production as well as area under cultivation. Kamdem et al. (2013) reported that the volume of the waste produced was double the weight of the banana produced. Sellin et al. (2013) reported that waste generated for 1 ton of banana was 1.5 tons of leaves and 2.5 tons of pseudostem, which makes the total waste about four times that of banana fruit. The waste production in banana for one hectare cultivated area has been estimated as follows: 8 tons of pseudostems, 7.7 tons of foliage, and 0.5 of tons of rachis, for a total of 16.2 tons/ha. Amarnath and Balakrishnan (2007) estimated the residual biomass of pseudostem and leaves to be 13–20 tons of dry matter per hectare per year. Published reports on the waste production indicated that current

Table 10.1 Estimated solid waste produced from banana (in million tons, MT).

Year	Acreage (million hectare)[a]	Pseudostems (MT)[b]	Foliage (MT)[b]	Rachis (MT)[b]	Total waste (MT)[b]
1970	5.9	47	45	3	96
1980	6.6	53	51	3	107
1990	7.7	61	59	4	124
2000	9.5	76	73	5	154
2010	10.3	83	80	5	167
2017	11.2	89	86	6	181

Source: Adapted from [a]FAO (2019b); [b]Kamdem et al. (2013).

solid waste production on farms was 200 million tons based on area under cultivation and 300 million tons based on production (Table 10.1).

Banana peel waste is produced in fruit markets, households, institutional catering, and the food processing industry. Degradation of this biomass produces gases that give off odor. The banana waste is disposed of by the farmers into the rivers, lakes, or dumped in low-lying areas, causing a serious threat to the environment due to the release of greenhouse gases (Shah et al. 2005). Banana peel contributes about 40% of the total weight of fruit (Anhwange 2008) and the total peel waste produced as processing and municipal waste was estimated at about 60 million tons.

Waste Composition

All parts of the banana plant yield solid waste except the edible part inside a finger or fruit. However, edible tissues may also end up as solid waste in a damaged bunch, hand, or fingers. The composition of different parts of banana has been reported from different regions of the world. Pseudostem contains 12% lignin, 34.5% cellulose, 60.1% holocellulose, and 13.9% ash on dry mass basis (Cordeiro et al. 2004). Oliveira et al. (2007) reported the composition of the petiole, leaf blade, floral stalk, leaf sheath and rachis, as shown in Table 10.2. The major constituent of these wastes was holocellulose, which consists of mainly cellulose and hemicelluloses. Lignin content was highest in leaf blade, and holocellulose content was highest in petiole, whereas leaf sheath contained the highest level of cellulose. Floral stalk contained a high amount of starch and the petiole contained a high amount of pentosans. Banana sheath contains 6.4% dry matter, which is composed of 3.4% crude protein, 31.4% crude fiber, 34.6% cellulose, 15.5% hemicelluloses, and 6% lignin on dry basis (Subramanian et al. 1988). The outer covering of the pseudostem contains a significant amount of cellulosic material whereas the core or pith is rich in polysaccharides (Cordeiro et al. 2004).

Comparison between unripe and ripe banana peel showed that there was a substantial decrease in starch content as the fruit ripens (Table 10.3). Waghmare and Arya (2016) reported that unripe banana peel was rich in starch and total carbohydrates. Gebregergs et al. (2016) reported low starch and high sugar content in ripe banana peel. Banana peel is a good source of lignin (6–12%), pectin (10–21%), cellulose (7.6–9.6%), hemicelluloses

Table 10.2 Chemical composition of parts of banana plant discarded as waste at the time of harvesting (%, w/w dry weight basis).

Constituent	Pseudostem[a]	Petioles[b]	Leaf blade[b]	Floral stalk[b]	Leaf sheaths[b]	Rachis[b]
Lignin	12.0	18.0	24.3	10.7	13.3	10.5
Cellulose	34.5	31.0	20.4	15.7	37.3	31.0
Holocellulose	60.1	62.7	32.1	20.3	49.7	37.9
Pentosans	–	16.2	12.1	8.0	12.4	8.3
Starch	–	0.4	1.1	26.3	8.4	1.4
Proteins	–	1.6	8.3	3.2	1.9	2.0
Ash	13.9	11.6	19.4	26.1	19.0	26.8

Source: Adapted from [a]Cordeiro et al. (2004); [b]Oliveira et al. (2007).

Table 10.3 Chemical composition of unripe and ripe banana peel.

Parameters	Unripe banana peel (%)[a]	Ripe banana peel (%)[b]
Proximate		
Moisture	10.0	20.0
Protein	8.4	6.0
Fat	4.7	6.0
Ash	7.6	–
Carbohydrate	69.4	–
Carbohydrates		
Water soluble reducing sugar	2.1	–
Starch	41.2	3.0
Pectin	7.4	11.0
Cellulose	9.3	9.0
Hemicellulose	3.2	8.0
Lignin	2.3	9.0
Acid detergent fiber	17.5	–
Neutral detergent fiber	20.7	–
Dietary fiber	–	19.0
Glucose	–	2.0
Xylose	–	1.0

Source: Adapted from [a]Waghmare and Arya (2016); [b]Gebregergs et al. (2016).

(6.4–9.4%), and galacturonic acid (Davey et al. 2009). Pectin extracted from banana peel contained glucose, galactose, arabinose, rhamnose, and xylose. Banana peel is a rich source of starch (3%), crude protein (6–9%), crude fat (3.8–11%), total dietary fiber (43.2–49.7%), polyunsaturated fatty acids, particularly linoleic acid and linolenic acid, pectin, essential amino acids, and micronutrients (Emaga et al. 2007, 2008). These reports confirm that banana parts are an excellent source of nutrients, which can be exploited to get a variety of products of natural origin.

Waste Utilization

Quantity and purity of any agro-waste play an important role in its utilization. Waste generated in small quantity over a large area becomes uneconomical for processing due to the cost of collection and shipping to waste handling and processing facilities. Another major problem is the level of impurities in the waste. Generally, waste produced at farm, processing unit or municipal collection center varies in terms of quantity and purity. Farm waste is available in large quantities in the growing area and is relatively free from impurities. Food processing waste is also available in large quantities at the processing unit and is free from other impurities. Banana farm waste such as rhizome, suckers, pseudostem, petiole, leaf blade, peduncle, rachis, and male flower has been utilized to get a variety of value-added products. Banana stalk and peel wastes generated off the farm have also been studied to find suitable technology for their utilization.

Domestic and Agriculture Use

The pith in banana stem is used for human consumption in India after cooking in water and the addition of salt and spices. Fibrous matter of the pseudostem is used for making ropes for agriculture and domestic purposes. Pseudostem is decomposed along with the other agricultural residues, such as wheat straw, and used for mushroom cultivation.

Banana leaves are available in abundance in banana growing areas. Traditionally, leaves are used to serve meals or snacks to family and guests. Many dishes are prepared by wrapping the food in banana leaves during cooking. Banana leaves are dried and used as a fuel for domestic cooking. Leaves are conditioned and used to prepare a variety of household items such as mats, baskets, plates, bowls, cups, trays, etc. Leaves are also used for covering the agricultural produce to protect it from contamination. Leaves are used as fodder for domestic animals along with other materials. Leaves are also used as mulching material to preserve the soil moisture in orchards and agricultural fields. Banana is considered an auspicious plant and is used in a number of social and religious ceremonies. It is a common practice in India to decorate gates or doors with banana leaves. Banana peel contains sugars which can be used in the manufacture of alcoholic beverages and vinegar (Bakhru 1995).

Food and Feed Products

Starch

Floral stalk of banana plant contains high amount of starch, which can be extracted and used in pharmaceutical and food industry (Oliveira et al. 2007). NMR analysis and

microscopic examination of banana parts of "Dwarf Cavendish" variety indicated the presence of starch. The starch contents of floral stalk and leaf sheaths were 26.3% and 8.4%, respectively, whereas petioles/midrib, leaf blades and rachis contained about 1% starch.

Animal Feed

The effect of feeding banana tops or stem as the forage component of a molasses-based diet was studied by Ruiz and Rowe (1980). Volatile fatty acid concentration and rate of dry matter degradation were higher when soybean meal was given along with chopped banana stem than the stem alone. The efficiency of utilization of banana tops and stem increased with dietary protein supplement. Banana sheath was found suitable for feeding lambs (Subramanian et al. 1988).

Amarnath and Balakrishnan (2007) studied the microbial biomass growth by degrading banana waste substrate. Study results indicated that pseudostem, leaves, and stem supported microbial growth at 24, 36, and 48 hours of incubation. Banana leaves produced the higher microbial biomass than stem and pseudostem and ranked first in fodder potential to cattle followed by pseudostem and stem. The micronutrient (Fe and Zn) content of peel was higher compared with pulp, making it more suitable as an ingredient in cattle and poultry feed (Davey et al. 2009). El-Ghani (1999) studied the effect of banana plant wastes on milk yield and composition, rumen fermentation, nutrient digestibility as well as the nutritive value of the experimental rations. It was demonstrated that 15% of banana plant waste can be used for dairy cows without affecting the milk yield and quality.

Non-food Products

Enzyme Production

Osma et al. (2007) reported that banana skin is highly suitable as an attachment place for filamentous fungi. This fungus adherence property together with its high carbohydrate content makes banana skin an excellent support-substrate for solid-state fermentation (SSF) processes. The scanning electron microscopy (SEM) microphotographs of banana skin with and without fungus (Figure 10.2) show that the fungus grows well by attaching to the banana skin. This process is facilitated due to the high hydrophobicity of the banana skin, which enables the attachment of the fungus to the carrier.

Reddy et al. (2003) investigated *Pleurotus ostreatus* and *Pleurotus sajor-caju* for their viability to produce various lignolytic and cellulolytic enzymes, such as laccase, lignin peroxidase, xylanase, endo-1,4-β-D-glucanase, and exo-1,4-β-D-glucanase, on banana leaf biomass and pseudostems using solid substrate fermentation. The production patterns of these enzymes were studied during a 40-day growth period of the organisms. A similar level of enzyme activity and production pattern was observed for both organisms. Leaf biomass was shown to be a more suitable substrate than pseudostems for enzyme production. Generally, maximum specific activities of enzymes were observed between day 10 and day 20 of culture growth. However, very low levels of cellulolytic enzyme activities were detected compared with lignin degrading enzymes by both the organisms. Figure 10.3 shows production patterns of lignolytic and cellulolytic enzymes by *P. ostreatus*.

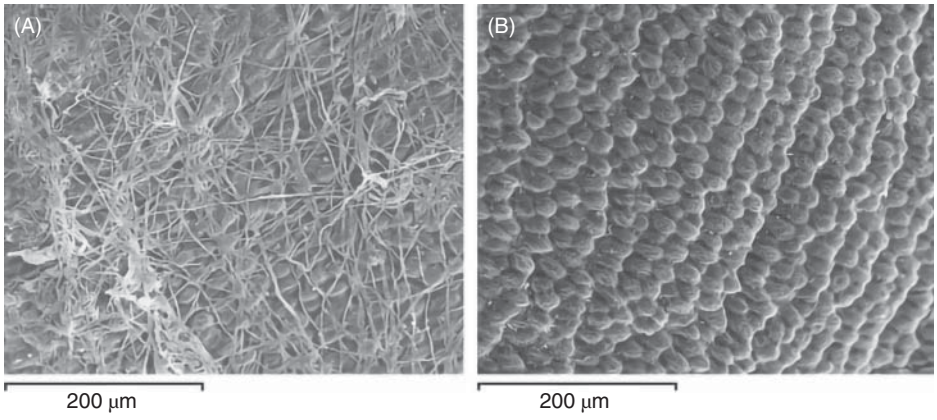

Figure 10.2 SEM microphotographs of banana skin: (A) with fungus; and (B) without fungus. Source: Osma et al. (2007). Reproduced with permission of Elsevier.

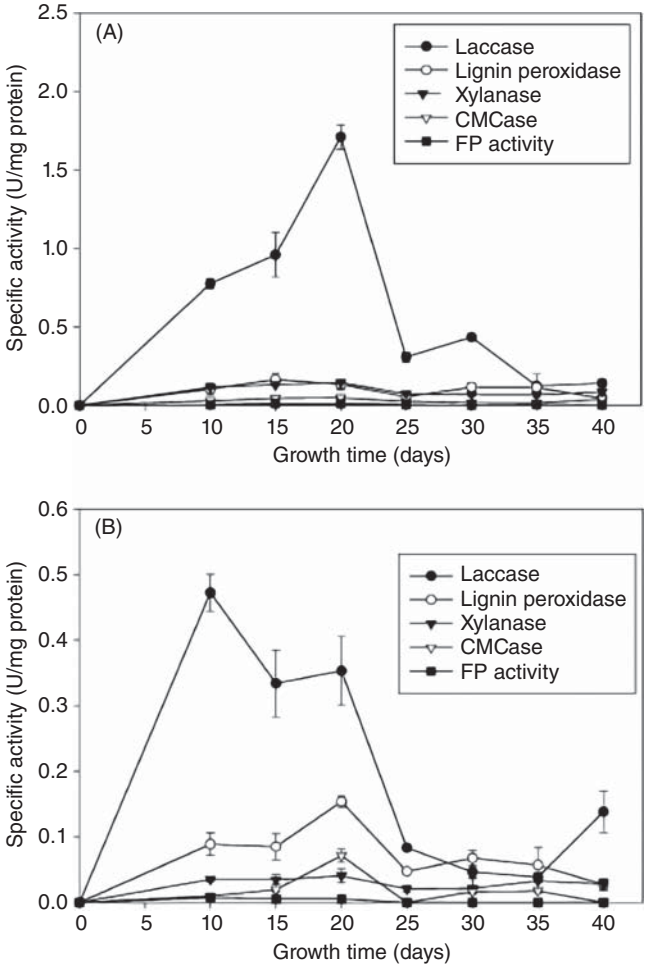

Figure 10.3 Production patterns of lignolytic and cellulolytic enzymes on leaf (A) and pseudostem (B) biomass of banana waste by *Pleurotus ostreatus*. Source: Reddy et al. (2003). Reproduced with permission of Elsevier.

The feasibility of producing bacterial cellulases by solid-state bioprocessing of banana wastes was investigated by Krishna (1999). Banana fruit stalk (peduncle) was sliced, dried at 70 °C for 24 hours, ground and passed through a sieve to get particles 200–2400 μm in size. The effects of pretreatment on the substrate, moisture content, particle size, pH of the medium, incubation temperature, enrichment of the medium with nitrogen and carbon sources, inoculum size, and the incubation period were studied for optimal production of cellulase enzymes by *Bacillus subtilis* (CBTK 106). The optimal filter paper activity of 2.8 IU/g dry fermented substrate (g-ds), carboxymethyl cellulase activity of 9.6 IU/g-ds and cellobiase activity of 4.5 IU/g-ds were obtained at 72 hours of incubation in media containing banana fruit stalk (autoclaved at 121 °C for 60 minutes, particles size 400 μm, optimal moisture content of 70%, pH 7.0, incubation at 35 °C, minerals, and nutrients of $(NH_4)_2SO_4$ or $NaNO_3$ or glucose at 1.0% using inoculums at a rate of 15%). Banana fruit stalk was found to be the most suitable lignocellulosic substrate. The total enzyme production was 12-fold higher in SSF than that in submerged fermentation. It was suggested that banana fruit stalk could be an excellent substrate for SSF on a commercial scale.

Alpha amylase (α-amylase) is one of the main enzymes used in various sectors such as the food, textile, paper and detergent industries. Mazumdar and Maumdar (2018) optimized the production of α-amylase by the fungus *Aspergillus oryzae* on banana peel as a substrate using solid-state fermentation. A number of parameters such as incubation period, incubation temperature, initial pH of the media, and substrate content can affect the production of α-amylase in the SSF system. Results showed that optimum conditions for the maximum α-amylase (6.55 U/g) production were an incubation period of 96 hours, incubation temperature of 35 °C, initial pH of the medium of 5.0, and substrate amount of 50 g.

Paper and Paperboard

Banana waste, rich in cellulosic matter, is used in the manufacture of paper. Manual and mechanical methods are used to extract the fibers from banana waste (Chauhan and Sharma 2014). Quality and purity of the manually extracted fiber is high, producing higher grade paper than machine extracted fiber. However, machine extracted fibers are cheaper than those from the manual process. Chauhan and Sharma (2014) improved the mechanical process for fiber extracted from banana leaves, green stem and trunk by using enzyme treatment (0.5% enzyme at 40 °C for 4 hours) followed by pulping (8% NaOH, 3.5 hours, at 100 °C, bath ratio 1:8). Black liquor was drained, and cooked fibers were washed and subjected to the beating treatment. The enzyme assisted mechanical process was shown to be useful for handmade paper manufacturers to utilize banana fibers for high quality paper production.

Alarcón and Marzocchi (2015) processed fresh pseudostem to obtain fibrous material by drying under ambient conditions and cooking under alkaline condition (10.5% active alkali concentration) in a horizontal rotary digester at 145 °C for 45 minutes. The extraction process of pulp from pseudostem of the banana tree was technically feasible, with the resulting pulp having the potential to be used for the manufacture of paper board products.

Nanofibers

Nanofibers have potential application as reinforcing elements in composite material. Tibolla et al. (2014) isolated cellulose nanofibers from banana peel having an average

Table 10.4 Physical and mechanical properties of the control film (FC) and nanocomposites reinforced with cellulose nanofibers that were passed through the high-pressure homogenizer zero (FN-0), three (FN-3), five (FN-5), and seven (FN-7) times.

Sample	Thickness (μm)	Density (g/cm^3)	Moisture content (%)	Tensile strength (MPa)	Elongation at break (%)
FC	85	1.21	15.9	7.3	32.2
FN-0	85	1.15	15.6	8.9	25.9
FN-3	85	1.17	15.2	10.1	21.6
FN-5	86	1.17	14.9	11.1	21.4
FN-7	86	1.15	14.5	9.9	20.7

Source: Pelissari et al. (2017). Reproduced with permission of Elsevier.

diameter of 10.9 and 7.6 nm and a length of 454.9 and 2889.7 nm from chemical and enzymatic processes, respectively. The aspect ratio was in the range of long fibers. Pelissari et al. (2017) isolated cellulose nanofibers from banana peel to prepare nanocomposites. The most suitable mechanical treatment was five passages through the high-pressure homogenizer (Table 10.4). The cellulose nanofibers improved the features of the starch-based film.

