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Foreword

Fruits in the horticultural sense are succulent or fleshy seed-bearing structures (although some have become seedless) that are usually consumed fresh but can be processed in various ways. They may be borne on perennial trees, such as apple, peach, and mango or herbaceous plants or vines, such as tomato, banana, or melon. Horticultural groupings include temperate tree fruits, such as apple or peach, where the plant requires dormancy brought about by cold temperatures; subtropical tree fruits, such as orange or avocado, where the dormancy requirement is very low but cool temperatures may affect certain characteristics, such as skin color or flavor; and tropical tree fruits, such as durian or mangosteen, where dormancy, if present, is a result of water stress rather than temperature, and where plants are usually extremely susceptible to freezing temperatures and often injured by low temperatures above freezing.

The fruit organ serves mainly as a protective mantle for its seed but has been adapted for a number of functions, including germination inhibition and the distribution function of seed dispersal through various morphological modifications, such as hooks, wings or floats, and by interactions with other organisms where fruit ingestion serves to distribute the seed. Thus, many fruits have developed colors, aromas and flavors that are attractive to the birds and mammals that have become key vectors in seed dispersal. In some cases when fruit is consumed, the seed passing through the digestive track stimulates germination. The characteristics of skin color, aroma, sweetness, and soft texture that usually develop upon seed maturation have made fruits highly appreciated by humans and, as a result, have become an important part of human culture, religious practices, mythology and art. In fact, fruits are among the most beloved of plant products, acclaimed and desired for their delectable flavor, pleasing aroma and beautiful appearance. Thus, production of fruits has become an important world industry. In some of the most desirable multi-functional fruit species centuries of human selection combined with vegetative propagation has resulted in a plethora

of distinct cultivars. Fruits are used in myriad forms, mostly fresh but also dried, canned, frozen, pickled and fermented. Most fruits are consumed out of hand, as snacks or desserts, but are often used in salads, cooked as a side dish, made into jams and preserves, baked into pies or torts, or consumed as pickles, wine or liqueurs. A great majority of fruits are considered an important source of calories and some are now classed as functional foods or nutraceuticals on the basis of the presence of vitamins, minerals and/or antioxidants. A few are rich in fats and oils, such as avocado and oil palm; the latter has become a vast industry in Southeast Asia. Most fruits are low in protein, which is usually contained in the seed embryo.

Fruits are consumed by humans because they are delicious. They develop flavor, a combination of sugars, acids, and aromatic compounds, as a result of the ripening process. This desired state is usually associated with maturity and is very transitory. Thus, the very physiological stage that makes fruit desirable is an impediment to their storage and preservation. The transitory nature of many succulent or fleshy fruits has been an impediment to their postharvest life. In the case of temperate fruits, the ancient technology of extending fruit life has been associated with the low temperatures found in cellars or caves. In fact, ancient caves constructed from excavated tuff are still used to store citrus fruit, in Cappadocia, Turkey. Modern cold storage has been transformed with air conditioning and other techniques, such as controlled and modified atmospheres, that reduce oxygen levels to lower respiration and associated senescence processes. Our understanding of the climacteric phenomenon in some fruits along with the role of ethylene in fruit ripening has improved storage management. Recent advances have been made in the use of anti-ethylene compounds and other substances that are applied to reduce storage disorders. The technology of postharvest storage has involved an interaction with genotype, crop load management, time of optimum harvest, temperature control, and the use of specific growth regulators. Postharvest storage has reached its apex in the storage of apples, which can be kept in an edible condition for over a year, depending on the cultivar.

Tropical fruits are much more difficult to control because of susceptibility to cold injury. Furthermore, despite their vulnerability to postharvest breakdown, they must be transported long distances for economic viability. With the exception of banana and citrus, many types of tropical fruits have not received the research attention that they deserve. Many underexploited fruits are being discovered that would make useful crops if their postharvest life could be extended. This present four volume work, organized and edited by Professor Elhadi Yahia, is an attempt to remedy the information gap concerning postharvest physiology and storage of an array of promising tropical fruits, which heretofore has been scattered in the scientific literature. There are a total of 78 chapters contributed by an international team of authors. The index makes it easy to find information on specific fruits. Most chapters follow a similar outline. The plethora of citations will make this book a valuable resource for scientists, students, and industry workers.