Pectin and cellulose nanocrystals (CNCs) isolated from banana peels were used to prepare films, with or without the addition of citric acid, by Oliveira et al. (2017). The dispersion was prepared with CNC (0–10%), 5 g pectin, glycerol as a plasticizer, citric acid, and distilled water to get solid content of 2.5 g/100 ml. The film-forming dispersion was homogenized for 30 minutes, deaerated under vacuum, cast on petri dishes and dried at 40 °C for 16 hours. The water resistance and water vapor barrier properties were enhanced with the addition of CNCs. Further, the tensile strength, water resistance and barrier to water vapor were improved by the presence of citric acid.

Fuel Briquettes

Sellin et al. (2013) pressed the pseudostem in a hydraulic press to remove water, followed by dehydration at 60 °C for 24 hours. Dried leaves and pseudostem were milled to get an average particle size of 2.5 mm and then pressed in a briquetting hydraulic press using compaction pressure of 18 MPa for 0.6 and 1 second. The dimensions of the briquettes produced were 50 × 50 mm, diameter and length. The moisture content in the wastes for briquetting varied between 8% and 15%. The banana leaves and pseudostem had carbon contents of 43.28 and 38.92%, respectively. The high heating values of the leaves and pseudostem were approximately 17.10 and 13.70 MJ/kg, respectively. Maximum release of energy by waste and briquettes were at 580 and 300 °C, respectively. The briquettes of pseudostem and leaves offered compressive strength of 15 and 5.3 MPa, respectively. The thermal properties and physicochemical characteristics of banana wastes demonstrated their potential application as fuel in the form of briquettes.

The suitability of banana biomass for pyrolysis in comparison with other lignocellulosic biomasses was assessed by Kabenge et al. (2018). The high levels of fixed carbon, volatile matter and ash contents were strong indicators that banana peel is an adequate feedstock for pyrolysis work to yield value-added bio-infrastructure products. The maximum weight

degradation rate for the banana peel biomass occurred in the temperature range of 450–550 °C. The lignin, cellulose, and hemicellulose fractions had significant correlation between the biomass heating values and chemical composition. Pyrolysis characteristics of the banana leaves, pseudostem and peel biomasses were comparable.

Biogas

There are two available methods for conversion of banana biomass into energy: thermal and biological (Tock et al. 2010). Thermal conversion includes direct combustion and gasification, whereas biological conversion is carried out using anaerobic digestion. Biological conversion (e.g., anaerobic digestion) is typically preferred for high water content biomass. Anaerobic digestion is a low-temperature process that can be used to process both wet and dry feeds (with water addition) and is cost effective for low, medium or high scale production. Carbon dioxide and methane with small traces of hydrogen sulfide are the primary gases produced by this process. A general schematic for the anaerobic digestion of biomass is shown in Figure 10.4.

Biogas production from six morphological parts of the "Williams Cavendish" banana cultivar was investigated by Kamdem et al. (2013). The bulbs, leaf sheaths, petioles–midribs, leaf blades, rachis stems, and floral stalks gave total biogas production of 256, 205, 198,

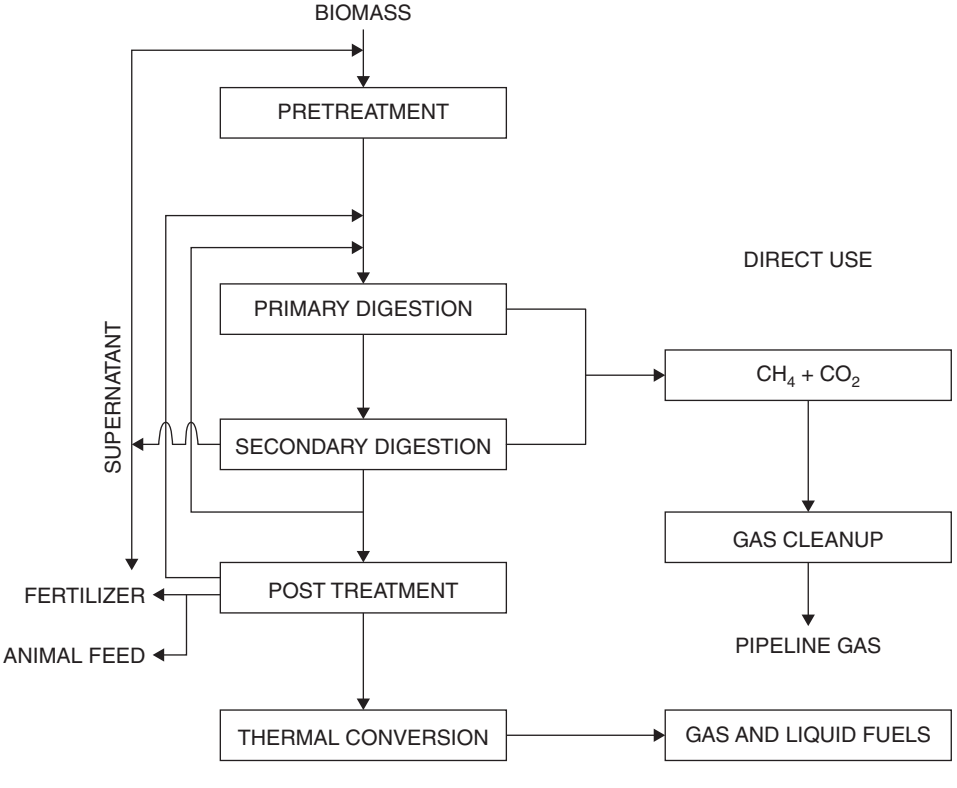

Figure 10.4 A general schematic of anaerobic digestion process for value-added utilization of banana biomass. Source: Tock et al. (2010). Reproduced with permission of Elsevier.

126, 253, and 221 ml/g dry matter, respectively, and total biomethane production of 150, 141, 127, 98, 162, and 144 ml/g, respectively. The biogas production rates and yields were dependent on the biochemical composition of the banana parts and the ability of anaerobic microbes to access the fermentable substrates. The bioconversion yield for each banana part was below 50%, showing that these substrates were not fully biodegraded after 188 days.

Odedina et al. (2017) reported that ground banana waste produced 330.6 ml CH_4/g volatile solids which was higher than chopped banana, rambutan or longan waste. The combination of a thermophilic reactor with a retention time of four days and a mesophilic reactor with a retention time of 20 days performed better than a single stage mesophilic reactor. A two-stage digestion process resulted in volatile solids destruction of 68.5% and energy yield of 2510.9 kJ/kg volatile solids at a feed concentration of 2% total solids under optimal conditions. Divyabharathi et al. (2018) evaluated the performance of a solid-state anaerobic digester of one cubic meter capacity to treat banana wastes for biogas generation. The process was initiated by adding 500 kg of fresh cow dung, 500 kg of water, and 100 l of slurry from a running biogas plant. Later, mashed banana peel waste was added as feed material which produced about 730 l of biogas with 56–65% methane content. The specific biogas production of banana wastes was 23–27 l/kg of feed. The maximum specific gas production was 379 l/kg of total solids destruction and 2100 l/kg of volatile solids destruction.

Bioethanol

In recent years, there has been increasing effort to develop biofuels to minimize dependence on fossil fuels, which negatively impact the environment (Molino et al. 2018). Two types of paths have been explored for producing cost-effective biofuels. First generation biofuels are generally made from carbohydrates, lipids, and oils from agroindustry wastes using conventional methods. Second generation biofuels are typically derived from mainly plant biomass such as the stalks, stems, leaves, and wood (Ingale et al. 2014). In this regard, banana biomass offers a great potential to develop biofuels, e.g., bioethanol. Guerrero et al. (2018) optimized the saccharification and fermentation conditions of banana pseudostem and rachis for bioethanol production. The highest ethanol yield from pseudostem was 112 l/ton, while from rachis it was 103 l/ton, at high solid loading, low enzyme dosage, low yeast inoculums and no mineral salt supplementation.

Prakash et al. (2018) investigated *Geobacillus stearothermophilus* HPA19 for the production of a cocktail of thermo-alkali-stable xylano-pectino-cellulolytic enzymes. The enzyme cocktail showed stability at 80 °C and at pH as high as 10.0. Response surface methodology (RSM) was used to optimize saccharification leading to twofold increase in reducing sugar. Subsequent fermentation produced 2.1% alcohol with 76.5% efficiency within 30 hours. In another study, banana peel was chopped, sun dried, oven dried at 60 °C, ground, and washed. This mass was subsequently hydrolyzed using 1.50% acid concentration, at 91 °C and a retention time of 21.7 minutes to get maximum ethanol recovery (Gebregergs et al. 2016). Waghmare and Arya (2016) hydrolyzed unripe banana peel powder of hybrid variety of *Musa acuminate* × *Musa balbisiana* under optimized conditions of 1.5% H_2SO_4 at 120 °C for 20 minutes. The results showed that *Saccharomyces cerevisiae* NCIM 3095 produced 35.5 g/l ethanol at optimized fermentation conditions.

Wastewater Treatment

In a comprehensive review, Ahmad and Danish (2018) discussed the conversion of banana waste into a variety of adsorbents (Figure 10.5). The use of banana waste derived adsorbents in water, and wastewater industries have significant potential advantages. For example, it is low cost, widely available, and protecting the environment by preventing methane/CO_2 gas formation due to unsafe damping in wetlands or burning, which also produces CO_2 gas and water vapor – thereby contributing to global warming. However, there are some research gaps that need more attention, e.g., (i) optimized production of the banana waste derived adsorbents, (ii) comparative studies of banana waste derived activated carbon production methods, and (iii) its commercial utilization by various food and non-food industries.

Waste banana pith can be used for effluent treatment for color removal by absorbing dyes (Namasivayam and Kanchana 1992; Namasivayam et al. 1998). The banana stem was pre-carbonized at 250 °C for 2.5 hours and then passed through a chemical activation process using 0.4 M KOH solution (Taer et al. 2018). The pellets were formed with eight ton hydraulic pressure, carbonized at 600 °C and physically activated using CO_2 gas at 900 °C for two hours in order to get the highest specific capacitance.

Oyewo et al. (2016) used nano-structured banana peel to treat mine water for the removal of uranium and thorium. Carboxylic and amine groups of nano-structured banana peel were successful in removal of metals. Palm oil mill effluent contains a high amount of

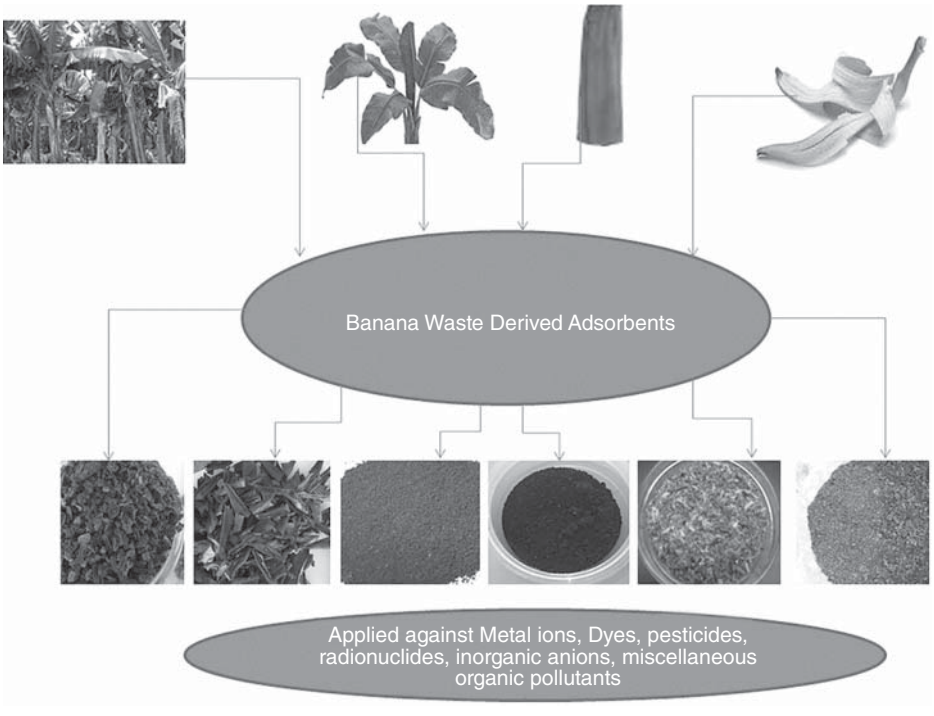

Figure 10.5 Banana waste derived adsorbents for use in wastewater treatment. Source: Ahmad and Danish (2018). Reproduced with permission of Elsevier.

organic matter with potential threat to the environment (Mohammed and Chong 2014). Natural, chemically and thermally modified banana peel was used as sorbent for the treatment of biologically treated palm oil effluent. Removal of color, total soluble solids (TSSs), chemical oxygen demand (COD), biological oxygen demand (BOD), and tannin and lignin was 95.96, 100, 100, 97.41, and 76.74%, respectively. Fresh or dried banana peel was soaked in 20% phosphoric acid in 1:10 ratio for two hours and then heated at 230 °C for two hours to get bio-char (Zhou et al. 2017). The bio-chars from dehydrated and fresh peel showed excellent lead clarification capability of 359 and 193 mg/g, respectively.

Conclusions

Banana plant bears one bunch of fruit in its life span, therefore, at least 200 million tons of agricultural waste is generated worldwide whereas postharvest processing or consumption generates about 60 million tons of waste. Banana waste varies in composition but invariably contains cellulose, hemicelluloses, lignin, starch, sugars, protein, and minerals. Banana parts are traditionally used for domestic and agricultural purposes. It is considered an auspicious plant and its leaves, pseudostem, and fruit are used in social and religious ceremonies. Banana leaf is widely used to serve meals and snacks in banana growing areas as well as for wrapping the food during cooking. Farm animals are fed banana leaf which is rich in cellulose, starch, sugar, vitamins, and minerals. Banana parts have been successfully utilized for bioethanol and biogas production. Pseudostem and sheath are processed to obtain fibers for rope making. Cellulosic pulp has been used successfully for the preparation of paper and paper board. Activated carbon from banana parts has demonstrated its potential for wastewater treatment as an absorbent. In recent years, nanotechnology has been applied to isolate nanoparticles from banana waste for modification of conventional material especially for the packaging industry. In summary, each part of the banana waste or by-product has potential to be utilized for food, fiber, feed, and energy purposes.

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11

Chemical Composition and Nutritional Profile of Raw and Processed Banana Products

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Introduction

Fruits and fruit products are known not only to promote general good health and well-being but also to lower the risk of various chronic diseases, such as heart diseases, stroke, gastrointestinal disorders, certain types of cancer, hypertension, age-related macular degeneration, eye cataracts, and skin rejuvination and improve the immune system (Sidhu and Zafar 2018). Banana belongs to the tropical fruits as it grows more profusely in tropical rain forest areas. Unripe banana fruit has flesh rich in starch which converts into sugars on ripening. Banana is known to be rich in carbohydrates (particularly, starch and dietary fiber), certain vitamins, and minerals.

Banana (*Musa* spp.) is an edible fruit and an herbaceous flowering plant belonging to the genus *Musa*, and the family Musaceae. In some producing countries, banana is consumed as a cooked vegetable (called plantains). All the edible banana fruits now are seedless (parthenocarpic) and belong to two species, *Musa acuminata* Colla and *Musa balbisiana* Colla; the hybrid from these two species is *Musa* × *paradisiaca* L. (Morton 1987). Mostly, bananas are eaten in ripe form and known as dessert banana whereas plantains are consumed in cooked form and are also a staple food source in many developing countries. This chapter describes the chemical composition, nutritional profile and health benefits of bananas. Additionally, the nutritional composition of selected banana-based products is also discussed.

Nutritional Composition

The nutritional profile of raw bananas, by weight and size, is presented in Table 11.1 (USDA 2019). The values shown here are for bananas available in the USA, therefore, some differences can be anticipated in composition of bananas in other parts of the world owing to variable climatic and soil conditions, agricultural practices, postharvest handling, and processing techniques, etc. Additionally, varietal differences can also contribute to variations in the composition of raw and finished products. Banana fruit is a rich source of

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Table 11.1 Nutritional profile of raw bananas, per 100 g and by size.

Composition	100 g	Extra small (81 g)	Small (101 g)	Medium (118 g)	Large (136 g)
Proximate, Energy, and Sugars					
Water	74.91	60.7	75.7	88.4	102
Energy	89	72.1	89.9	105	121
Protein	1.09	0.883	1.1	1.29	1.48
Total lipid (fat)	0.33	0.267	0.333	0.389	0.449
Carbohydrate, by difference	22.84	18.5	23.1	27	31.1
Fiber, total dietary	2.6	2.11	2.63	3.07	3.54
Sugars, total	12.23	9.91	12.4	14.4	16.6
Minerals					
Calcium	5	4.05	5.05	5.9	6.8
Iron	0.26	0.211	0.263	0.307	0.354
Magnesium	27	21.9	27.3	31.9	36.7
Phosphorus	22	17.8	22.2	26	29.9
Potassium	358	290	362	422	487
Sodium	1	0.81	1.01	1.18	1.36
Vitamins					
Vitamin C, total ascorbic acid	8.7	7.05	8.79	10.3	11.8
Niacin	0.665	0.539	0.672	0.785	0.904
Folate, total	20	16.2	20.2	23.6	27.2
Choline, total	9.8	7.94	9.9	11.6	13.3
Vitamin A, RAE	3	2.43	3.03	3.54	4.08
β-Carotene	26	21.1	26.3	30.7	35.4
α-Carotene	25	20.2	25.2	29.5	34
Lutein + zeaxanthin	22	17.8	22.2	26	29.9
Vitamin K (phylloquinone)	0.5	0.405	0.505	0.59	0.68

Source: USDA (2019).

carbohydrates (e.g., starch and fiber), several minerals and vitamins. Potassium content in bananas is among the highest found in all fruits. Appel et al. (1997) reported that the significantly high potassium and low sodium contents in banana are optimum for people suffering from hypertension and on a low-sodium diet.

For dessert banana, the right level of sourness, sweetness, firmness, mealiness, and aroma are some of the important sensory attributes of consumer preferences for the fruit. Bugaud et al. (2016) reported the optimal and acceptable levels of these sensory attributes for dessert banana and have suggested that 33% level of unsatisfied consumers can be taken as the cut-off point for these sensory attributes. The stage of maturity determines the chemical

composition of banana fruit and its peel. Peel can be up to about 40% of the fruit and ends up as a waste product.

Using high-resolution NMR, Yuan et al. (2017) analyzed various metabolites during postharvest senescence of banana fruit. The chemical profiles for the primary and secondary metabolites consisting of organic acids, amino acids, carbohydrates (starch and fiber), and phenolics were similar at all five stages of maturity but the individual compounds showed large variations. According to their findings, valine, alanine, aspartic acid, choline, acetate, glucose, malic acid, gallic acid, and dopamine were the principal metabolites responsible for the postharvest senescence of banana fruits. At the last stage of maturity (stage 5), ethanol was produced from glucose metabolism, and salsolinol from dopamine, which was a typical marker for the postharvest senescence of banana fruit. However, Goswami and Borthakur (1996) have reported that moisture, crude fat, crude protein, and most of the minerals were higher in the early stages of postharvest development of banana but decreased as the fruit ripened. Potassium was found to be the most abundant mineral (4.10–5.55 g/100 g, dry weight). During the development of fruit, the starch content increased but the total soluble sugars decreased. The total phenolics decreased throughout the development period of the fruit. The activity of α-glucan phosphorylase increased during the starch synthesis when the fruit was developing, but the acid phosphorylase activity declined during this period.

Dessert banana pulp and peel composition from different sources is shown in Table 11.2. The data on banana pulp is from AAA and AAB varieties of the fruit. Banana peel, which is

Table 11.2 Dessert banana's pulp and peel composition (per 100 g, fresh weight basis).

Composition	Unit	Banana pulp		Banana peel
		AAA variety	AAB variety	
Moisture	%	73.8	68.5	83.5
Protein	%	2.2	—	1.8
Fat	%	0.1	—	1.7[1]
Starch	%	10.0	—	1.2
Total sugars	%	40.0	—	29.0
Sodium	mg	17.4	16.0	24.3
Iron	mg	0.8	0.8	0.6
Calcium	mg	4.9	7.2	19.2
Potassium	mg	318.9	342.3	78.1
Magnesium	mg	30.8	39.4	—
Phosphorus	mg	21.7	26.3	—
Manganese	mg	0.2	0.7	76.2
Vitamin C	mg	4.5	12.7	—
Vitamin A, RAE	μg	8.2	12.4	—
β-Carotene	μg	55.7	96.9	—

[1] Dry weight basis.
Source: Adapted from Lustre et al. (1976), Adisa and Okey (1987), Wall (2006), and Mohapatra et al. (2010).

primarily a waste, is also rich in certain nutrients, e.g., total sugars, which makes it suitable for processing into a variety of by-products (Chapter 10 is dedicated to the value-added utilization of banana plant and fruit waste).

Alkarkhi et al. (2011) compared certain physicochemical properties of banana pulp and peel flours obtained from green as well as ripe fruits. To differentiate between the peel and pulp flour, they recommended the use of total soluble solids (TSS), water holding capacity, and back extrusion force, whereas to discriminate between flour prepared from green and ripe banana, TSS and viscosity were better measures. Physicochemical quality and antioxidant changes in "Leb Mue Nang" cultivar of banana fruit during the three stages of ripening was investigated by Youryon and Supapvanich (2017). They found no differences in both the peel and pulp color, texture, TSS, and total acidity during three stages of ripening. On full maturity, the highest amount of total phenolics and total antioxidant activity were observed in this cultivar. Emaga et al. (2007) investigated the effect of stage of maturity and variety on the chemical composition of banana and plantain peels. According to their findings, peel had 8–11% protein and was rich in linoleic acid and α-linolenic acid, and potassium; plantain peel was richer in starch than dessert banana. As the fruit matured, the soluble sugars increased but the starch decreased.

Carbohydrates

Banana fruit is rich in carbohydrates, such as starch, fiber, pectin, sucrose, glucose, and fructose. Banana carbohydrates (particularly, starch and sugars) change significantly from the green to ripe (full yellow) and over-ripe (brown > yellow) stages. As shown in Figure 11.1, starch decreased from 58.6 to 2.6% during ripening. Further, sucrose content increased from 6.0 to 53.2% while reducing sugars accumulated from 1.3% to 33.6% during transition to full ripening. These changes in carbohydrates contribute to the desirable sensory attributes of

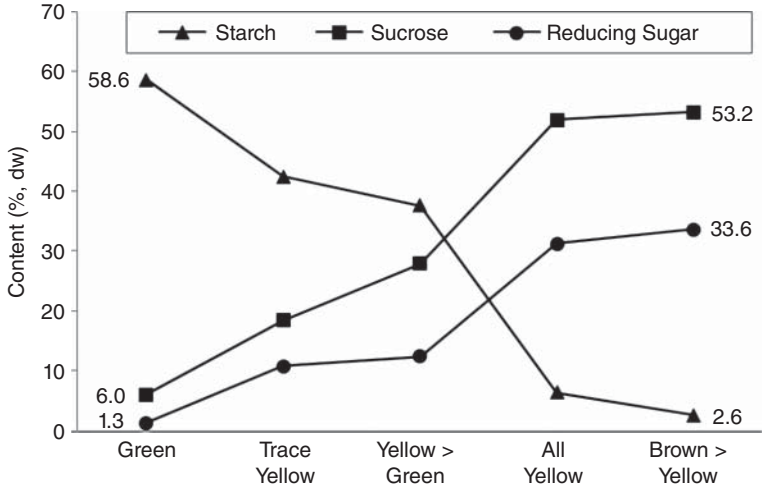

Figure 11.1 Changes in the carbohydrate fractions at selected stages of banana ripeness. Source: Lii et al. (1982). Reproduced with permission of John Wiley and Sons.

sweet flavor and smooth texture or mouthfeel in ripe bananas. Green bananas by contrast have starchy taste and sticky mouthfeel.

Adão and Gloria (2005) studied the changes in carbohydrates and bioactive amines during the postharvest storage of banana fruits for 35 days at 16 °C and 85% relative humidity (RH). It was observed that the desirable yellow color developed in 21 days, whereas black spots appeared after 28 days, with a significant increase in the pulp-to-peel ratio. The green banana fruit had higher starch content and lower soluble sugars, however, as the ripening process progressed, starch content decreased significantly. After 28 days, glucose and fructose were predominant. The decrease in starch content followed first-order reaction kinetics, whereas the increase in glucose and fructose followed zero-order kinetics. They also detected a few bioactive amines, including putrescine, spermidine, and serotonin. Upon storage, a significant decrease in serotonin and putrescine was observed after 14 and 21 days, respectively.

Banana starch was isolated from unripe green fruit that had a high solubility of 16.8% at 90 °C and swelling power of 17.1 g water/g starch (Torres-Gutierrez et al. 2008). The banana starch showed high syneresis and low stability in refrigeration and freezing cycles. Considering these properties, banana starch can be used in food systems requiring high-temperature processing such as jellies, sausages, bakery, and canned foods, but is not suitable in refrigerated and frozen foods. In a similar study, Liu et al. (2017) isolated a carbohydrate consisting of polygalacturonic acid, with a molecular weight of 8.9 kDa from banana (*Musa nana* Lour.), which can be used for the development of functional foods and phytomedicines.

The resistant degradation during the postharvest ripening of Cavendish banana and plantains, as well as starch granule structure and action of amylases was investigated by Gao et al. (2016). Plantain banana had the higher content of total starch and resistant starch (RS), and a faster rate of starch degradation. Shiga et al. (2017) identified two wild cultivars of banana having potentially immunomodulatory mannan and arabinogalactan. As the immunomodulatory activity is associated with the interaction of these polysaccharides, it would be beneficial to breed new cultivars by introducing disease resistance from these wild plants into domesticated dessert and plantain banana cultivars.

Campuzano et al. (2018) investigated the physicochemical and nutritional characteristics of flour produced from banana at different stages of maturity. Fruits from the 1st and 2nd stages, being higher in starch content, can be used in emulsions, whereas fruit from the 3rd and 4th stages of ripening, when it is low in starch but high in sugars, and bioactive compounds, can be used in the preparation of beverages and baby foods.

The chemical and physical properties of green banana peel and pulp flour, as reported by Yangilar (2015), are shown in Table 11.3. Banana peel flour had significantly higher content of ash, total starch, and total dietary fiber, including soluble and insoluble dietary fiber (IDF), than found in the pulp flour. Agama-Acevedo et al. (2016) also reported that banana peel flour is a rich source of dietary fiber, extractable polyphenolics, ash, starch, and antioxidant activity, making it suitable for use as a functional ingredient for developing new food products.

Banana peel also has significant amounts of carbohydrates, with the potential to develop value-added by-products from it, e.g., pectin, bioethanol, and enzymes. Oliveira et al. (2016) extracted pectin from banana peels with citric acid, using different pH, temperature, and

Table 11.3 Composition of flour from green banana pulp and peel (g/100 g).

Parameter	Pulp flour	Peel flour
Dry matter	9.87	11.06
Ash	3.10	4.4
Total starch	73.8	60.66
Soluble dietary fiber	8.8	8.2
Insoluble dietary fiber	40.8	58.6
Total dietary fiber	49.6	66.8
Total phenolics, GAE[1]	0.61	0.80

[1]Gallic acid equivalent.
Source: Adapted from Yangilar (2015).

extraction time. The higher temperature and pH conditions resulted in higher extraction yield; however, the degree of methoxylation decreased from 79 to 43%. The optimum conditions of pectin extraction, i.e., those which gave a maximum yield of galacturonic acid with at least 51% degree of methoxylation, were: temperature, 87 °C; pH, 2.0; and residence time, 160 minutes.

Aroma and Flavor Compounds

The typical flavor of fruit develops primarily during the ripening period. A fruit may have more than one hundred volatile flavor components; however, these compounds constitute only a tiny fraction of the whole fruit, typically, a few parts per million (ppm). Boudhrioua et al. (2003) identified 12 aromatic compounds (2 alcohols, 9 esters, and 1 phenol) by GC-MS in fresh and air-dried bananas. The moisture content of pulp and drying temperature were found to affect the content of aromatic compounds in the finished product. Vermeir et al. (2009) characterized the flavor components of banana fruit using GC-MS. The sweetness of the fruit is attributed to the presence of D-glucose, D-fructose, and sucrose, whereas L-malic acid and citric acid maintain the sourness. The ability of the banana cultivars to tolerate low temperature is related to the metabolism responsible for producing flavor compounds. A number of studies have reported in detail about the flavor compounds of banana fruit (Sidhu and Kabir 2010; Kabir and Sidhu 2012).

Free and glycol-conjugated volatile flavor components from three cultivars of banana and plantain were reported by Aurore et al. (2011). The main volatile components were: (E)-2-hexenal and acetoin in Cavendish; (E)-2-hexenal and hexanal in plantain; and 2,3-butanediol, and two distereoisomer sterols in Frayssinette bananas. The most abundant aglycones detected in these banana samples were 3-methyl-butanol, 3-methyl-butanoic acid, sterols, and acetovanillone. While studying two banana cultivars, Facundo et al. (2012) found that the cold storage temperature affected volatile components more strongly in "Nanicao" than in the "Prata" cultivar. In the "Nanicao" cultivar, cold storage reduced esters, such as 2-pentanol acetate, 3-methyl-1-butanol acetate, 2-methylpropyl butanoate, 3-methylbutyl butanoate, 2-methylpropyl-3-methylbutanoate, and butyl butanoate. Using GC-FID and GC-MS techniques, Pino and Febles (2013) isolated 146 flavor compounds from "Giant Cavendish" banana cultivar, out of which 124 compounds were positively

identified; out of these, 31 odorants were considered to contribute to the typical aroma of bananas.

Bugaud and Alter (2016) studied 13 cultivars and 4 new triploid hybrids of banana for both sensory profiling and chemical analyses using solid-phase microextraction (SPME) GC-MS. They detected 41 volatile compounds in banana cultivars and built a partial least square regression model, which suggested that two butanoate esters, 2-methylpropyl butanoate and 3-methylbutyl butanoate, mainly contributed to banana odor and aroma. The 3-methylbutyl esters were found to be the most abundant in 17 cultivars.

Minerals and Vitamins

Banana fruit is rich in certain minerals and vitamins. Hardisson et al. (2001) measured the macro-elements (sodium, potassium, calcium, magnesium, and phosphorus) and micro-elements (iron, copper, zinc, and manganese) in banana fruit in the Canary Islands. Bananas grown in the north island were rich in potassium, magnesium, phosphorus, iron, copper, and zinc, whereas the fruit obtained from the southern part was rich in calcium. The dwarf Brazilian banana grown in Hawaii, on per 100 g basis, had 12.7 mg ascorbic acid, 96.9 μg β-carotene, 104 μg α-carotene, and had higher phosphorus, calcium, magnesium, manganese, and zinc than the William cultivar (Wall 2006). The average potassium content for banana grown in Hawaii was 336.6 mg/100 g.

The carotenoid (β-carotene and α-carotene) and riboflavin content of Fe'i and also non-Fe'i banana cultivars grown on the Solomon Islands indicated that the β-carotene equivalents ranged from 45 to 7124 μg/100 g (Englberger et al. 2010). All Fe'i cultivars had a riboflavin content ranging from 0.10 to 2.72 mg/100 g. The consumption of these cultivars was recommended to alleviate vitamin A deficiency and improve overall health. Facundo et al. (2015) identified 10 carotenoids in two cultivars of banana; the major ones were all-trans lutein, all-trans α-carotene, and all-trans β-carotene. However, the accumulation of carotenoids was found to be significantly reduced by the low-temperature storage of bananas.

Postharvest Storage and Composition

Cold storage is not suitable for extending the shelf life of banana because it suffers from cold injury. Several alternative treatments have been tried to extend the shelf life of banana fruit to avoid chilling injury as well as to retain most of the antioxidants (Wang et al. 2015; Ahmed and Palta 2016; Lo'ay and El-Khateeb 2018). Nitric oxide treatment (sodium nitroprusside 0.05 mM) inhibited chlorophyll degradation and enhanced the antioxidant capacity of the banana fruits during cold storage (Wang et al. 2015). The treatment with exogenous dipping application of ascorbic acid (9 mM) increased the chilling tolerance by increasing antioxidant enzyme activities of banana during cold storage (Lo'ay and El-Khateeb 2018).

The wax coating of banana has been reported to improve the retention of moisture, ascorbic acid, soluble solids, and freshness during seven-day cold storage (Orishagbemi et al. 2015). Irradiation treatment with UV-C rays at 200–280 nm has been shown not only to extend the shelf life of banana fruit but also enhance its phenolic contents and antioxidant capacity (Ding and Nur 2015). Coating of banana fruits with 1% shrimp chitosan solution resulted in lower weight loss, reduced darkening, and delayed changes by three to four days in TSS and titratable acidity during storage at 26 °C and 85% RH (Hossain and Iqbal 2016).

Nutritional Quality of Processed Banana Products

Nectar, Fried, Baked, and Chips Products

The proximate composition of raw banana and nectar, fried, baked, and chips is shown in Figure 11.2. Nectar is prepared from banana pulp. Protein, carbohydrate (total dietary fiber, and total sugars) content are highest in dried banana chips. Fried and baked bananas have similar protein and total dietary fiber content, whereas carbohydrates, especially, total sugars are higher in baked banana versus fried banana.

At stage 5 ripening, when the skin color turns yellow, the fruit is ready for conversion into pulp/puree (Yao et al. 2017). The banana pulps were rich in minerals, in particular, potassium (584 mg/100 g) and magnesium (58 mg/100 g), total sugars (5.2 g/100 g), and starch (1.8 g/100 g) with excellent sensory attributes. High-pressure treatment of banana pulp at 500 MPa for a holding time of 90 seconds retained the total phenolic content – flavonoids (0.22 g ellagic acid equivalent/kg dry weight) and total antioxidant activity at the highest levels (Jimenez-Martinez et al. 2017).

Banana fruit pulp and powder have been used for developing various functional foods based on cereals, milk, and meat, which are briefly discussed here. The ripe banana flour when added to layer and sponge cakes (20–40% replacement) lowered the sensory

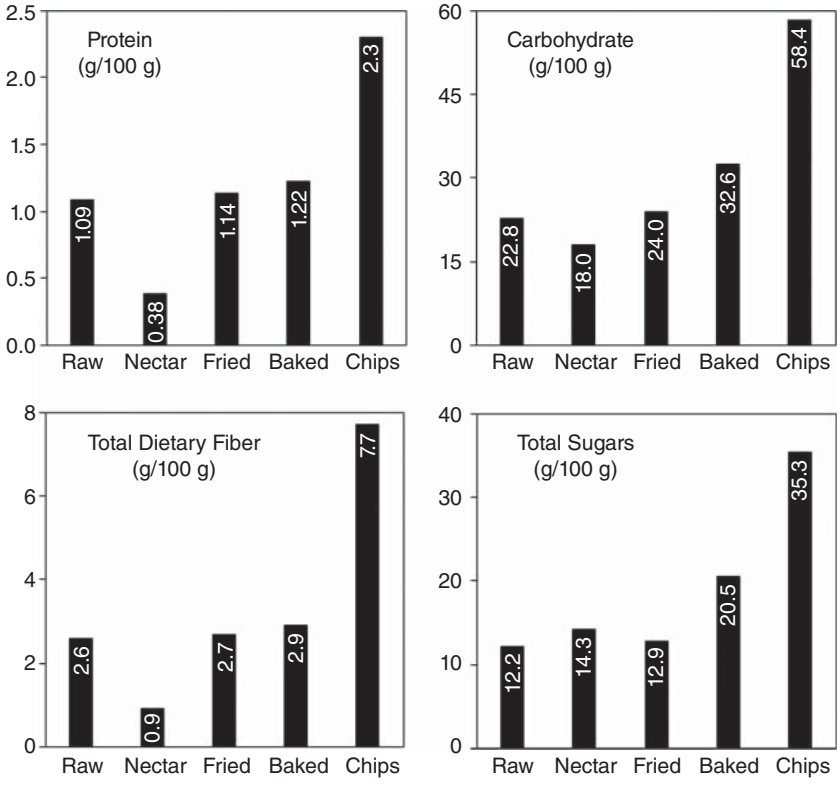

Figure 11.2 Selected proximate composition of raw banana and processed banana products. Source: Based on data from USDA (2019).

quality but improved the dietary fiber, polyphenols and antioxidant capacity significantly (Segundo et al. 2017). The replacement of 50% wheat flour by banana flour (unripe and ripe) produced cookies with higher dietary fiber and with acceptability index of 64.4% (Santos et al. 2015). The unripe banana flour (UBF) had higher amount of starch and lower sugars, and was found suitable for cookie making. In contrast, the ripe banana flour exhibited hygroscopicity because of the high sugar content, and found application in bread making (Pragati et al. 2014).

Green banana pulp (GBP) flour-based extruded snacks were developed by Mridula et al. (2017). The snacks were evaluated for expansion ratio, bulk density, water absorption index, chemical composition and sensory acceptability. Based on multiple response analysis, it was observed that the addition of 8 g of banana pulp in the formulation with feed moisture content of 14%, and screw speed of 350 RPM, resulted in the best quality snacks. The protein and iron contents in the snacks were 15.46 g/100 g and 4.48 mg/100 g, respectively.