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Açai (*Euterpe oleracea* Martius)

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Abstract: *Euterpe oleracea* Martius (açai palm) is a palm tree that is widespread in the Amazonian region. The juice of *E. oleracea* fruits, known as açai, is viscous (approximately 8 to 15% dry matter) and is typically prepared by macerating the fruits and adding water while the pulp is extracted. Açai juice is the most commonly consumed beverage in the Amazon region, where individual consumption can reach one liter per day. The juice presents several potential health benefits for consumers, mainly due to its high concentration of polyphenols. High concentrations of anthocyanins (mainly cyanidin-3-glucoside and cyanidin-3-rutinoside) are responsible for the black-purple color of açai juice.

Key words: *Euterpe oleracea*, açai, polyphenols, postharvest.

1.1 Introduction

1.1.1 Origin and botany of the açai palm

The American literature mentions 30 species of the *Euterpe* genus in Central and South America (Moore, 1973; Uhl and Dransfield, 1991). *Euterpe oleracea* Martius is a palm tree that is found throughout the Amazon basin and is particularly abundant in the Eastern Amazon. The species occurs in floodplains, on land and in swampland soils. The açai palm often grows alongside other palm trees, typically alongside another palm from the Amazon, the buriti (*Mauritia flexuosa*). Floodplain soils are, from a biological point of view, favorable for the development of hygrophilic vegetation species like the açai palm, not only because of the humid soil but also because of the greater light intensity due to the limited vegetation cover (Pires, 1973; Cavalcante and Johnson, 1977). The açai palm forms a multi-stem clump structure as it grows. *E. oleracea* grows in the shape of a big tree shoot (Plate Ia: see colour section between pages 244 and 245) that is composed of stems. Fruiting occurs throughout the year, with a period of higher production occurring between July and December, when it is less humid. During

this period, the ripeness of the fruit is also more homogeneous. Fruit production begins when the palms are three years old, and the trees become fully productive three years later (Rogez, 2000).

The stem of the açai palm is smooth, slim, generally upright and gray in color. In the adult stage it is of medium height (10 to 15 meters) and has a diameter of 12 to 18 cm. The apex is composed of a crown of nine to 15 leaves. The mature leaf has a petiole measuring 20 to 40 cm and a total length of 2 to 3.5 meters. The leaves are pinnately divided, with 50 to 80 regularly spaced green and glabrous segments or leaflets, each measuring 40 to 80 cm in length and 4 to 5 cm in width. Six to 11 leaves are shed each year; the greater the number of leaves shed, the greater the fruit production (Castro, 1992). The thick and wide base of the petiole that surrounds the tree at the crown is called the sheath. The section of the stem equivalent to the sheath is cut and processed. It is traded as palm heart, a product that is widely recognized in Brazil and around the world. The açai palm's inflorescence consists of branches with a variety of male and female flowers that grow in bunches after the fruit has developed (Plate Ib: see colour section between pages 244 and 245).

1.1.2 Fruit morphology and structure

The açai fruit has a globular, round shape, with a diameter of 1 to 2 cm and a weight of 0.8 to 2.3 g. It is composed of core and pulp. The fruit pulp represents 5 to 15% of the fruit's volume, varying according to the origin and maturity of the fruit (Plate Ic: see colour section; Rogez, 2000). Each fruit has a core that is surrounded by a fibrous tuft of feathers, covered by a thin greasy cuticle. The core has a small and solid endosperm, which is attached to the tegument. The pericarp is partially stringy, rich in silica and poor in lipids, proteins, and starch. At maturity, the endosperm is rich in cellulose, hemicelluloses, and inulin crystals; however, before the fruit reaches maturity, it is rich in lipids. The embryo is small, with a cotyledon that is rich in starch grains, and poor in inulin crystals (Rogez, 2000).

As already mentioned, fruit are more abundant from July to December, in the season that is less rainy. This is also when the *tuira* fruit (fruit at the ideal stage of maturation – see section 1.2.1), are produced. The *tuira* fruit, identifiable by their waxy white macula, provide a juice of greater quality (Cavalcante, 1976). All fruit varieties (i.e. *green, tinga, black* varieties) are green before maturing. Fruits of the *green* and *tinga* varieties remain green after maturation, but fruits of the *black* variety, which is the most abundant (more than 95% of the market) become dark reddish-blue. The variety of fruits differs according to the phenotypic characteristics of the plant. It is the presence or absence of anthocyanins that is responsible for the change in color (Rogez, 2000).