Baby Foods

Banana is a popular fruit for preparation of a wide variety of baby foods. For example, applesauce with bananas, apple-banana juice, banana juice with low-fat yogurt, orange-apple-banana juice, strained bananas, banana-apple dessert, banana-yogurt dessert, banana with mixed berries, bananas with apples and pears (strained), banana pudding, bananas and pineapple (strained), bananas and strawberry (strained), mixed cereal with applesauce and bananas, mixed cereal with bananas (dry, instant), oatmeal with applesauce and bananas, oatmeal cereal with bananas (dry, instant), plums, bananas, and rice (strained), rice cereal with applesauce and bananas, and rice cereal with bananas (dry, instant). The nutritional composition of selected banana-based baby foods is shown in Table 11.4.

Porridge and Pasta

A nutritious instant porridge was prepared by replacing brown rice (0–100%) with pregelatinized UBF (Loypimai and Moongngarm 2015). Replacement of brown rice with pregelatinized UBF up to 80% level produced an acceptable porridge with significantly improved level of RS, dietary fiber, antioxidant activity and total phenolics contents. Castelo-Branco et al. (2017) compared pasta made from wheat flour and a blend of wheat flour, green banana flour (GBF), and green banana peel flour and found that 15% banana flour enriched pasta had higher ash, total dietary fiber and total phenolics contents.

Meat Products

To improve the dietary fiber contents in meat products, Kumar et al. (2013) incorporated GBF and soybean hull flours (SHFs) in chicken nuggets and evaluated the physicochemical characteristics and storage stability. With the addition of these ingredients, the protein content in nuggets was decreased but the dietary fiber and mineral contents increased significantly, while energy values decreased significantly compared with the control or 100% chicken meat nuggets (Table 11.5).

Bastos et al. (2014) prepared hamburger patties using flours obtained from GBP, green banana peel, apple peel, and oatmeal flour, as partial fat substitutes. Substitution with GBFs

Table 11.4 Nutritional composition of selected banana-based baby foods (per 100 g).

Composition	Unit	Banana, strained	Banana-yogurt, strained	Banana pudding	Apple- banana Juice
Proximate, energy, and sugars					
Water	g	76.7	80.7	83.5	87.1
Energy	kcal	91	78	68	51
Protein	g	1	1.1	1	0.2
Total lipid (fat)	g	0.2	0.52	0.8	0.1
Carbohydrate[1]	g	21.34	17.35	14.14	12.3
Dietary fiber, total	g	1.6	0.5	0.8	0.2
Sugars, total	g	11.36	12.2	10.55	11
Minerals[2]					
Calcium	mg	4	30	11	7
Magnesium	mg	26	10	5	6
Phosphorus	mg	20	28	34	8
Potassium	mg	290	100	90	123
Sodium	mg	2	14	54	4
Selenium	μg	1.1	0.9	1.1	0.3
Vitamins[2]					
Vitamin C[3]	mg	21.9	13.9	12	27.9
Choline, total	mg	4.1	4.7	10.7	2.3

[1]By difference.
[2]Minerals and vitamins <1.0 mg not shown.
[3]Total ascorbic acid.
Source: USDA (2019).

Table 11.5 Effects of green banana flour (GBF) and soybean hull flour (SHF) on the proximate composition of chicken meat nuggets.

Nugget formulation	Protein (%)	Fat (%)	Crude fiber (%)	Ash (%)	Energy (kcal/100 g)
Control[1]	20.9	11.9	0.5	0.3	193.9
GBF, 3%	19.8	9.4	2.8	2.3	173.7
GBF, 4%	18.8	9.1	3	2.5	169.1
GBF, 5%	18.7	8.8	3.2	2.7	167.5
Control[2]	20.5	9.5	0.6	2.4	183.0
GBF, 3% + SHF, 1%	19.6	9.1	2.8	2.8	166.5
GBF, 2% + SHF, 2%	19.9	8.7	3.3	2.9	160.2
GBF, 1% + SHF, 3%	19.8	9.0	3.2	2.7	161.9

GBF, green banana flour; SHF, soybean hull flour.
[1]Chicken only, with 11.9% fat.
[2]Chicken only, with 9.5% fat.
Source: Adapted from Kumar et al. (2013).

gave higher yield of hamburgers, with higher water-holding capacity during cooking, lower toughness, and less shrinkage. Their sensory analysis results showed that banana peel and pulp flour and the oatmeal flour are excellent choices for fat substitution in beef burgers without adversely affecting the quality of the end products.

Milk Products

Various cultured dairy products are popular in different parts of the world and are valued for their nutritional values. *Shrikhand*, an Indian indigenous dairy product, was formulated by adding 20% unripe banana pulp. It was found that the finished product contained slightly lower fat, protein, total solids, and titratable acidity (Bhoyar et al. 2015). Furthermore, the incorporation of GBF (10–25%) lowered the microbiological quality and shelf life of *Shrikhand* (Hole et al. 2017). At the lower loading concentration of GBP at 3–10% level to yogurt, the growth of two probiotics, *Lactobacillus acidophilus* and *Bifidobacterium bifidum,* was improved. Though no dose–response effect was observed, the GBP has a prebiotic potential without interfering with the physicochemical or sensory characteristics of yogurt (Costa et al. 2017). Addition of GBP flour (at 2% level) to ice cream improved the chemical composition (Table 11.6) and gave higher sensory scores than the control (Yangilar 2015). A new oat-banana fermented beverage has been reported for lactose-intolerant consumers (Goncerzewicz et al. 2016).

Table 11.6 Effect of added green banana peel and pulp flour on the physicochemical properties of ice cream.

Parameter	Unit	Control	Banana peel flour		Banana pulp flour	
			1%	2%	1%	2%
Dry matter	%	34.12	33.51	33.02	34.26	34.60
Ash	%	0.91	1.17	1.21	0.88	1.02
Fat	%	4.6	4.2	4.2	4.3	4.6
Acidity	%	0.2	0.12	0.13	0.14	0.2
Calcium	mg/kg	1844.4	1723.0	1547.5	1214.5	1129.0
Potassium	mg/kg	1654.6	1905.0	2140.0	1716.5	1745.0
Sodium	mg/kg	29.2	564.1	572.5	537.7	548.1
Phosphorus	mg/kg	964.8	1369.6	1430.6	1091.3	1279.6
Sulfur	mg/kg	938.7	1015.0	1074.6	928.6	980.5
Magnesium	mg/kg	159.3	193.0	164.0	194.0	181.0
Iron	mg/kg	10.8	92.6	97.4	69.4	71.4
Zinc	mg/kg	57.8	117.0	201.5	82.8	96.0
pH	—	6.20	6.35	6.49	6.47	6.22
Overrun	%	40.5	31.7	29.8	28.7	28.2
Melting ratio	g/min	0.4	0.5	0.47	0.36	0.4

Source: Adapted from Yangilar (2015).

Health Benefits

Banana is known not only as a source of carbohydrates (e.g., starch and fiber), several minerals and vitamins, but also contains various bioactive compounds, such as biogenic amines, flavonoids, alkaloids, steroids, and glycosides which may offer various physiological and health benefits. Some of these phytochemicals have higher antioxidant capacities to scavenge free radicals in the human body. Sidhu and Zafar (2018) summarized a number of health benefits derived from bioactive compounds found in banana:

- *Tannic acid:* Applied as medicinal agents for the treatment of burns.
- *Catechin:* Resistance of low-density lipoprotein (LDL) to oxidation, brachial artery dilation increased plasma antioxidant activity, and fat oxidation.
- *Gallic acid:* Antioxidant and potential hepatoprotective effects.
- *Cinnamic acid:* A precursor to the sweetener aspartame by means of enzyme catalyzed amination to phenylalanine.
- *p-Coumaric acid:* Antioxidant properties and potentially reduces the risk of stomach cancer.
- *Gallocatechin gallate:* Cholesterol reduction.
- *Quercetin:* Promotes overall cardiovascular health by encouraging blood flow.
- *Ferulic acid:* Antioxidant, antimicrobial, anti-inflammatory, anti-allergic, anti-carcinogenic, modulation of enzyme activity, antiviral, and vasodilatory actions.
- *Trans-α-carotene:* Precursor to vitamin A.
- *Trans-β-carotene:* Reduces the risk of cardiovascular disease and cancer.
- *Cryptoxanthin:* Potential to reduce the risk of lung cancer.
- *Serotonin:* Potentially contributes to feelings of well-being and happiness.
- *Dopamine:* Reduces plasma oxidative stress and enhances the resistance to oxidative modification of LDL.
- *Catecholamines:* Increases blood pressure, glucose levels, and heart beat rate.
- *β-Sitosterol:* Potential to reduce blood cholesterol levels and benign prostatic hyperplasia.
- *Campesterol and stigmasterol:* Reduces the absorption of cholesterol in the human intestines.

In major banana producing countries, traditionally, all parts of the banana plant are consumed, with potential medicinal benefits. Banana pseudostem is comprised of concentric layers of leaf sheaths, and is reported to be rich in nutrients such as minerals, sugars, RS, dietary fibers, and antioxidant compounds (Aziz et al. 2011; Ho et al. 2012). Banana pseudostem has been reported as a potential source of polyphenols or antioxidants, such as gentisic acid, (+)-catechin, protocatechuic acid, caffeic acid, ferulic acid, and cinnamic acid. Banana pseudostem extract has been reported to be very effective in exerting antidiabetic effects (Bhaskar et al. 2011; Ramu et al. 2017).

In addition to the health benefits listed above, the health benefits of banana RS, low glycemic effect, and cholesterol lowering effect steryl glucoside are discussed in the following in more detail.

Resistant Starch (RS) and Hypoglycemic Effect

Dessert bananas, at green stage, and cooking bananas are rich in starch. There are three types of starches based on their digestibility: rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) (Zhang et al. 2005; Sajilata et al. 2006). Among these three, RDS and SDS are typically digested completely in the small intestine and readily converted to glucose molecules. RS is the portion of dietary starch which does not undergo rapid digestion and absorption, and instead enters the large intestine where it is fermented partially or wholly (Sajilata et al. 2006). Nutritionally, RS can be determined using the following formula (Thakorlal et al. 2010):

$$\text{RS} = \text{Total starch} - (\text{RDS} + \text{SDS})$$

The slow digestion of RS influences the rate at which glucose is released. The slow release of glucose induces a relatively small increase in blood glucose (i.e., hypoglycaemic effect), as it is metabolized 5–7 hours after consumption versus normally cooked starch that is digested immediately (Thakorlal et al. 2010; Hamad et al. 2018). Due to this particular health benefit, RS has been classified as a prebiotic, as it positively impacts the host by selectively stimulating the growth/activity of the microflora in the colon, which improves the host's health (Sajilata et al. 2006; Birkett and Brown 2007). In weight management, RS has two main roles with respect to energy metabolism and metabolic control: (i) the digestible energy available from RS is reduced in comparison with RDS and hence lowers caloric density; and (ii) the resulting lower glucose and insulin effect of RS causes subsequent changes in lipid metabolism, which induces lower lipid production and storage thereby burning fat at increased levels (Thakorlal et al. 2010).

Sardá et al. (2016) investigated the impact of consuming RS from UBF on hunger, satiety, and glucose homeostasis in healthy volunteers, and they found the use of UBF in developing functional foods, which may contribute to a reduced risk of certain chronic diseases (e.g., type II diabetes). The *in vitro* digestibility and physicochemical properties of flour and starch from six Thai banana cultivars were reported by Vatanasuchart et al. (2012). The amount of RS ranged from 52.2 to 68.1% and 70.1 to 79.2% in the six banana flour and isolated starch samples, respectively. The amount of amylose content and the crystallinity of amylopectin was shown to determine the resistance of banana starch granules during *in vitro* enzymatic digestion.

The effect of ripening on the nutritional composition, *in vitro* starch digestibility and estimated glycemic index (GI) from banana pulp from three cultivars was investigated by Vatanasuchart et al. (2015). The IDF decreased while soluble dietary fiber (SDF) increased with the ripening. The banana pulp from different stages of ripening had a GI value of <55. The refined wheat flour bread's GI of 100 is used as a reference for GI comparisons from different foods. Flour and extruded snacks prepared from green banana showed a lower GI value due to the RS presence in these banana cultivars.

Flour obtained from banana pulp and peels has been studied for its chemical composition and glycemic response in rats by de Angelis-Pereira et al. (2016). Flour from pulp and peel of unripe banana had higher content of carbohydrates (starch and fiber) and minerals. The peel flour was rich in IDF, whereas pulp flour had both IDF and SDF fractions. Pulp flour

Table 11.7 Steryl glucosides identified in *M. acuminata* Colla var. Cavendish (mg/kg of the vegetal fraction dry weight).

Steryl glucoside	Leaf blades	Floral stalk	Leaf sheaths	Rachis
Campesteryl 3-β-D-glucopyranoside	101.0	119.2	223.8	106.4
Stigmasteryl 3-β-D-glucopyranoside	208.9	263.3	624.1	290.8
Sitosteryl 3-β-D-glucopyranoside	1350.5	678.8	976.4	441.2
Total	1660.4	1061.3	1824.3	838.4

Source: Oliveira et al. (2005). Reproduced with permission of Elsevier.

fed at 10–15% levels in the diet stimulated significantly lower GI in rats. Soto-Maldonado et al. (2018) utilized overripe whole banana for the manufacturing of muffins, and it was found that it gave a GI of 84. The product could be classified as intermediate GI since a 50 g portion of the muffin had a glycemic load of 15. Sharma et al. (2017) reported an innovative method for biotransformation of banana pseudostem extract into a functional juice, containing a significant of amount nondigestible oligosaccharides, and rare monosaccharide (D-allulose) with nearly zero caloric value.

Cholesterol Lowering Steryl Glucosides

Oliveira et al. (2005) reported that *M. acuminata* Colla (var. Cavendish) vegetal parts can be a good source of steryl glucosides (Table 11.7), particularly when they are expected to be used in functional food formulations. Steryl glucosides belong to the phytosterols family, which have been intensively investigated for a wide variety of health benefits, especially their capacity to lower blood cholesterol, associated with their inclusion in human diet (Moreau et al. 2002; Qúılez et al. 2003). Furthermore, steryl glucosides, and particularly the β-sitosteryl derivative, have elicited particular attention because of their specific properties. The β-sitosteryl glucosides have been reported to possess a number of pharmacological activities, such as hepatoprotective and anti-inflammatory (Bouic et al. 1999; Oliveira et al. 2005).

Summary and Future Research Needs

Banana fruit is not only eaten as raw or cooked as a vegetable but is also consumed for its excellent nutritional and nutraceutical properties. Banana is known to be rich in carbohydrates (particularly, starch and dietary fiber) and certain vitamins and minerals. Unripe banana fruit is rich in starch which converts into sugars on ripening. Resistant starch in green banana and plantain makes it a low GI fruit. The high potassium and low sodium contents in banana are optimum for people suffering from hypertension and on a low-sodium diet. Banana is also considered as one of the most important antioxidant-rich staple foods among the easily affordable fruits. The fruit is a rich source of phytosterols, biogenic amines, and many bioactive compounds having antioxidant properties, such as phenolics, carotenoids, and ascorbic acid. Various pharmacological studies on the health

benefits of banana and plantain have attributed these to the presence of antioxidant compounds. However, more focused research, particularly clinical studies, is needed for developing improved quality control, efficacy, safety and toxicity of these banana phytochemicals. Some research data are available on the chemical and nutritional properties of a very important banana by-product (i.e., peel), but there is a need for additional research on the utilization of this antioxidant-rich valuable by-product for the development of functional foods.

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12

Banana (*Musa* spp.) as a Source of Bioactive Compounds for Health Promotion

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Introduction

Banana and plantain are monocotyledonous plants belonging to the genus *Musa*, family Musaceae, and order Zingiberales (Shetty et al. 2016). Musaceae is a small family comprising six genera (*Strelitzia*, *Ravenala*, *Musa*, *Orchidantha*, *Ensete*, and *Heliconia*), whereas some phanerogams recognize Musaceae comprising only two genera, *Musa* and *Ensete* (Qamar and Shaikh 2018). *Musa* is represented by 70 species encompassing the wild and domesticated bananas and plantains (Čížková et al. 2015). Dessert or table bananas have firm pulp when the fruit is unripe and the pulp softens significantly upon ripening, while plantains are generally larger and contain more angular starchy fruits intended for cooking (Pereira and Maraschin 2015).

The taxonomy of the genus *Musa* remains poorly resolved, not least because of the widespread vegetative reproduction and natural occurrence of many hybrids (Heslop-Harrison and Schwarzacher 2007). Linnaeus, in *Species Plantarum* (1753) (Hansen and Maule 1973), was the first to attribute scientific nomenclature to bananas, describing *Musa paradisiaca* (based on *Musa cliffortiana* – Linnaeus, 1736), establishing at the same time the modern botanical nomenclature, which still today is widely used (Häkkinen 2013). The first classification of the genus *Musa* L. was proposed by Sagot (1887), who divided this genus into three unnamed groups (called "sections"). Baker (1893) adopted Sagot's division almost unchanged by defining three subgenus (Häkkinen 2013). In 1947, based on the plant phenotype and on the number of chromosomes, the genus was divided into four sections as proposed by Cheesman: *Eumusa* ($x = 11$), *Rhodochlamys* ($x = 11$), *Callimusa* ($x = 10$), and *Australimusa* (Bartoš et al. 2005; Häkkinen 2013). Later, in 1976, Argent created a separate section, *Ingentimusa*, which contains only one *M. ingens* species ($x = 7$). This classification was recently questioned, and several regroupings were suggested (Čížková et al. 2015). Genotyping with several types of DNA markers confirmed

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the need for review of the *Musa* sections (Čížková et al. 2015). Based on molecular analyzes, wild banana species were reclassified into two sections, *Musa* (merging *Eumusa* with *Rhodochlamys*) and *Callimusa* ($x = 9, 10$), with the inclusion of *Australimusa* and *Ingentimusa* (Shetty et al. 2016).

Four genomes, i.e., A, B, S, and T, corresponding to the species *Musa acuminata*, *Musa balbisiana*, *Musa schizocarpa*, and *Musa textilis*, respectively, are known (Sardos et al. 2016). However, a few cultivars are thought to have originated from hybridization of *M. schizocarpa* (S genome) with either *M. acuminata* or *M. balbisiana*. One clone is thought to have resulted from hybridization between *M. balbisiana* and *M. textilis* (T genome) (Alakonya et al. 2018). The four species at the origin of cultivated bananas have combined to generate a wide diversity of diploid and triploid cultivars with diverse genetic make-ups, varying from AA, AB, AS, AT, AAA, AAB, ABB, AAS to AAT (Sardos et al. 2016). Commercially available bananas are diploid or triploid from the genomes A and B, or are hybrids of the two species produced with their crossings, resulting in groups of AAA, AA, AB, AAB, and ABB classification (Shiga et al. 2017). Inter-crossings among species and subspecies have resulted in the appearance of sterility, a trait that was selected during banana domestication, together with parthenocarpy and vegetative propagation (Creste et al. 2004).