1.1.3 Worldwide importance and economic value

There is currently increased interest in açai fruit production. Açai was initially only produced and sold locally, but it is now sold in new markets internationally, and has become a significant source of jobs and income. In 2006, 500 000 tons of

açai fruit was produced, and consumption of the juice reached 240 000 tons in Pará state (Northern Brazil), 58 000 tons in the rest of Brazil, and 12 000 tons abroad (Santana and Costa, in press).

The US has the largest functional food and beverage market in the world and it is expected to have an annual growth rate of 6.1% between 2007 and 2012. Concern about health is driving a number of sub-trends in the US market and fuelling interest in certain ingredients, such as low-calorie sweeteners, fiber, probiotics, omega fatty acids, and antioxidants. Antioxidants are turning up in all sorts of food products, from beverages to baby food. These products are using 'superfruits' as ingredients, which are fruits that are high in antioxidants and have high Oxygen Radical Absorbing Capacity (ORAC) values. Common superfruits include blueberries, pomegranate, açai and cranberry. Globally, between 2003 and 2008 pomegranate and açai appeared in the greatest number of new products (Evani, 2009). These trends demonstrate that consumers are increasingly looking out for antioxidants, which they associate with health promotion, mainly in terms of the prevention of cancer and cardiovascular diseases, neutralization of free radicals and memory improvement. Although the global 'health foods' industry grows by only 4.5 to 5% each year, sales of products that are recognized as 'functional' through 'claims' are expected to grow by 12 to 14% annually (ABIA, 2008).

1.1.4 Culinary uses

Açai or açai drink is made from the fruit. This drink is traditionally prepared in two steps. First, the fruit is softened in warm water, and then it is mechanically depulped, as water is added. In the Amazon region, açai is frequently consumed with mandioca flour, fish, shrimp or meat, the basic foods of the local people who live along the rivers in Amazonia (Rogez, 2000). Ice cream, liquors, candies, nectars, and jam are also made from açai fruit. More recently, an anthocyanin extract or dye has been separated from clarified açai.

1.1.5 Nutritional value

In terms of nutritional macrocomposition, açai has a significant proportion of lipids, ranging from 40.7 to 60.4% of its dry matter (DM), and contains 6.7 to 10.5% protein (Table 1.1). Lipids represent approximately 90% of the caloric fraction of açai, providing 15.5 to 27.5% of the RDI in a 200-ml serving of açai drink, which contains about 12% DM, depending on the quantity of water added to the juice. The total content of digestible sugars is particularly poor in comparison to many tropical fruits, contributing less than 1% of the RDI. Therefore, natural açai cannot be considered as a drink that provides quick energy to consumers (Rogez, 2000).

Interestingly, the concentration of total dietary fiber is remarkably high, ranging from 20.9 to 21.8% of DM, which makes fiber the second most prevalent constituent of açai. The ratio of soluble to insoluble fibers (SDF:IDF) is 1:3, whereas the recommended ratio is 1:2. Açai contributes 20% of the recommended

Table 1.1 Physical-chemical, amino acid, and mineral composition of açai juice

Constituents	100 g DM	200 g juice (1 serving)	Daily recommendations	Contribution (%) per serving
pH	–	5.21	–	–
Titrable acidity (mg CAE)	–	21.99	–	–
Dry matter (g)	–	12.00	–	–
Lipids (g)	50.53	12.13	44–78[a]	15.5–27.5
Protein (g)	8.62	2.07	56[a]	3.64
Ash (g)	3.09	0.74	–	–
Total dietary fiber (g)	21.36	5.13	25–30[a]	17.2–20.0
Soluble dietary fiber (SDF)	5.30	1.27	–	–
Insoluble dietary fiber (IDF)	15.85	3.80	–	–
Ratio SDF/IDF	–	1:3	1:2[b]	–
Sugars (g)	2.96	0.71	130[a]	0.54
Glucose	1.55	0.37	–	–
Fructose	1.36	0.33	–	–
Sucrose	0.05	0.01	–	–
α-Tocopherol (mg)	45.00	10.80	7.5–10[c]	>100
	–	–	–	–
Aminoacids (mg)				
Valine	562.69	135.02	1,820[d]	7.42
Leucine	720.38	172.89	2,730[d]	6.33
Isoleucine	445.95	107.03	1,400[d]	7.64
Phenylalanine	562.59	135.02	1,750[d]	7.72
Threonine	507.70	121.85	1,050[d]	11.60
Methionine	157.80	37.87	700[d]	5.41
Lysine	555.72	133.37	2,100[d]	6.35
Histidine (newborns)	205.82	49.40	700[d]	7.06
Glicine	411.65	98.80	–	–
Alanine	473.40	113.61	–	–

Proline	480.26	115.26	–	–
Tyrosine	343.04	82.33	–	–
Serine	480.26	115.26	–	–
Cysteine	274.43	65.86	–	–
Asparagine + aspartic acid	754.69	181.13	–	–
Glutamine + glutamic acid	699.80	167.95	–	–
Arginine	445.95	107.03	–	–
			–	–
Minerals	100 g DM	200 g juice (1 serving)	Daily recommendations	Contribution (%) per serving
Ca (g)	0.309	0.074	1.000[e]	7.42
P (g)	0.147	0.035	0.700[e]	5.04
Mg (g)	0.178	0.043	0.280[e]	15.26
K (g)	0.990	0.238	4.700[f]	5.06
Na (g)	0.076	0.018	1.500[f]	1.22
Zn (mg)	1.730	0.415	8.0–11.0[g]	4.0–5.2
B (mg)	1.584	0.380	20.00[g]	1.90
Fe (mg)	2.059	0.494	14–29[g]	1.70–3.52
Se (mg)*	1.321	0.317	0.055[h]	>100
Mn (mg)	32.300	7.752	1.8–2.3[g]	>100
Cu (mg)	1.376	0.330	0.900[g]	36.69
Ni (mg)	0.203	0.049	0.350[g]	13.92
Cr (mg)	0.531	0.127	0.035[g]	>100
Cd (mg)**	0.046	0.011	0.070[i]	15.77
Pb (mg)**	0.408	0.098	0.250[i]	39.18
Sr (mg)	4.466	1.072	–	–

Sources: Rogez (2000). [a]RDA (2002); [b]Figuerola et al. (2005); [c]FAO/WHO (2001); [d]FAO/WHO/UNU (2007); [e]RDA (1997); [f]RDA (2004); [g]RDA (2000a); [h]RDA (2000b); [i]Salgado (2003).

Notes
* Total mineral selenium (not only aminoacid-Se).
** TTDI: Total tolerable daily intake.
CAE: Citric acid equivalent.

daily intake in only one serving. Therefore, it can be considered as a good source of dietary fiber.

The total amount of α-tocopherol found in açai is high, ranging from 37 to 52 mg 100 g^{-1} DM, which makes the juice of this fruit an excellent source of this form of vitamin E. Each serving of açai provides more than 100% of the intake recommended by FAO/WHO (2001) for adult men and women. Açai also has a good fatty acid profile (49.72% oleic acid, 25.31% palmitic acid, and 13.51% linoleic acid as a proportion of total fatty acids: Table 1.2), but its content of omega-3 fatty acids is poor (approximately 1%), in contrast to the information presented on many websites.

1.1.6 Phenolic compounds of açai fruit

The violet color of the açai drink is due to the high concentration of anthocyanins: antioxidant compounds that are also natural pigments. Anthocyanins belong to the flavonoid family, and include cyanidin-3-glucoside (C3G), and cyanidin-3-rutinoside (C3R). These two pigments are the major phenolic compounds in açai. Anthocyanins are predominantly present close to the açai fruit's epidermis. Pompeu *et al.* (2009a) found levels of anthocyanins of approximately 2890 mg Kg^{-1} fruit when they studied different solvents to optimize the extraction of phenolic compounds from açai fruit.

Our research team found an average total content of anthocyanins of 1,441 mg 100 g^{-1} (dry matter) DM in açai pulp (1841 mg Kg^{-1} fruits), accounting for 37% of the total phenolic content, with 79.2% C-3-R, and 20.8% C-3-G. We found a

Table 1.2 Fatty acid profile of açai oil

Fatty acids (g 100 g^{-1} total fatty acids analyzed)		Daily recommendations	Contribution (%) per serving
Palmitic acid (C16:0)	25.3	–	–
Palmitoleic acid (C16:1)	1.5	–	–
Estearic acid (C18:0)	4.46	–	–
Oleic acid (C18:1)	49.7	–	–
Linoleic acid (C18:2)	13.5	12.0–17.0[a]	6.28–8.90
α-Linolenic acid (C18:3)	1.16	1.1–1.6[a]	5.72–8.30
Vacenic acid (C18:1 cis 11)	4.37	–	–
SFA/UFA	0.42	<1.0[j]	–
MUFA/PUFA	3.790	–	–
ω6:ω3	11.65:1	4:1[k]	–

Sources: Rogez (2000). [a]RDA (2002); [j]Nascimento (2008); [k]Martin (2006).