Bananas are widely cultivated in tropical and subtropical regions as important staple foods and commodities in many countries (de Jesus et al. 2013). In recent times, more attention has been paid to banana due to its economic and nutritional importance (Omolola et al. 2015). All around the world, the importance of banana plant increases with its different applications in pharmaceutical and food industries (Qamar and Shaikh 2018) and in other biotechnologically related processes (Ehiowemwenguan et al. 2014). This chapter provides an overview of bioactive compounds in banana and biological activities of banana's secondary metabolites.

Bioactive Compounds in Banana

For a long time, plants have been a valuable source of natural products for maintaining human health, especially in the last decade, with more intensive studies for natural therapies (Karuppiah and Mustaffa 2013). Besides the fruit as a therapeutic alternative, peels, leaves, stem, root, twig, and sap of the banana plant have been used as ingredients for traditional medicines to treat cough, fever, asthma, diarrhea, indigestion, and skin diseases (Khoo et al. 2016).

Bananas are good sources of starch, fibers, minerals (potassium, magnesium, phosphorus, manganese), and vitamin B6 for consumers (Tsamo et al. 2014). In addition, raw and mature bananas have a characteristic matrix of bioactive compounds such as phenolics, carotenoids, biogenic amines, and phytosterols, which are highly desirable in the diet as they have many positive effects on human health and well-being (Pereira and Maraschin 2015; Singh et al. 2016).

Phenolic Compounds

Polyphenols are a complex class of compounds having a phenolic ring in their structure. They can be classified on the basis of the number of phenol rings they contain and the

structural elements binding these rings. In plants, the majority of polyphenols exist as glycosides, esters, hydroxylated forms, and polymers. They are extensively modified throughout the stomach, small intestine, colon, and liver; thus, a single polyphenol can generate several active metabolites (Santangelo et al. 2016). Phenolics, including flavonoids, phenolic acids, tannins, stilbenes, and lignins, have been reported as beneficial components of functional food by nutritionists (Dong et al. 2016). These antioxidants neutralize free radicals by inhibiting the initiation chain or by stopping the chain of propagation of oxidative reactions, converting free radicals into less harmful molecules and repairing oxidative damage in human cells (Du et al. 2009).

Banana fruit has been reported as an important source of phenolic compounds, with flavonoids being the predominant form present. Flavonoids are the most abundant polyphenols in human diets and the most common group of polyphenols in plants as well. They present anti-inflammatory, antitumor, and hepatoprotective activities, as well as a strong antioxidant capacity due to the direct cleaning mechanism of oxygen-free radicals. They also inhibit oxidative enzymes that generate these reactive oxygen species (Dong et al. 2016). Extracts from banana peel and pulp are shown to contain a significant amount of total phenolics and flavonoids and antioxidant activity (Table 12.1). As reported by Baskar et al. (2011), total phenolic and flavonoid content of banana vary significantly with respect to varietal differences (Table 12.2).

Banana and plantain pulp and peel have the potential to be exploited in the food and pharmaceutical industries, mainly for their catechin and rutin content (Borges et al. 2014; Tsamo et al. 2015a). Borges et al. (2014) suggested that parental combinations of genotypes can be selected for the development of hybrids. These can be developed as improved diploid, triploid, and tetraploid hybrids with higher amounts of bioactive compounds. A number of studies have reported catechin, epicatechin, and gallocatechin as major compounds in *Musa* spp. accessions, highlighting the triploids Nam and Highgate with contents of 114.44 mg epicatechin/100 g dry weight basis and 591.41 mg gallocatechin/100 g dry weight basis. In addition to catechin, compounds such as gallic acid, protocatechuic acid, 7-*O*-neohesperoside naringenin, and hydroxycinnamic acids have also been identified in banana pulp (Aurore et al. 2009; Bennett et al. 2010; Borges et al. 2014; Tsamo et al. 2015b).

Plantain pulps and peels have been reported as a good source of phenolics, which could be involved in the health benefits associated with their current applications. Recent studies on

Table 12.1 Total phenolics, flavonoids, and antioxidant activity in banana peel and pulp from green and ripe stages.

	Green stage		Ripe stage	
	Peel	**Pulp**	**Peel**	**Pulp**
Total phenolics (mg GAE/100 g)	685.87	373.88	585.29	230.21
Total flavonoids (mg CE/100 g)	389.33	281.18	225.91	196.45
DPPH inhibition (%)	52.66	35.21	45.08	29.38

CE, catechol equivalent; GAE, gallic acid equivalent.
Source: Adapted from Fatemeh et al. (2012).

Table 12.2 Phytochemical content in peel of different banana varieties.

Banana variety	Total phenolics (mg CE/g)	Flavonoids (mg rutin/mg)
Kadali	0.15	13.80
Karpooravalli	0.19	16.91
Monthan	0.32	11.91
Nendran	0.49	21.72
Poovan	0.39	22.83
Pachainadan	0.30	18.79
Rasthali	0.60	21.33
Robusta	0.20	17.93
Sevvazhai	0.46	12.96

CE, catechol equivalent.
Source: Baskar et al. (2011).

plantains have found that hydroxycinnamic acids are among the majority phenolic compounds in fruit pulps, while flavonoids are mostly found in higher concentrations in the peels (Tsamo et al. 2015b). However, since raw and ripe fruits were used in that study and the ripening stages can affect the content of phenolic compounds thereof, it is important to emphasize the need for further investigations on the impact of these factors in the banana's secondary metabolite profiles.

There are studies on banana fruit reporting their potential contribution to health promotion effects both in *in vitro* and *in vivo* models. The results suggest that phenolic compounds play an important role against a wide range of physiological disorders, e.g., cancer, diabetes, neurodegenerative impairments, cardiovascular disorders, gastrointestinal lesions, and bone damage (Rodriguez-Morato et al. 2015). The benefits of secondary metabolites found in banana biomasses to human health result from their various biological activities such as antioxidant, anti-inflammatory, enzyme expression regulation, and chemoprevention (Manosroi et al. 2013).

The healing and antimicrobial properties of banana peel are associated with the presence of tannin, which is found in higher concentration in unripe banana peels (Shiga et al. 2017). However, few studies have considered that sometimes bananas undergo pre-consumption cooking processes. Changes in phenolic compounds due to cooking are of great complexity, because they vary according to their structures, original food material, and the cooking method used. Studies indicate that thermal treatments weaken the cell wall and facilitate the release of phenolic compounds (Tsamo et al. 2015b). Research performed in Africa has shown that boiling plantain pulps with or without peel increases the amount of phenols in pulps, boiling fruits with peel was shown to increase the ferulic acid content (Tsamo et al. 2015b). However, further studies on the bioavailability of these phenolic compounds and their conjugated forms should be carried out to confirm that boiling pulp with peel is actually more advantageous than boiling without peel. In addition, it is important to investigate other cooking processes such as steam, roasting, and frying to determine which of these treatments best preserve the phenolic compounds in banana.

Carotenoids (Provitamin A)

Approximately 600 unique carotenoids can be found in plant species, as well as in certain species of algae and fungi. In plants and animals, carotenoids serve as pigments responsible for a variety of vivid colors present in nature. These isoprenoid lipids exert complementary and superimposed physiological functions as pigments, antioxidants, and light filters in plants and animals, besides being precursors of vitamin A (Hammond and Renzi 2007). Mammals cannot synthesize carotenoids and, therefore, carotenoids must be obtained from diet. Dietary intake of carotenoids varies widely across individuals and cultures (Hammond and Renzi 2007).

Vitamin A deficiency is a serious public health problem worldwide and is most pronounced in developing countries, affecting 118 countries with about 20 million pregnant women with vitamin A deficiency. In addition, it has been estimated that 100–140 million pre-school children are deficient in vitamin A. One of the sustainable ways to mitigate the problem of vitamin A deficiency is to stimulate consumption of foods naturally rich in carotenoids, such as dark green leafy fruits and vegetables. The diversification of the diet, by direct introduction of genotypes rich in functional compounds and/or the introduction of biofortified crop products (i.e., improved cultivars), besides complementing the existing nutrition interventions, provides greater sustainability and cost effectiveness for producers and consumers (Borges and Maraschin 2016).

Carotenoids and vitamins A and C are the most abundant antioxidants in banana pulp and peel (Toh et al. 2016). The chemical structures of some common carotenoids are shown in Figure 12.1.

A number of studies have shown a great diversity of bioactive carotenoids in *Musa* spp. biomasses, also pointing to cultivars with appreciable amounts of these compounds in comparison with those currently commercialized (Amorim et al. 2011; Borges et al. 2014).

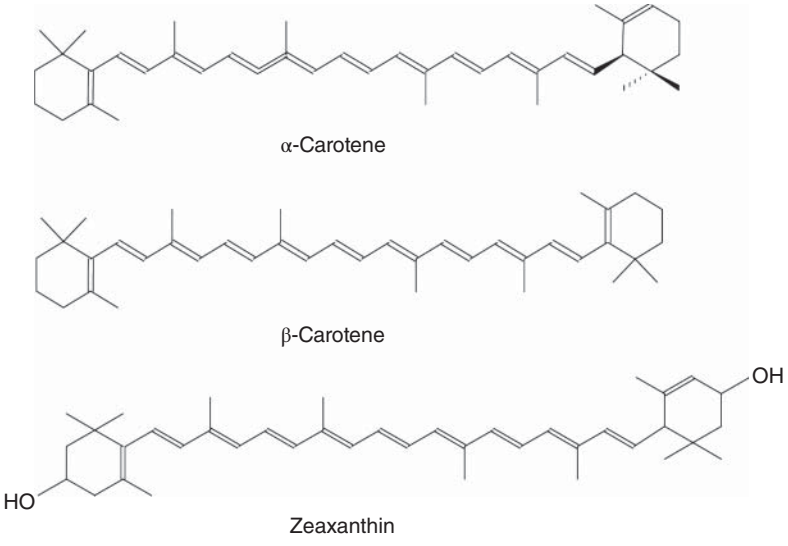

Figure 12.1 Chemical structures of selected common carotenoids. Source: Shahidi et al. (2018). Reproduced with permission of John Wiley and Sons.

This trait can be explored in order to identify potential genotypes to be used in genetic breeding programs. Such programs should focus on culturally appropriate biofortification and/or promote and incorporate existing agricultural systems. Indeed, the regular consumption of some banana genotypes can provide high amounts of vitamin A precursors, approximately 90% as α- and β-carotene (Davey et al. 2009; Borges et al. 2014; Saini et al. 2015).

Various studies have identified accessions in active germplasm banks with high carotenoid contents (Englberger et al. 2010; Borges et al. 2014; Ekesa et al. 2015). *Musa* spp. is a major staple food in African countries and common banana cultivars within East Africa (plantain groups) have amounts of provitamin A ranging from 3.89 to 18.75 mg/g fresh weight basis (Ekesa et al. 2015). Cultivars indigenous to the Pacific region (orange-fleshed cultivars) are significantly higher in provitamin A carotenoids (pVACs), with levels up to 61.40 μg β-carotene/g fresh weight basis (Englberger et al. 2003). Research has shown a possible importance of genomic groups in the concentration of carotenoids, where superior amounts of these pigments were found in plantain varieties (AAB group) with orange pulp color, in comparison with triploids of the AAA group (Davey et al. 2009).

Borges et al. (2014) found significant amounts (84.57%) of pVACs in 12 accessions of the Embrapa's banana active germplasm bank, with an average of 231.15 μg pVACs/g (i.e., 97.88 μg *trans*-β-carotene/g). It was found that the pulp color is a phenotypic trait indicative of the amount of pVACs in bananas. The results of this study revealed a great diversity in the content of provitamin A among the germplasm of *Musa* spp. Accessions with appreciable amounts of these compounds were identified, especially compared with the main cultivars that are currently marketed. Apart from the main role in nutrition, this indicates a strong genetic basis for establishing breeding programs to obtain new banana varieties rich in provitamin A. Cultivars with specific nutritional values might contribute to an increase the intake of pVACs and other selected nutrients in disadvantaged populations.

More recently, studies have indicated changes in contents and retention of provitamin A during ripening of nonindigenous banana cultivars in eastern Africa. In fact, the levels of these substances vary according to the stages of fruit development and this variation depends on the genotype analyzed. During postharvest maturation (from unripe to ripe), there was a significant increase in the content of pVACs in all banana cultivars analyzed. In this study, the mean total pVACs ranged from 560 to 4680 μg/100 g fresh weight basis in unripe fruit and from 1680 to 10 630 μg/100 g fresh weight basis in ripe fruit (Ekesa et al. 2015).

Cooking bananas and plantains are consumed after cooking. Therefore, studies on the retention of compounds after thermal processes are essential, since many factors influence the retention, absorption, and bioconversion of antioxidant and provitamin A compounds (carotenoids). There is a demand for investigating the real benefits to health provided by the consumption of biofortified biomasses of cooking bananas and plantain, making the confirmation of their nutraceutical properties necessary.

Retention studies of the pVACs in different thermal processes indicate that the prolonged exposure to the heat during frying/cooking results in substantial losses of these bioactive compounds. However, the reported data are conflicting and many times difficult to interpret. Generally, the processing conditions are inadequately described. In addition, variable

time and temperature conditions hamper the comparisons among studies. Retention studies performed with different genotypes of cooking bananas and plantains consumed in Africa showed high pVACs retention from different forms of preparation used in the regions studied (Ekesa et al. 2012). The carotenoids retentions after the boiling process can vary from 40 to 95%, depending on the analyzed genotype. In addition, the total of pVACs has been described to increase twofold in the "Musilongo" genotype after the boiling treatment when compared with the *in natura* value (Ekesa et al. 2012). The carotenoids can suffer chemical modifications and alterations in their contents according to the thermal process adopted in the preparation of foods (Ekesa et al. 2012). The thermal treatment affects the cell wall of the food matrix, which can lead to a better extraction of the antioxidant compounds from the cell matrix, also including carotenoids (Blessington et al. 2010; Murador et al. 2018).

Bioactive Amines (Polyamines and Biogenic Amines)

Bioactive amines are found in foods and, depending on their concentrations, may be relevant not only to the shelf life and final quality of food, but also to human health (Kalač 2014). Serotonin has been detected in high amounts in *Musa* spp. fruits, especially when compared with other fruits and vegetables (Islam et al. 2016). According to Xiao et al. (1998), the ingestion of banana, which is considered relatively rich in serotonin, leads to a rapid increase in the level of that hormone in the blood. In addition, banana peel has also been pointed to as a promising source of dopamine for the future development of pharmaceutical formulations for treating diseases such as Parkinson's disease (Pereira and Maraschin 2015). Determining the biogenic amine content in foods is relevant for nutraceutical purposes, moreover, it is important to quantify the toxic effect of some amines (e.g., histamine and tyramine). In fact, when consumed in excess, they can cause different pharmacological, physiological, and toxic effects. The amount and type of these biogenic amines formed are strongly influenced by the composition of the food, microbial flora, storage (e.g., degree of ripeness and temperature), and processing to which they are subjected (Adão and Glória 2005; Bomtempo et al. 2016; Plonka and Michalski 2017).

Several studies have indicated that polyamines and biogenic amines may contribute to antioxidant activity in bananas (Adão and Glória 2005; Larqué et al. 2007; Gloria and Adão 2013). The antioxidant action of these amines correlates with the amount of amino groups. The most common are spermidine and spermine, being classified as having more than two amino groups. Diamines putrescina and agmatina are precursors of these polyamines (Moinard et al. 2005). Interestingly, *in vitro* studies have shown that dopamine has a higher antioxidant activity (as shown by the 1,1-diphenyl-2-picrylhydrazyl [DPPH] assay) compared with other natural antioxidants, such as ascorbic acid, reduced glutathione, and phenolic compounds, i.e., gallocatechin (González-Montelongo et al. 2010).

Biogenic amines are organic aliphatics that play important metabolic and physiological functions in animals, plants, and microorganisms. In plants, polyamines are associated with many developmental processes, being important regulators of plant growth with the ability to inhibit maturation and senescence in a number of tissues. Polyamines are also involved in the control and regulation of biotic and abiotic stress responses that limit

the quality and fruit's shelf life (Agudelo-Romero et al. 2013). Amines such as histamine, phenylethylamine, and serotonin may act as protective substances against insects and fungi. On the other hand, dopamine and noradrenaline are susceptible to enzymatic browning and responsible for such reactions in bananas (Marriott 1980).

Dopamine, serotonin, and histamine have been detected in bananas and their by-products (Adão and Glória (2005). Serotonin has been detected in high amounts in *Musa* spp. fruits, especially when compared with other fruits and vegetables (Islam et al. 2016). According to Xiao et al. (1998), following the ingestion of banana an increase in the serotonin level in the blood plasma has been been recorded. Dopamine and serotonin have also been described as showing antioxidant activity (Kanazawa and Sakakibara 2000), similar to ascorbic acid, and also presenting anti-inflammatory effects (Bajwa et al. 2015). In addition, dopamine has been linked to the decrease of symptoms of Parkinson's disease in humans (Patil et al. 2013).

Amines, such as histamine and tyramine, are related to allergic and intoxication processes and the determination of these compounds is important for the analysis of quality in foods (Larqué et al. 2007). Importantly, a few studies have reported the presence of histamine and tyramine in *Musa* spp. These studies show that histamine and tyramine amounts increase over the maturation process and are related to the characteristic flavor and aroma of the fruits (Plonka and Michalski 2017). Studies with a commercially available banana ("Prata" variety) in Brazil revealed low levels of these compounds (Adão and Glória 2005) and suggest that biofortification studies are necessary to identify accessions with appreciable amounts of histamine and tyramine in active germplasm banks.

The amounts of these secondary metabolites vary according to the stages of fruit development and this variation depends on the genotype analyzed. Therefore, studies with different genotypes and stages of fruit development are necessary to verify the occurrence of these amines and their role in the physiology of fruits and in the health promoting properties of *Musa* spp. Roasting, frying and preferably boiling are the primary preparation methods for plantain and cooking bananas. The fruits can be cooked with or without peel, according to the preparations in the different regions of fruit consumption worldwide (Ekesa et al. 2012). Studies focusing on the retention of bioactive amines in different thermal processes indicate that prolonged exposure to thermal processes results in substantial losses of these bioactive compounds (Plonka and Michalski 2017). In this scenario, it seems to be necessary to investigate cultivars and the domestic methods for food preparation adopted in the different regions of banana consumption. Such an approach will allow the true nutraceutical property of that important staple food to be proved, for instance by means of retention studies of the amine compounds after processing, followed by *in vitro* tests, since many factors influence the retention, absorption, and bioconversion of those antioxidant bioactive metabolites.

Phytosterols

Phytosterols have been recognized for many years by their beneficial effects on human health, the reduction of blood cholesterol level being the most well-known (Oliveira et al. 2008). Due to their structural similarity with cholesterol, these compounds interfere with the solubilization of that steroid in the gut, reducing its absorption. Numerous research

studies have indicated that banana fruit contains substantial amounts of phytosterols (Sheng et al. 2017). Steryl glucosides, in particular the sitosteryl glucoside, have deserved particular attention because of their pharmacological activities, e.g., hepatoprotective, anti-inflammatory, antimutagenic, and antitumoral (Oliveira et al. 2008).

Phytosterols such as campesterol, β-sitosterol, and stigmasterol occur widely in plants in variable amounts. Steryl esters and free sterols are the major lipophilic components found in unripe banana peel, while free fatty acids and sterols dominate banana pulp. In fact, banana has been pointed out as a good source of phytosterols and steryl glucosides (Menezes et al. 2011).

The chemical composition of the lipophilic extracts of unripe pulp and peel of the banana fruit "Dwarf Cavendish" was studied by gas chromatography-mass spectrometry. Fatty acids, sterols, and steryl esters were the major families of lipophilic compounds detected in banana tissues, followed by diacylglycerols, steryl glucosides, long chain fatty alcohols, and aromatic compounds. Fatty acids are more abundant in the banana pulp (29–90% of the total amount of lipophilic extract), with linoleic, linolenic and oleic acids as the major compounds of this family. In banana peel, sterols represent about 49–71% of the lipophilic extract with two triterpenic ketones (31-norcyclolaudenone and cycloeucalenone) as the major components. These data show that certain banana cultivars are sources of valuable phytochemicals, such as ω-3 and ω-6 fatty acids and sterols, with beneficial effects on human nutrition and health (Vilela et al. 2014).

Besides fruit's pulp and peel, banana flowers also contain phytosterols. β-Sitosterol was isolated from many species of banana flowers and reported to have activity in the treatment of benign prostatic hyperplasia, hyperglycemia, prostatic carcinoma, and hypercholesterolemia. In addition, the cycloanane-type triterpenoid, 31-norcyclolaudenone, was isolated from *Musa errans* and *Musa sapientum* species. Its derivatives exhibited anti-HIV, anti-inflammatory and antidiabetic effects. Tetracyclic triterpene (24R)-4α,14α,24-trimethyl-5α-cholesta-8,25(27)-dien-3β-ol was found in the flowers of *M. paradisiaca* (Sheng et al. 2017).

Biological Activities of Banana's Secondary Metabolites

In recent years, much attention has been paid to the activity of natural antioxidants present in fruits, because these components may potentially reduce the level of cell oxidative stress (Apriasari and Suhartono 2014). Antioxidants serve to keep down the levels of free radicals, permitting them to perform useful biological functions without damaging cells and preventing diseases (Halliwell 2006). In this regard, Tamri et al. (2016) have shown that banana peel (*M. acuminata*) extract is a potential source of bioactive compounds such as flavonoids and polyphenols, with a wide range of medicinal properties, in particular the high free radical scavenging activity. Sundaram et al. (2011) determined the correlation between total phenolic and mineral contents with the antioxidant activity of pulp and peel extracts of eight banana cultivars. They suggested that the antioxidant activity of banana extracts was not only due to their phenolic contents, but also due to other compounds, such as vitamin C, vitamin E, β-carotene, and biogenic amines – dopamine and levodopa (Singh et al. 2016).

Interestingly, the antioxidant activity of *M. paradisiaca* peel extracts was also related to a protective effect against oxidative hemolysis in erythrocytes (Sundaram et al. 2011).

Several studies, mostly based on *in vitro* and animal models, indicate that dietary polyphenols, mainly flavonoids, positively modulate the insulin signaling pathway by attenuating hyperglycemia and insulin resistance, reducing inflammatory adipokines, and modifying microRNA (miRNA) profiles (Santangelo et al. 2016). This anti-hyperglycemic effect was observed by Navghare and Dhawale (2017) when the ethanolic extract of the inner peels of *M. sapientum*, *M. paradisiaca*, *Musa cavendish* and *M. acuminata* fruit was evaluated using oral glucose tolerance test in normoglycemic rats. The extract of *M. acuminata* (200 and 400 mg/kg) showed a greater decrease in the blood glucose level, followed by *M. cavendish* (500 and 1000 mg/kg) after 150 minutes of administration of doses. Similarly, de Angelis-Pereira et al. (2016) reported significantly lower glycemic responses in Wistar rats treated with the pulp flour of *M. paradisiaca*, suggesting biomass as a potential source of bioactive compounds for the prevention of certain metabolic diseases, e.g., diabetes, obesity, and dyslipidemia. In addition, oral administration of the chloroform extract of *M. sapientum* flowers in rats caused a significant reduction of blood glucose and glycosylated hemoglobin, increased total hemoglobin, and prevented the loss of body weight (Timsina and Nadumane 2014). The lyophilized juice of banana stem orally administered (50 mg/kg) also showed promising results, significantly reducing the plasma glucose content and increasing serum insulin in diabetic rats after four weeks of treatment (Dikshit et al. 2012).

In another approach, banana peel is known by its traditional use in folk medicine to promote wound healing mainly from burns (Pereira and Maraschin 2015). Von Atzingen et al. (2011) demonstrated a positive effect on the wound healing process, especially in the repair of operative lesions in rats using gel from unripe *M. sapientum* peel. Treated groups with methanolic and hexanoic extracts of *M. paradisiaca* peel showed better wound healing activity in mice (Padilla-Camberos et al. 2016). Similarly, in an excisional wound healing model in rabbits, a healing effect of banana peel extract has also been demonstrated. Significant decrease was observed in the re-epithelialization period and a high contraction rate of the wound (Tamri et al. 2016). In another scenario, Budi et al. (2016) demonstrated that the ambonese banana stem sap accelerates healing after tooth extraction in rats, contributing to increase in the expression of PDGF-BB (platelet-derived growth factor family) and also to fibroblast proliferation. More recently, Rifasanto et al. (2018) have shown an increase in fibroblast cells in the wound healing process after incision in rat's buccal mucosa and treatment with a gel containing ethanolic extract of stem of *M. acuminata*.

In the tissue repair process, inflammatory cells promote the migration and proliferation of endothelial cells followed by keratinocytes, leading to the neovascularization of connective tissue cells that synthesize extracellular matrices including collagen, resulting in the re-epithelialization of the wounded tissue (Agarwal et al. 2009). In this regard, Phuaklee et al. (2012) found that banana peel extract decreased relaxant processors to inflammatory events in macrophage cultures of rats, speculating a regulatory effect of bioactive compounds on the inflammation phase in the tissue repair process.

Antibiotic activities are also attributed to the extracts of peel and pulp of mature bananas (Semoretta and Sumathy 2016). Ehiowemwenguan et al. (2014) evaluated the antibacterial activity of the aqueous and ethanolic extracts of *M. sapientum* peel against *Salmonella typhi*,

Escherichia coli, *Klebsiella pneumoniae*, and *Staphylococcus aureus*. It was verified that the ethanolic extract presented greater zone of inhibition of the bacterial growth compared with the aqueous extract. On the basis of these results, it can be concluded that the ethanolic extract of banana peels has a broad spectrum of *in vitro* antibacterial activity.

Exposure of human skin to UV radiation might lead to various pathological skin disorders, including erythema, immunosuppression, edema, sunburn, hyperplasia, hyperpigmentation, skin cancer, and premature aging, also referred to as photoaging (Hu et al. 2016; Pérez-Sánchez et al. 2016). In addition, radiation, in particular UVB, creates reactive oxygen species (ROS) and reactive nitrogen species (RNS) radicals, which cause DNA strand-breaks, protein cross-linking, and the oxidation of numerous functional groups of proteins and lipids in the skin. In an experiment where mice were fed banana, a decrease in skin damage caused by chronic UVB exposure was observed. There was increase in the expression of γ-glutamylcysteine synthetase (which is involved in the cellular defense mechanism against free radicals), reduction of the final oxidation products, including carbonyls, malondialdehyde, and 4-hydroxynonenal occurred, and of metalloproteinase-1 (MMP-1) expression (Leerach et al. 2017). It is known that the mechanism of photoaging involves decreased collagen synthesis and over-expression of matrix MMPs, which are responsible for the formation of wrinkles in the skin. In another study, Yoo et al. (2016) examined the possibility of using *M. sapientum* leaves as a cosmetic raw material. The results revealed that the leaf extract promoted the expression of procollagen and inhibited the expression of MMP-1 and MMP-2 in fibroblasts, which are important enzymes involved in the degradation of collagen.

Many types of cancer treatments have been adopted in recent decades, including surgery, chemotherapy, radiation therapy, hormonal therapy, and combined therapy. However, all these therapies lead to different and uncomfortable side-effects. Hence, identifying and developing new chemotherapeutic agents from plants (i.e., phytochemicals) have gained significant recognition in the field of cancer therapy and become a major area of experimental cancer research (Praveena et al. 2018). A review by Mathew and Negi (2017) shows the strong anticancer activity of extracts developed with different parts of *M. acuminata*, e.g., leaves, bracts, and rhizome. For instance, a decrease of the cell growth of the lineages of MCF-7 (breast adenocarcinoma), HeLa (human epithelial carcinoma), Ehrlich ascites carcinoma, and Hep G2 (hepatic carcinoma) has been observed. Similarly, (Praveena et al. 2018) illustrated that banana fruit juice inhibited the proliferation of colon cancer cell line HT-29 by up to 55%, with the treatment of 200 μg/ml through *in vitro* assay. Timsina and Nadumane (2014) evaluated the effect of ethanolic extract of the banana flower in HeLa and CHO (hamster ovary tumor line) cells, detecting a dose-dependent cell antiproliferative effect.

Renal lithiasis, i.e., calcium kidney stones, is an important urological and nephrological pathological condition that affects a high percentage of the population worldwide, with varying incidence according to distinct geographical region (Arrabal-Polo et al. 2013). Calcium-based stones, both in oxalate and in phosphate form, prevail in developed countries, while infectious lithiasis remains the main cause in developing countries (Alapont et al. 2001). Administration of oral banana stem juice in rats helped to reduce the formation and also the breakdown of the ammonium phosphate-calcium oxalate stones in the rat bladder (Qamar and Shaikh 2018).

Other diverse biological activities have also been reported through preclinical and clinical assays when administering extracts of different parts of banana. Published research demonstrate an anti-ulcer effect in rats orally treated with the methanolic extract of *M. sapientum* peels (Onasanwo et al. 2013). Interestingly, the same banana species also presented satisfactory results in the prevention of arterosclerosis (Fu et al. 2012). Mosa and Khalil (2015) suggest that the consumption of fresh and dried banana peels of *M. acuminate* may reduce the risk of acute liver failure in human patients. Besides, banana pulp intake was suggested as important to decrease hypertension due to the amount of sodium found in that biomass (Mohamed 2014; Dayanand et al. 2015). Finally, banana fruit and other parts of the plant appear to be sources of bioactive compounds with interesting pharmacological activities regarding the gastrointestinal tract. For instance, root extracts of *M. paradisiaca* are antihelmintic, flowers are astringent, and fruits are mildly laxative. Additionally, root extracts were also useful in treating celiac disease, constipation, and peptic ulcer (Karuppiah and Mustaffa 2013).

Summary

Banana consumption can potentially decrease the occurrence of different diseases since this fruit is rich in several bioactive compounds, such as secondary metabolites, minerals, and fibers. Additionally, new strategies to use banana biomasses have been employed, e.g., the extraction of bioactive compounds from different parts of the plant. These extracts have been studied mostly for the determination of their antioxidant activity. A series of investigations developed in recent years corroborates significant results showing banana biomasses as sources of secondary metabolites with effective pharmacological activities in various biological models.

Banana peel as a food processing by-product represents a major problem for the industry and has been considered a waste of low economic value. However, this residue is also a promising source of compounds with relevant biological and nutritional properties. Thus, targeting this biomass to health care or cosmetics industries can be an alternative to its reuse by adding economic value and considerably reducing its environmental impact. There are opportunities and challenges to turn banana biomasses into biotechnologically relevant products.

Although the results so far reported in the literature regarding the use of banana extracts – from different plant parts and varieties of *Musa* spp. in different biological models – are favorable, there are some important technological gaps that need to be addressed before any application in industry is envisaged. For example, a standard method for extracting certain bioactive compounds should be developed and validated, and the origin of biomasses used to recover pharmacologically important secondary metabolites must be certified, avoiding the use of donor plants from conventional agricultural systems where pesticides are currently adopted. Besides, the variability in chemical profiles of extracts commonly reported in studies represents a relevant challenge to be overcome, aimed at guaranteeing the reproducibility of biological assays and, ultimately, the composition of a phytomedicine or food.

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13

Microbiology of Fresh Bananas and Processed Banana Products

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Introduction

Banana or plantain family (Musaceae) includes more than 1,000 genera with diverse members belonging to ornamental, domesticated, and wild accession categories (Li et al. 2013a). However, in general two basic types of banana are cultivated across the globe, i.e., dessert and cooking. Ecologically, this fruit grows in hot and humid regions of the world encompassing about 130 countries in the tropics and subtropical areas in Asia, Africa, and Latin America (Jones and Daniells 2019).

Banana fruit is a highly perishable commodity owing to its climacteric nature, neutral pH, and high sugar content. Therefore, it exhibits microbial diversity spanning over bacterial to fungal genera, which may infect during pre- as well as postharvest phases of cultivation and also during storage and transportation of the produce. This chapter provides comprehensive information regarding the microbiology of raw banana and processed banana products, and methods of banana quality evaluation.

Microflora of Fresh Banana Products

The ripened dessert banana is the most commonly consumed banana fruit in Asia and Latin America, which is eaten raw after removing peel. The fruit pulp contains substantial amounts of sugars, minerals (e.g., potassium, manganese), and vitamins (e.g., carotene or provitamin A, vitamin C and vitamins B1, B2, and B6), and dietary fiber (Singh et al. 2018). The microflora of the raw dessert type banana is typically affected by the sugar and phenolic content present in the ripened versus unripened fruits. The microbial counts also vary during the different stages of cultivation from farm to the table. The average microbial populations over the various growth stages of bananas range from 10^3 to 10^5 colony forming units (CFUs) for both bacterial and fungal genera (Gultie and Sahile 2013).

The bacterial and fungal counts of the unripened banana are substantially lower or even non-existent in comparison with the ripened banana. This may be due to the presence of

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resistant starch, very low concentration of reducing or available sugars, and variation in the relative concentrations and diversity of the bioactive secondary metabolites, namely catechin, epicatechin, gallocatechin, lignin and tannins, and anthocyanins, which have considerable antimicrobial potential (Pereira and Maraschin 2015). The unripened fruits also have very low yeast and filamentous fungal counts that may also be attributed to high phenolic and low substrate concentrations. However, in comparison to yeast and mold counts, the bacterial counts particularly of gram-negative genera, such as *Pseudomonas* and *Enterobacter,* and gram-positive genera including *Bacillus, Lactobacillus,* streptococci, and micrococci populations in unripened banana are higher possibly due to the appropriate pH conditions for proliferation of bacteria. In a fruit and vegetable market survey study, Obetta et al. (2011) reported substantial mean absolute mesophilic aerobic plate count (APC), yeast and mold depicted as 113, 23.7, and 28.0 log CFU/in^2 for the bananas sampled from three different locations in Nigerian Benue state town, Markudi. The ripened banana pulp exhibits occurrence of wild yeast cells, such as *Pichia, Candida* sp. besides the classical *Saccharomyces cerevisiae* that can be utilized as isolates for carrying out banana pulp/peel fermentation (Lathar et al. 2010).

Banana pulp is well-guarded by tough and fleshy peel, which also contains high amounts of catechins, epicatechin and gallocatechin, proanthocyanins, anthocyanidins, flavonols, flavanones, and glycoside-substituted flavanols/flavanones (Vu et al. 2018). Therefore, there are limited reports on occurrence of contaminating food-pathogenic microbes on consumption of raw banana. Despite the peel protection, published reports have indicated incidences of pathogenic microbial contaminants in whole bananas. Al-Kharousi et al. (2016) performed microbiological analysis of banana pulp and observed the presence of opportunistic human pathogenic bacteria *Klebsiella pneumoniae* and plant pathogenic *Pantoea* sp. Nwankwo et al. (2015) reported high fungal counts for fresh and whole bananas procured from a fruit market in Nigeria, which was predominated by *Saccharomyces* spp., *Aspergillus* spp. and *Penicillium* spp. fungal cultures. Similarly, the over-ripened or rotten banana may exhibit the presence of a high number of *Candida* sp. and *S. cerevisiae*, as the yeast genera, with *Fusarium oxysporum*, as the filamentous mold (Hasan and Zanuddin 2018), in addition to increased counts of gram-positive bacterial genera including *Staphylococcus* sp. and *Bacillus* sp. (Hasan and Zulkahar 2018). The number of mycotoxigenic fungi, such as *Aspergillus, Penicillium,* and *Fusarium* sp. also gets enhanced in rotten bananas (Sarkar et al. 2011).

The fresh-cut fruit industry has been getting positive impetus due to the convenience and nutritional intactness features of such products. However, being consumed raw, the fresh-cut fruit preparations are often known to harbor diverse microbial pathogens as contaminants including the spoilage pathogens as well as human pathogenic gram-positive and -negative bacteria. The fresh-cut artisan fruit salads or chats containing banana slices along with other seasonal fruits are the most popular street vended food items. Incidences of occurrence of a variety of enterotoxin producing gram positive bacteria (*Staphylococcus aureus*) have been reported on sampling of these street vended fresh-cut products in Asia (Kumar et al. 2006) and South America (Lucero Estrada et al. 2013). Likewise, the common fecal contaminants including the gram negative *Salmonella typhi, Shigella, Escherichia coli, Enterobacter faecalis,* and *Yersinia enterocolitica* have also been identified in fresh-cut fruit salads and similar products (Kalia and Gupta 2006, 2012). The presence of these human

pathogenic bacteria indicates the contamination of the fruits salads either due to washing with contaminated water or prevalence of cross-contamination due to use of contaminated cutting knives/cutting boards/trays, unhygienic practice of cutting fruits with bare hands and due to dust or air contamination (Lucero Estrada et al. 2013). Therefore, improved microbiological safety of the fresh-cut fruits demands that appropriate food safety steps during minimal processing should be followed.