Notes
SFA: Saturated fatty acids.
UFA: Unsaturated fatty acids.
MUFA: Monounsaturated fatty acids.
PUFA: Polyunsaturated fatty acids.

high content of phenols in açai (3.8% DM as Gallic Acid Equivalent), which is higher than the 1.39% DM found by Schauss *et al.* (2006a).

Gallori *et al.* (2004) confirmed the presence of C-3-G and C-3-R as major anthocyanin compounds in açai. Another four major compounds were also identified: homoorientin, orientin, taxifolin deoxyhexose, and isovitexin. Pozo-Insfran *et al.* (2004) found several other polyphenols in açai pulp, including ferulic acid, epicatechin, *p*-hydroxy benzoic acid, gallic acid, protocatechin acid, (+)-catechin, ellagic acid, vanillic acid, and *p*-coumaric acid, at concentrations that ranged from 17 to 212 mg L^{-1}. Kang *et al.* (2010) were the first to report that two other compounds, vitexin, and quercetin, are found in açai pulp.

Açai has substantially higher values of antioxidant capacity compared to most dark-colored berries, or to any fruit or vegetable, as measured either by the Oxygen Radical Absorbance Capacity (ORAC; Schauss *et al.*, 2006b; Hogan *et al.*, 2010) or the Total Oxidant Scavenging Capacity (TOSC; Lichtenthaler *et al.*, 2005) assays. Even with the addition of water to depulp the fruits, the value obtained by our research team (9685 μmol Trolox Equivalent 100 g^{-1}) is higher than that found in the pure pulp of other tropical fruits, such as oranges (2887 μmol TE 100 g^{-1}), lemons (1848 μmol TE 100 g^{-1}), watermelon (1385 μmol TE 100 g^{-1}), avocado (1343 μmol TE 100 g^{-1}), pineapple (1055 μmol TE 100 g^{-1}), and bananas (565 μmol TE 100 g^{-1}; Wolfe *et al.*, 2008).

The functional properties of açai in human beings have recently been suggested by *in vitro* (Coisson *et al.*, 2005; Pacheco-Palencia *et al.*, 2008), and *in vivo* (Pacheco-Palencia *et al.*, 2008; Sampaio *et al.*, 2006) assays, stimulating interest in the production of bioactive extracts.

1.1.7 Health benefits

Açai has become a product of international interest, not only owing to its exotic flavor, but also because of its potential benefits for human health. Many studies have demonstrated that diets rich in polyphenols, especially in flavonoids, are directly associated with reductions in cardiovascular disease (Lagiou *et al.*, 2004, Lapointe *et al.*, 2006). Thus, açai, which is rich in polyphenols, may provide benefits to human health.

Bioavailability of açai anthocyanins

Bastos *et al.* (2007) evaluated the human bioavailability of açai anthocyanins in an experiment with six healthy male volunteers. In the first week, the volunteers received a lunch without açai (blank), and one week later, they received the same diet with 500 mL of açai containing 354.5 mg anthocyanins (41.9 ± 1.4 mg C3G, and 312.6 ± 2.0 mg C3R). The urinary excretion of C3G and C3R was maximal in the 2 to 4 hours after ingestion of the açai (39.47%, and 39.28% of total excretion for C3G, and C3R, respectively). The average total mass of anthocyanins excreted in their natural chemical form was 6688 ng for C3G, and 47 299 ng for C3R, which corresponds to 0.016% and 0.015% respectively, of the amount ingested.

An increase in the antioxidant plasma capacity was observed using the Total Reactive Antioxidant Potential (TRAP), and Trolox Equivalent Antioxidant Capacity (TEAC) methods, indicating that the polyphenols absorbed had antioxidant activity *in vivo*.

Another study was developed by Mertens-Talcott *et al.* (2008). The pharmacokinetics and antioxidant effects of anthocyanins in 12 healthy human volunteers were studied after the consumption of clarified açai juice and pulp, containing 165.9 mg of total anthocyanins/L and 303.8 mg of total anthocyanins/kg, respectively. They used a dose of 7 mL/kg of body weight after a washout phase and overnight fast, and plasma was repeatedly sampled over 12 h and urine over 24 h after consumption. Individual increases in plasma ORAC antioxidant capacity of up to 2.3- and 3-fold for açai juice and pulp respectively, were observed. The antioxidant capacity in urine, generation of reactive oxygen species, and uric acid concentrations in plasma were not significantly altered by the treatments. Results demonstrate the absorption and antioxidant effects of anthocyanins in açai in plasma in an acute human consumption trial.

In vivo study of the functional properties of açai

Sampaio *et al.* (2006) evaluated the benefits of açai in the human body. Thirty men were given a diet that included daily ingestion of açai for 28 days. The study showed very good outcomes, with an improvement in the plasma antioxidant status of all of the subjects: the thiobarbituric acid-reactive substances (TBARS) value decreased, there was an increase in the lag phase observed using the conjugated diene method, and a stable or slightly increased plasma antioxidant capacity was observed using the Oxygen Radical Absorbance Capacity (ORAC), and TRAP methods. However, all these changes were not statistically significant ($p > 0.05$). Low-density lipoprotein (LDL) TBARS was expressed in mmol MDA g^{-1} LDL. This method evaluates the formation of malondialdehyde (MDA), which is an important biomarker for the evaluation of oxidative stress. On day 28, the LDL-TBARS had decreased significantly, especially in subjects observed to have high initial values. The average initial and final values for thirteen volunteers were 4.12 ± 1.99, and 1.81 ± 0.86 mmol MDA g^{-1} LDL, respectively. These results demonstrate that daily intake of açai juice, which is rich in phenolic compounds, has a positive impact on the reduction of LDL oxidability and has a tendency to increase plasma antioxidant capacity, suggesting a protective effect against cardiovascular disease.

Jensen *et al.* (2008) investigated the antioxidant and anti-inflammatory properties of a juice blend (JB), containing a mixture of fruits with known antioxidant activity, including açai as the predominant ingredient. A treatment with 12 healthy subjects examined the JB's antioxidant activity in vivo. Blood samples at baseline, 1 h, and 2 h following consumption of the JB or placebo were tested for antioxidant capacity using several antioxidant assays and the TBARS assay. A *within* subject comparison showed an increase in serum antioxidants at 1 h ($p < 0.03$) and 2 h ($p < 0.015$), as well as inhibition of lipid peroxidation at 2 h ($p < 0.01$) postconsumption.

1.2 Fruit ripening, seasonality and accumulation of anthocyanins

1.2.1 Fruit ripening

Like other fruits rich in anthocyanins (e.g. raspberries, strawberries, mulberries, grapes, and cherries), the açai fruit is not climacteric. Therefore, if the fruit bunches are picked before they are ripe, the pigmentation will not change subsequently and the fruits will shrivel up and detach from the spadices.

The color of the açai fruit changes during the ripening process. For the *black* variety, which represents more than 95% of commercially produced fruit, farmers exclusively use the external color to determine the level of maturity. Based on field data, we can distinguish five stages of ripening for the *black* variety, and for each bunch:

- *Green* fruits are at least half green in color.
- *Slightly mature* or *Vitrin* fruits are those in which the majority of the fruit is *black*, and a smaller portion is *green*. At this stage, the fruit can be sold commercially, but pulp production is low because the fruit is not yet ripe.
- *Black* fruits are *black* in color with a shiny surface. The fruit and its juice are of good quality, however, this is not considered the ideal phase for harvesting.
- *Tuira* fruits are black, but are covered by a thin layer of wax, which gives them a white appearance. The quality of the pulp and juice is considered to be very good.
- *Over-ripe* fruits are covered by the same layer of wax as *Tuira* fruits but are a little bit drier, and flatter. Typically, bunches picked at this stage have been picked too late.

1.2.2 Seasonality

Açai palms collectively produce fruit between March and June (the low season or rainy season) and between August and December (the high season), with individual, açai palms bearing fruit for four to six months of the year. Seventy percent of the annual production occurs during the high season. During the low season, the fruits are traded at different stages of maturity, whereas they are more uniformly ripe during the high season. This variable affects both the growth of micro-organisms in these fruits, and the concentration of anthocyanins. Despite the lower quality, the price of açai fruits is between two and eight times higher during the low season, as fruit supply is four times lower during this season than during the high season.