Processed Banana Products

The microbiology of the processed banana products is quite complex, as it largely depends on the type, extent and time for processing. Banana chips are the products derived from the cooking banana, which is one of the staple foods on the African continent. Cooking bananas are rich in starch, including resistant starch, dietary fiber, and contain diverse bioactive compounds of antioxidant potential particularly quercetin and other phenolics and flavonoid compounds (Singh et al. 2018). Banana chips are one the most popular processed products, which are produced by either sun or air-drying, vacuum drying, and microwave treatment of the cut slices, to reduce the water activity of the chips. Mui et al. (2002) optimized the process of decreasing the water content to 3% for obtaining crispier chips having significantly higher volatile compounds and sensory properties by using a combination of 90% air-drying combined with 10% vacuum microwave drying.

The fresh-cut or minimally processed banana chips are prone to infection by several types of microbes. However, pretreatment of the fresh-cut banana chips may alter the microbial diversity and abundance. A report on minimally processed plantain variety Alukesel showed improved shelf life on storage at 5–7 °C on treatment of the fresh-cut pieces with 3% citric acid (Siriwardana et al. 2016). Further, this pretreatment may also possibly control or even eliminate food-borne pathogenic bacteria, such as *Salmonella, Listeria, Clostridium,* and *Yersinia* (Siriwardana et al. 2016). However, the extent of microbial inactivation, which can be obtained by the above techniques, is still elusive. Therefore, new rapid and microbiologically safe techniques, such as low pressure superheated steam drying, have to be tested for drying of osmotically and thermally sensitive banana chips (Bourdoux et al. 2016).

Moderately processed banana products include banana puree and smoothies. Generally, puree can be prepared from bananas having low commercial value, such as second grade bananas with fifth grade ripening stage. This category of banana fruits was observed to exhibit the best sensory and other properties on preparation of puree compared with even the commercial grade fruits (Yap et al. 2017). The dairy-based products with banana supplementation are quite popular in many parts of the world. Smoothies are the blended beverages, which exhibit loss of important sensory qualities on thermal treatments. Therefore, non-thermal techniques, such as high pressure processing, can be a useful alternative for such products. However, there is scarce information available regarding the microbiological and enzymatic status of the products developed through these processing techniques.

Li et al. (2015) performed the total aerobic bacteria and yeast and mold count studies of high pressure processed and nitrogen-infused and -degassed banana smoothies and observed stable microbiological status of the nitrogen-infused smoothies on storage for two

weeks at refrigerated temperature. Likewise, a stirred yogurt-based banana puree fortified with calcium lactate (400 mg/100 g) was observed to exhibit product properties close to a non-calcium fortified one in spite of weakening of the casein network on calcium salt fortification. Therefore, such mineral fortified dairy products can improve the gut microflora besides improving the mineral absorption on consumption (Pachekrepapol et al. 2018). The microbiological analysis of this fortified yogurt product showed slightly improved survival of the lactic acid bacteria (log CFU/ml) compared with the control yogurt. This enhanced survivability of the lactic acid bacteria may possibly be attributed to occurrence of banana oligo- and polysaccharides having prebiotic potential besides the presence of fermentable sugars. Considering the beneficial role of banana flour, another report on the formation of instant kefir by supplementation of dried and milled banana flour (10% w/w) showed high yeast (8.8×10^4 CFU/ml) and lactic acid bacteria (9.8×10^5 CFU/ml) counts (Azara et al. 2018).

Banana-based fermentation products are the other category of processed products that have a huge product scale ranging from the bakery to the brewing industry. Nigerian farming women prepare *Dockounou*, a traditional ripened banana mixed with starchy (rice/maize) flour (Kouadio et al. 2014). The dough undergoes spontaneous fermentation after which it is fried. Microbiological studies of this product showed the presence of yeast, and bacteria (*Bacillus* sp. and lactic acid bacteria) but an absence of acetic acid bacteria thereby imparting the characteristic sensory and nutritional properties to the product (Kouadio et al. 2014). Among the bakery products, bread can be prepared by supplementation of banana pseudo-stem flour (100 g/kg) along with two different hydrocolloids (xanthan gum/sodium carboxymethyl cellulose; 8 g/kg flour, w/w basis) (Ho et al. 2014). These types of composite breads can exhibit improved values for the onset and peak temperatures and higher water holding capacities or lower enthalpy change temperature and delayed bread firmness on storage compared with control bread. Further, the microbial counts of aerobic bacteria, mold, and yeast also increased with the time of storage (Ho et al. 2014).

The microbiological dissection study for the generation of Tanzanian specialty banana beer *Mbege* revealed the role of the banana and germinated finger millet porridge, which on mixing led to alcoholic fermentation initiated by wild yeast cultures in banana porridge (Kubo and Kilasara 2016). Interestingly, the yeast counts were observed to be higher for the beer produced on supplementation of stem bark of *Rauvolfia caffra* compared with the control preparation. The banana must can also be processed to obtain wine. The wine clarification issues can be addressed by treatment of must with pectinase and alpha-amylase enzymes (Cheirsilp and Umsakul 2008).

Pre- and Postharvest Factors Affecting Banana Yield and Quality

Preharvest Factors

Biotic Agencies

Banana can be affected by several types of microbial pathogens during cultivation. The most prevalent and devastating diseases in banana plant, such as finger rot and fruit rot,

Bugtok and blood diseases, banana wilt, heart rot and rhizome/pseudostem wet rot, are caused by fungal and bacterial pathogens. The fungal diseases tremendously affect banana productivity and are also the major cause of huge economic losses in Latin American countries. Fusarium wilt (*F. oxysporum* f. sp. *cubense*) and black leaf streak disease (*Mycosphaerella fijiensis*) are among the major fungal disorders of banana (Blomme et al. 2017). Viral diseases, such as the streak disease (Banana streak Obinol'Ewai virus), can also lead to considerable economic losses in banana cultivation (Geering et al. 2005).

Fungal Diseases of Banana

Fungal pathogens of banana have devastating potential for both plant and yield losses (Cook et al. 2015). Fusarium wilt or Panama disease has been held responsible for completely wiping out the Gros Michel cultivar of banana in Latin America (Costa Rica and Panama) besides incurring huge economic losses (Butler 2013). Therefore, a Cavendish cultivar of banana resistant to *Fusarium oxysporum* f. sp. *cubense* (Foc) race 1, the causative agent of this disease, came as a Foc race 1 resistant alternative (Ploetz 2005). However, as highly susceptible monoculture cultivation practice for banana is followed, a new variant of Foc, Tropical Race 4, can recreate the scenario of the gradual demise of industrial Cavendish cultivation similar to the Gros Michel episode (Cook et al. 2015). Banana plants are also susceptible to other fungal pathogens, such as *Mycosphaerella musicola*, which causes yellow sigatoka, *Pseudocercospora fijiensis* (synonym *Mycosphaerella fijiensis*), which causes the leaf streak disorder called black sigatoka, *Gloeosporium musae* causes anthracnose, and *Verticillium theobromae*, *Trachsphaera fructigena,* and *Gloeosporium musarum* causing cigar end tip rot and heart rot caused by *Botrydiplodia* sp., *Gloeosporium* sp., and *Fusarium* sp.

Bacterial Diseases of Banana

The bacterial diseases related to banana can be subcategorized on the basis of the bacterial pathogen and the host banana species. Radical economic losses are caused by three subgroups causing specific diseases with characteristic symptoms (Blomme et al. 2017). *Ralstonia,* non-spore forming, aerobic, gram-negative bacteria (*Ralstonia solanacearum*), has been responsible for causing vascular infections, namely Moko/Bugtok disease, while *R. syzygii* subsp. *celebesensis* causes banana blood disease. Two different species of *Erwinia* (*E. carotovora*s sp. *carotovora* and *E. chrysanthemi*) cause bacterial head rot or tip-over disease besides the wet rot of rhizome and pseudostem caused by reclassified *Dickeya paradisiaca*. Banana plant is prone to wilt disorders and the bacterial xanthomonas wilt caused by *Xanthomonas campestris* pv. *musacearum,* is another important disease, which causes serious yield losses in banana.

Viral Diseases of Banana

Both banana and plantain can get infected with 20 different virus species classified among five distinct families (Tripathi et al. 2016). These viral diseases can cause substantial economic losses (up to 100% yield loss) but the prominent viral disorder, banana bunchy top disease (BBTD), is caused by the banana bunchy top virus, which exhibits hybrid characteristics and symptoms of banana streak virus and banana bract mosaic virus (BBrMV) (Kumar et al. 2015). Similarly, aphid-transmitted potyvirus group member, BBrMV is the natural pathogen of wild banana (Abaca) and may cause yield losses ranging from 30 to 70%

(Geering 2009). The banana mild mosaic virus (BanMMV) exhibits infections in the early vegetative growth stages of banana while the characteristic symptoms disappear as the plant matures. Thus, it rarely shows overt disease symptoms (Kumar et al. 2015). Banana plants are also infected by an uncategorized *Flexiviridae* member, banana virus X (BVX), that leads to relatively more silent and subtle disease symptoms. Another occurrence of highly diverse endogenous badna viruses in banana, which are the causative agents of banana streak disease, has been reported by Geering et al. (2005).

Abiotic Agencies

Abiotic characteristics related to soil can play a significant role in the spread or control of several soil-borne diseases of banana (Orr and Nelson 2018). The soil texture, temperature, soil water content, dissolved oxygen amount, pH, electrical conductivity, organic carbon content, nutrient availability and their ratio proportions, and relative distribution are some of the physical and chemical properties of soil that may affect the percent disease incidence (Janvier et al. 2007). A significant variation exists for the soil edaphic and microbial characteristics among disease suppressive and conducive soils such that relative soil aggregate size, size distribution, and nutrient content, and aggregate-specific microbial and soil enzyme activities can also be used as an indicator (Li et al. 2018).

Banana, being a rhizome propagated herbaceous crop, has specific macro- and micronutrient element demands besides having high water requirements (Kalhoro et al. 2015). Likewise, the banana-specific fungal and bacterial pathogens also exhibit defined preferences for certain soil types, edaphic properties, and geographical conditions and niches, which can be utilized as indicators or descriptors for characterization of disease suppressive or conducive soils (Orr and Nelson 2018). However, as soil is a complex and dynamic substrate with its components exhibiting inter-relationships, the soil edaphic properties are also inter-dependent. Therefore, it is difficult to determine the effect of each soil characteristic separately. Nevertheless, the soil type, its clay mineral composition and pH (Deltour et al. 2017), and the amount of critical macro- (Ca and N) (Johnson and Oelmüller 2013; Mur et al. 2016) and micronutrients (Zn, Fe, Mn, B, and Mo) have a key significance for disease suppression (Siddiqui et al. 2015; Dong et al. 2016; López-Díaz et al. 2018).

Supplementation of the soil with micronutrients can have a controlling action on the soil-borne fungal pathogens particularly either through direct metal toxicity or through alterations in the plant metabolism related to production of phenolics and lignin besides elicitation of the induced systemic response (Siddiqui et al. 2015). Apart from the known macronutrients, silicon supplementation of the soil or spraying on banana foliage can be effective to decrease the soil-borne and foliar fungal pathogen disorders probably due to physical warding off of the pathogen (Freitas et al. 2017), improvement in the cell wall cementing material (Wang et al. 2017), and potentiation of the plant's phenylpropanoid pathway (Fortunato et al. 2013).

The geographical location and the microclimate of the region of cultivation can also affect the production as well as chemical composition of the banana. On growing Gran Enana cultivar of banana at two different locations, Tenerife (Canary islands) and Ecuador, variation in their protein, ash, ascorbic acid, glucose, fructose, and total sugars contents has been reported (Forster et al. 2002). Further, a factor analysis study concluded that this variation

in chemical composition in banana can be utilized to differentiate the alterations in the region of production, cultivation, and agronomic practices followed (Forster et al. 2002).

Postharvest Factors

Biotic Factors

Fungal Pathogens

The fungal pathogens are the characteristic microorganisms causing several diseases in banana both during the cultivation and postharvest stages. The epidemiological chronology of the two most common fungal pathogens namely, *Fusarium* and *Colletotrichum musae*, which form a fungal complex and cause crown rot disease, has been deduced (de Bellaire et al. 2008). The primary source of infection for both of these fungi is through the flowers and flower parts and last bunch bracts, respectively. The conidia get transferred via rain, or through insects or ascospores spread by air as the transmission agent. These conidia germinate and form quiescent appressoria till the advent of ripening of the banana. Therefore, the infection incidences can be decreased substantially by removal of the last bracts and the flower remnants (de Bellaire and Mourichon 1997).

Abiotic Factors

The major abiotic factors which affect the shelf life of the stored banana are temperature, relative humidity (RH) and the atmospheric composition of the enclosure where the fruit bunches have been stored (Lassois et al. 2010).

Temperature and Relative Humidity

The prime abiotic factor which affects the shelf life of banana is high temperature. The storage of banana at cooling temperatures ranging from 13 to 14 °C decrease the physiological ripening process of the harvested and stored bananas (Lassois et al. 2010). Further low temperatures induce oxidation of the phenols present in peel and pulp of the fruit leading to browning. The low temperature storage also benefits indirectly by decreasing the multiplication of the fungal pathogens particularly the crown rot fungi, which require warm and humid temperatures for growth.

Gawai and Sawant (2013) evaluated the effect of different storage temperatures on the susceptibility of banana fruits on artificial inoculation of most common fruit rot causing storage fungal pathogens of banana. They concluded that the predominant fungal cultures were *G. musarum*, *Aspergillus niger*, *Fusarium moniliforme,* and *C. musae*, which exhibited highest incidences of the disease in the 20–30 °C temperature range. Likewise, in a warehouse sanitation standard study, Diedhiou et al. (2014) observed substantial postharvest losses of stored banana due to anthracnose (*C. musae, Fusarium* sp.), with multiple infection by two *Aspergillus* species, *A. flavus* and *A. niger*, besides black sporulating *Alternaria* sp. and *Curvularia* sp. The occurrence of *Heminthosporium* sp. and *Thielaviopsis* sp. were also observed. The occurrence of these fungal genera indicates high temperature and humid conditions prevailing in the warehouse. Another study involving storage of bananas under refrigerated conditions exhibited prolongation in initiation of ripening of the *Musa sapientum* and *Musa acuminata* var. dwarf Cavendish banana varieties. Therefore, the temperature of storage and the sanitation conditions of the storage room are the crucial factors that affect the shelf life of the banana fruits.

Banana fruit is highly prone to water loss due to transpiration from the fruit peel under stored conditions. If the RH of the storage enclosure or container is not maintained at optimum conditions, higher transpiration losses lead to shriveling of the fruit peel predisposing it to bruising and other handling/storage losses (Luyckx et al. 2016). Though the transpiration losses from fruit peel are also genetically controlled, i.e., cultivar specific, still storage at 14 °C at 92–96% RH improves the storability and shelf life of the bananas (Murmu and Mishra 2016). Luyckx et al. (2016) reported that the incidences of peel splitting, a major postharvest physiological disorder, can be curbed by studying the peel morphological, biochemical and physiological characteristics which are cultivar-specific and thus genetically controlled.

Atmospheric Composition of the Storage Facility or Storage Method

Banana are climacteric fruits, which produce fruit ripening and tissue softening "ethylene" during storage (Luyckx et al. 2016). Further, these are highly susceptible to damage due to pressure or weight. Both of these factors predispose the fruits to facilitate elaborate microbial penetration and invasion of the fruit tissues thereby enhancing spoilage (Lassois et al. 2010). Therefore, the storage conditions or the methods followed can have a crucial impact on the shelf life and microbial load of the stored fruits (Fajinmi et al. 2011). The microbial loads will increase in a time-dependent manner and may involve composite microflora including certain common bacterial (*Bacillus* spp., *S. aureus*, *Lactobacillus* sp.), decay molds (*A. flavus, A. niger, Fusarium,* and *Penicillium* sp.) and yeast (*Saccharomyces* sp.) genera indicating the handling and storage conditions of bananas (Fajinmi et al. 2011). Further, modification of the atmosphere can be performed by altering the relative proportion of CO_2 and O_2 gases. Increasing the CO_2 gas and lowering the O_2 gas reduces the respiratory activities of the fruit, thereby lowering the production of ethylene gas (Lassois et al. 2010).

Spoilage and Postharvest Losses Due to Microbial Infections

Banana fruit is prone to attack by postharvest pathogens and thus has relatively very short storage life, which affects the marketing potential and influences the economic value (Figure 13.1). Bananas are prone to several fungal pathogenic diseases due to high water and sugar contents and low pH conditions leading to substantial subsequent loss in fruit quality, shelf life, and other marketable characteristics. Therefore, the factors contributing to the postharvest decay and spoilage are both abiotic and biotic in nature and origin. Among the biotic agencies responsible for causing moderate to high economic loss under storage conditions, crown rot, anthracnose (*C. musae* and *Fusarium* spp.), and finger rot/fruit rot (*Lasiodiplodia theobromae*) (Nath et al. 2014) are the primary spoilage disorders of banana fruit (Figure 13.2).

Crown rot of banana is the most prevalent disease manifested as the development of mycelia on the surface of the soft tissue 'crown' which joins the peduncle. This postharvest disease became dominant after the practice of cluster cutting and discontinuation of the practice of bunch shipment due to replacement of Gros Michel cultivation by the more fragile Cavendish banana (Lassois et al. 2010). Etiologically, it is characterized by infection of multiple fungal genera including those associated with preharvest diseases, such

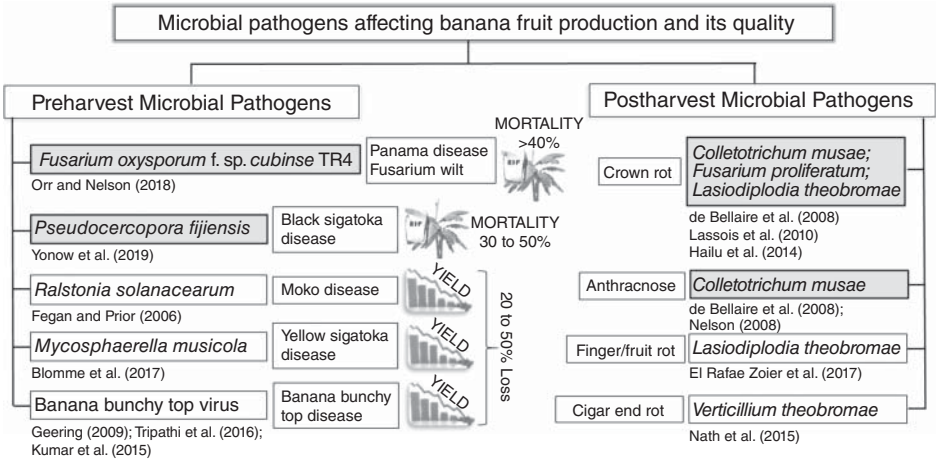

Figure 13.1 Diseases caused by specific pathogens and the economic losses incurred during cultivation and postharvest storage of the bananas (pathogens in gray-shaded rows inflict severe losses to yield or very high spoilage and those in unshaded rows inflict moderate to low yield or less spoilage).

Figure 13.2 Banana diseases caused by pathogenic fungi leading to spoilage and postharvest losses: (A) crown rot disease; and (B) anthracnose disease.

as *Fusarium* spp., *C. musae, L. theobromae, Musicillium theobromae, Nigrospora sphaerica,* and *Cladosporium* sp., as well as those which develop as co-infections during storage and transportation of the fruits, such as *Ceratocystis paradoxa, Acremonium* sp., *Penicillium* sp., *Aspergillus* sp., *Fusarium semitectum, F. oxysporum*, *F. verticillioides, F. sporotrichoides,* and *F. solaniintricate* (Lassois et al. 2010).

Among all fungal pathogens *L. theobromae* or *Botryodiplodia theobromae* is considered the most virulent to cause infections on healthy banana (Ekhuemelo and Yaaju 2017). However, frequent associations and co-infections with various fungal species such as *A. flavus*, *A. niger*, *Alternaria* sp., *Curvularia* sp., *Heminthosporium* sp., and *Thielaviopsis* sp. can also occur. These fungal pathogens may also exhibit pathological synergistic or augmenting effect for disease etiology on co-infection, such an effect is most evident on co-infection of *C. musae* with *F. moniliforme* (El Rafae Zoier et al. 2017).

Zakaria et al. (2012) isolated four different species of *Fusarium* from rotten bananas, i.e., *F. semitectum, F. solani, F. verticillioides,* and *F. oxysporum,* among which only *F. oxysporum* exhibited non-pathogenic characteristics. Another fungus, *Fusarium thapsinum,* was isolated from the bananas having macro- and micro-conidia but it lacked chlamydospore formation and can cause infection and yield loss in banana (Abd-Elsalam 2009). *F. moniliforme* (Sheldon) can cause banana heart rot disease (Shalaby et al. 2006). Ilyas et al. (2007) obtained *Aspergillus fumigatus*, *Alternaria tenuis*, *B. theobromae*, *C. musae*, and *V. theobromae* as the major spoilage fungal genera from rotten banana fruits. However, Abdullah et al. (2017) reported the growth of zygomycetous-*Mucor* spp. and *Rhizopus stolonifera* genera, trichocomaceous genera-*A. niger*, and *A. flavus*, Glomerellaceae genera-*C. musae*, and ascomycetous genera-*F. oxysporum*, and *Lasiodiplodia theobromea* as the predominant spoilage causing microbes in stored banana.

Microbial Safety of Banana and its Products

As discussed in the pre- and postharvest biotic factors affecting the quality of the bananas, *Fusarium* sp. causes several disorders in the infected banana plant. However, there are an increasing number of reports being published on the possibility of pathogenesis and disorders in humans on consumption of the infected fruit (Li et al. 2013b; Triest and Hendrickx 2016; López-Díaz et al. 2018). These reports provide information on probability of direct infections due to *Fusarium musae*, a variant of the *Fusarium verticilloides* to be responsible for frequent spread of fusariosis in humans (Triest et al. 2016). Similarly, the production of mycotoxins by *F. oxysporum* f. sp. *cubense*, fusaric acid (López-Díaz et al. 2018), and beauvericin (Li et al. 2013b) can exhibit virulence in mammals, such as immunocompromised mice models as very low concentrations of the fusaric acid can be indirectly responsible for health complications.

The other fungal genera which cause spoilage of the banana fruit can also exhibit potential for the secretion of secondary metabolites, "mycotoxins," which can pose elaborate health hazards to the consumer particularly leading to liver complications and even cancer. Sarkar et al. (2011) identified the occurrence of nine different types of mycotoxins with predominance of Aflatoxin (B_1, B_2, G_1, G_2 types), zearalenone, Ochratoxin A, citrin, patulin, and T-2 toxin in stored bananas. These results indicate improving the surveillance checks and monitoring of the banana stored and marketed during warm and humid months as mycotoxin production gets enhanced during high temperature storage conditions (Sarkar et al. 2011).

As the banana fruit and different products of banana and plantain can get infected with both spoilage pathogens as well as human pathogenic microflora due to faulty storage conditions or unhygienic practices followed during production, processing, packaging, and storage phases, the prevalence of human pathogenic microbes in bananas are of a significant concern. The human microbial contaminations can be considered as "opportunistic infections" of the bacteria belonging to the family Enterobacteriaceae. The most reported incidences have been for the presence of *E. coli*, *Enterobacter* sp., *Shigella sonnie,* and *K. pneumoniae* particularly on the fruit surface (Abdullah et al. 2017). The coliform counts of the whole bananas sampled from local market of a Nigerian town were of the

order 42.7 log CFU/in^2, which increased as a function of storage duration (Obetta et al. 2011). Similarly, the occurrence of human pathogenic microbes causing food poisoning in starchy plantain derived products also indicate the overall lower microbial quality and the hygienic conditions prevailing during the preparation of the product. Olagaoke et al. (2018) observed heavy loads of gram positive as well as negative bacteria namely, *K. pneumoniae*, *S. aureus*, *Bacillus subtilis,* and *Pseudomonas aeruginosa*, which indicated poor hygienic practices of the vendors/producers in Dodo-Ikire, a popular Nigerian fried recipe prepared from over-ripened plantain.

Microbiological Quality Maintenance

Physical Control Agents

Hot Water Treatment

Banana bunches and cut clusters of banana fruits can be immersed in hot water (50 °C for 5–10 minutes) to decrease the microbial load on the fruit surface, elicit formation of compounds of higher antimicrobial potential due to modification or transformation of the phenolic compounds in the peel and delays ripening of the stored fruits; probably by increasing the antioxidant compounds (free phenolics and flavonoids) and decreasing the reactive oxygen producing compounds such as H_2O_2 and malondialdehyde contents (Ummarat et al. 2011). Therefore, the quality parameters of the bananas remain intact or even improve over the storage time on treatment with hot water (Kaka et al. 2019).

Irradiation Treatment

Gamma irradiation of the fresh produce can improve the shelf life to about two weeks, including bananas stored under ambient conditions by delaying the onset of postharvest decay (Abdullah et al. 2017). Further, radiation doses of 1.0 kGy also help in delaying the ripening process of fruits harvested in preclimacteric stage besides inhibition of bacterial and fungal growth. Irradiation dose of 1.0 kGy was found to be most effective in preserving the quality of stored bananas under ambient conditions. Likewise, irradiation treatment with germicidal UVC radiations can effectively decrease the incidences of postharvest crown rot. However, irradiation dosage of 0.01 kJ/m^2 did not caused significant browning (artifact due to UVC irradiation) of the fruits while maintain their organoleptic, and other quality parameters besides exhibiting >45% reduction in crown rot incidence in *Musa* AAA Berangan bananas as compared with non-irradiation treatment (Mohamed et al. 2017). The low dose exposure of X-rays ($3–5 \times 10^{-14}$ Gy) can also enhance the shelf life of the ambon banana (*Musa acuminanta*) fruits by delaying the process of ripening (Dwijananti et al. 2016).

Chemical Control Agents

Use of Fungicides

The microbiological quality of bananas and their products can be maintained through use of antifungal agents to particularly address the postharvest losses caused by fungal pathogens during storage and transportation of the whole banana. The incidences of storage fungal

diseases can be effectively decreased by dipping fruits in fungicide formulations, which may include single or combinations (Nath et al. 2014) and can be non-systemic (e.g., mancozeb, chlorothalonil, copper oxychloride) or systemic (e.g., carbendazim/bavistin, propiconazole, hexaconazole) in nature (Nath et al. 2015). Diedhiou et al. (2014) immersed bananas in four different fungicides for five minutes and observed that only Imazalil treatment improved the shelf life to 24 days on storage at 14 °C temperature.

Ozonation

Ozone (O_3) is a highly reactive molecule comprised of three oxygen atoms, which exhibits a short half-life of not more than 30 minutes. It is considered to be a natural oxidizer and the safest antimicrobial sanitizer having generally recognized as safe (GRAS) status for application on whole or peeled and fresh-cut produce as it exhibits formation of zero residues due to prompt degradation to molecular oxygen (Suslow 1998; Carletti et al. 2013). Ozonation of whole bananas can be performed by either immersing the whole fruit in ozonated water or fumigation with gaseous ozone in a closed chamber (de Alencar et al. 2013). However, immersion in ozonized water for a period of 10 minutes is the most effective technique to decrease the microbial cell load besides it induces natural molecules of antimicrobial and antioxidant significance (Suslow 1998). Further, ozone treatment can also be performed for the minimally processed products, particularly the fresh-cut banana. Alothman et al. (2010) observed significant increase in the flavonoids and total phenolic content in fresh-cut banana on treatment with 0.72 mmol of ozone for 30 minutes.

Plant Botanicals and Biological Control Agents

The plant derived botanicals are relatively cheap and green alternatives to pesticide control agents. Ekhuemelo and Yaaju (2017) evaluated the performance of extracts of garlic and ginger at different concentrations (10–30% w/v) in an *in vitro* study performed on a pure culture of *B. theobromae*. They reported complete inhibition of the mycelial growth of the test fungi on application of 30% (w/v) garlic extract. The essential oils (EOs) are considered to have known antifungal properties (Kaur et al. 2018). Application of these EOs can effectively eradicate postharvest fungal diseases of banana. Thus, these present an environmentally safe and effective option for tacking postharvest fungal diseases in a cost-effective manner. Abd-Alla et al. (2014) evaluated the commercial EOs of cinnamon, thyme, and sweet and bitter almond, and reported that the incidence of crown rot disease in stored bananas varied from 78.7 to 100% by application of 4.0% (v/v) concentration of EOs with absolute reduction by cinnamon and thyme EOs.

The biocontrol agents can also be very useful in reducing the incidences of fungal fruit rots of banana during storage. Adebesin et al. (2009) reported inhibition of *F. oxysporum* and *C. musae* mycelial growth on application of culture/conidial filtrates (at 50% v/v) of *Trichoderma asperellum* NG-T161. However, the action spectrum and efficacy of reduction in disease incidences can be improved by combined application of multiple species and strains of the biocontrol agent. Sangeetha et al. (2009) identified different *Trichoderma* sp. fungal inoculants exhibiting antagonism against *L. theobromae* and *C. musae* and observed that the consortia application led to disease inhibition equivalent to carbendazim fungicide control at both ambient and cold temperature storage conditions for 25 days.

Packaging Modules for Banana

Modified Atmosphere Packaging

Controlled atmosphere packaging is a prerequisite technique for improving the shelf life of fresh-cut banana as it can effectively deal with the increased reducing sugar content and higher predisposition to microbial attack and contamination of the packaged fruits (Rocha et al. 2011). The atmosphere in the packaging module can be modified by varying concentrations of the gases, CO_2 and O_2 involved in respiration by the cells. Decreasing the O_2 concentration from 1 to 10% while increasing the CO_2 concentration (from 2 to 14%) can improve the shelf life of banana by ceasing the respiration and production of ethylene (Lassois et al. 2010).

Esguerra et al. (2016) reported the application of vacuum packaging as the active MAP for organically grown Japanese Balangon bananas as an effective technology to keep the banana green for a period of 25 days stored at 13.0–13.5 °C. However, creation of a modified atmosphere passively by respiration in sealed low density polyethylene packages delayed development of yellow color in banana peel for up to 20 days of storage at 15 °C (Julianti and Yusraini 2012). Therefore, banana should not be stored at less than 13 °C otherwise the characteristic symptoms for the cold injury on the peel as well as the fruit will appear (Figure 13.3). Further modification of MAP may involve the application of ethylene/CO_2/moisture scrubbers and can extend the shelf life of stored banana more than one month (Chauhan et al. 2006).

Other Innovative Techniques

Polymer Films and Coatings

The shelf life of the stored bananas can be improved by packaging the produce in polymeric films or application of coatings on the fruit peel/surface. The peel of the banana fruit can be coated with both degradable as well as non-degradable coatings. Edible coatings on banana

Figure 13.3 Banana fruit showing typical cold injury symptoms characterized as the appearance of discoloration on the peel (A) and mesocarp texture loss and discoloration (B) on storing the fruit at 7 °C for a week.

fruit have also been evaluated for extension in shelf life of the stored fruit. These coatings reduce water loss, alter the gas exchange through the fruit surface, delay ripening, decrease decay, and thus improve fruit appearance and extend the shelf life (Kaur et al. 2017). The common polymers utilized are chitosan (Suseno et al. 2014; Hossain and Iqbal 2016; Zahoorullah et al. 2017; Dwivany et al. 2018), carboxymethyl cellulose (Senna et al. 2014), alginate, carrageenan (Bico et al. 2011; Rocha et al. 2011), gum Arabic (Maqbool et al. 2017), jojoba wax (Gol and Rao 2011), sucrose ester or Semperfresh™ (Yurdugül 2016), silk fibroin (Marelli et al. 2016), polyvinyl alcohol (Senna et al. 2014), starch (Thakur et al. 2019), and similar natural polymers. Further, these polymers can also be blended to improve the mechanical and gas exchange properties of the coatings on the fruit surface. Senna et al. (2014) prepared polyvinyl alcohol/carboxymethyl cellulose-tannin composites plasticized through gamma irradiation as degradable edible coatings for extending the shelf life of bananas from 9 to 19 days.

Nanotechnological Interventions for Improved Packaging Solutions

Different nanomaterials can be incorporated as reinforcing material in natural or synthetic polymers to alter the mechanical (tensile strength, Young modulus, elongation at break or stretchability, Poisson's ratio, thickness), gas barrier, and optical properties of the films besides improving their thermal stability. The supplementation of nanomaterials also imparts novel functional properties to the prepared films. Ogunsile and Oladeji (2016) reported the application of banana fibers as reinforcement material to alter the properties of synthetic thermoplastic composite, low density polyethylene films. However, the supplementation of nanomaterials is of great relevance particularly for improvement in various properties of the biopolymer derived edible and biodegradable films (Flores-López et al. 2016).

Orsuwan and Sothornvit (2017) reported fabrication of a banana flour-based film having improved mechanical and water vapor barrier properties due to supplementation of sodium saturated montmorillonite and banana starch nanoparticle (1:1, 5% w/w) making it suitable for both food packaging and pharma applications. Nanoformulations of the natural fibers can also be utilized to alter the mechanical and other properties of the biodegradable packaging films. Marelli et al. (2016) utilized silk fibroin micellar/nanoparticulate aqueous suspension to dip-coat banana fruits to enhance their shelf life. Another biocompatible biopolymer, cellulose, can also be a utilized as a filler to develop bionanocomposite films (dos Santos et al. 2016). The nanocellulose can be derived from the banana pseudostem fibers, which are a waste (Khawas and Deka 2016). The cellulose fibers can be defibrillated through cryo-crushing, or high intensity ultrasonication treatment (dos Santos et al. 2016). Similarly, the banana fiber derived cellulose-polymer composite can be reinforced with inorganic nanofiller, such as silica nanoparticles, to improve its film properties (Rahul et al. 2017).

Apart from whole fruit packaging systems, nano-enabled alternatives for the processed banana products are also available. Manikantan et al. (2012) described the development of 15 different nanocomposite packaging films by use of nano-clay and compatibilizer combinations. They reported 2% and 4% nanoclay and 5% and 10% compatibilizer combinations, respectively, to maintain the quality of the packaged banana chips. The nano-interventions

are finding their applicability in the development of scavengers and high-density absorption pads for effective removal of ethylene (Sundramoorthy et al. 2018), which is of utmost relevance for climacteric fruit, as banana ripens even after detachment from the parent plant due to action of pectin lyases and β-galactosidase enzymes (Wang et al. 2018).

Methods for Evaluation of Microbial and Overall Quality

Conventional Techniques

The postharvest shelf life of the banana fruit is largely affected by attack of fungal pathogens due to high sugar content and low pH conditions of the ripened fruit (Kuyu and Tola 2018). Therefore, standard methods, e.g., artificial inoculation, have to be devised to evaluate the susceptibility to different variants of anthracnose disease, such as wound, quiescent anthracnose, and crown rot in Cavendish banana (de Bellaire and Mourichon 1997). Similarly, the bacterial spoilage pathogens and other opportunistic contaminants can be detected by enumeration of the CFU on selective/differential media (broth or agar based) followed by biochemical and serological characterization of the purified isolates for identification of the genera and species. However, the fungal spoilage pathogens can be identified presumptively on the basis of their morphology. Further, both filamentous molds and unicellular yeast require molecular characterization through 26s rRNA D1/D2 domain and internal transcribed spacer (ITS) region amplification followed by sequencing. The ITS redundancy may result in ambiguity for identification of the fungal pathogen. Use of other gene targets, such as β-tubulin (*Penicillium* and *Aspergillus*), actin (*Cladosporium*) and similar genes can help in complete identification at the species level (Leyva Salas et al. 2017). Further, the aberrancy in the general fruit characteristics primarily including evaluation of the total soluble solids, starch, mineral and vitamin contents (chemometrics), and relative loss over different storage time durations could be indirect techniques indicating the fruit status and probably the attack by spoilage pathogens and postharvest shelf life status of the fruits (Magwaza and Tesfay 2015).

Non-Destructive Methods

These techniques involve rapid measurement of both external as well as internal fruit quality attributes non-invasively such that robust and accurate predictions regarding their shelf life during storage and transportation can be performed to decrease the postharvest losses (Zude 2003; Liew and Lau 2012; Ali et al. 2018; Pu et al. 2018; Toma et al. 2018). The non-destructive techniques are diverse and can involve imaging-based methods, spectroscopy-enabled protocols, chimeric imaging-spectroscopy techniques, and simulation modeling methods, which utilize statistical algorithms besides nanotechnology-inspired sensor platforms for evaluation of fruit quality of banana. The non-destructive methods (NDMs) can help both in instantaneous analysis of the fruit quality parameters under pre- and postharvest storage and transportation conditions. For instance, banana being a climacteric fruit exhibits peak respiratory activities as it reaches

maturity. Later, it quickly deteriorates due to onset of senescence resulting in the loss of shelf life (Li et al. 2016). Therefore, it is pertinent to develop methods involving detection of banana quality in a non-destructive manner which is more apt for ensuring automatic grading.

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