1.2.3 Accumulation of anthocyanins

Because the anthocyanin content of açai is of great interest, it is important to verify certain parameters at harvest to ensure that the fruit is picked when the anthocyanin level is adequate. The stage of maturity at the time of harvest is the main factor that affects the concentration of anthocyanins. The kinetics of anthocyanin accumulation in plants is poorly documented. Some studies report

changes in anthocyanin content with time or with the maturity stage, but they do not define the kinetics of this phenomenon. Therefore, our research team evaluated anthocyanin accumulation in açai fruits during the ripening process, and verified some important parameters using a sigmoid kinetic model. The variables assessed included the following:

- The maximum accumulation per day (dy);
- The maximum concentration in fruits (Cmax);
- The corresponding stage of maturity (S).

The average accumulation rate was 35.63 mg kg^{-1} fruit/day, and the total concentration was 1443 mg kg^{-1} fruit. The time required to reach Cmax, the optimal degree of ripeness, was very long for açai fruits: 69 to 94 days were required to reach ripeness after the appearance of the first black spots.

As anthocyanins are of great benefit to health, it is not recommended that the fruits are harvested when the concentration of anthocyanins is less than half of Cmax, or while the external appearance of the fruits is black. Açai fruits should be collected when the concentration of anthocyanins is at 85% of Cmax or higher, which corresponds to approximately 62 days after the appearance of the first black spots. Indeed, the rate of accumulation decreases progressively when the anthocyanin concentration approaches Cmax. Furthermore, structural and microbiological disorders may appear with time.

Producers usually evaluate the maturity of anthocyanin-rich fruits by looking at their external color instead of counting the time after the beginning of the ripening process (the first black spots). Therefore, each time fruit samples were collected in this study, the stage of ripeness of the fruits was determined based on their color. A preliminary assessment of the degree of ripeness of the fruits was conducted by visual observation. Then, a precise determination of the maturity stage was obtained based on the percentage of black coloration, and the presence of wax cuticles. The stage of maturity of the fruits was estimated according to the following scale: stages 1 to 6, green fruits that were at least 0, 20, 40, 60, 80 and 100% black, respectively; and stages 7 to 11, black fruits with a minimum of 20, 40, 60, 80 and 100% wax cuticle covering, respectively. When the anthocyanin concentration was plotted against the stage of ripening, it was possible to fit sigmoid curves to the data (Fig. 1.1). At a maturity stage of 8.5, the anthocyanin concentration was 85% of Cmax. As maturity class 9 is defined as the stage when a minimum of 60% of black fruits are covered with a wax cuticle on their surface, producers should be encouraged to wait at least until this stage is reached before the fruits are picked.

1.3 Maturity and quality components and indices

During the production of a crop of açai, the average composition of any of the macronutrients presented in Table 1.1 does not change significantly because the standard deviation is relatively large; however, there is evidence of significant

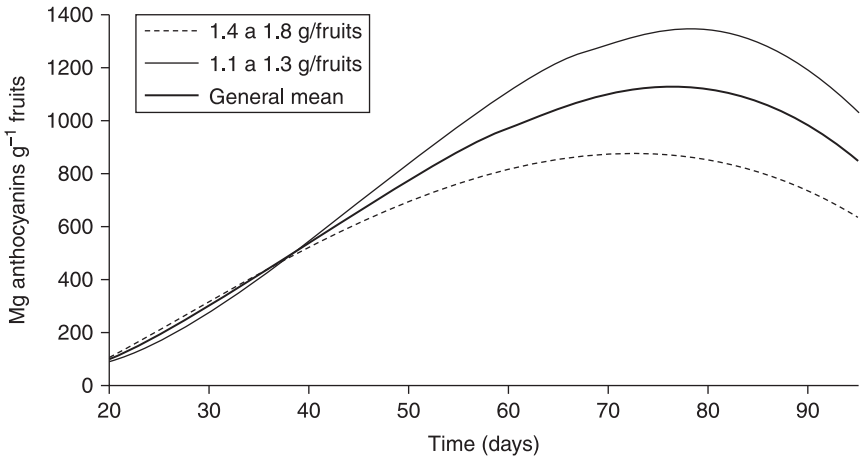

Fig. 1.1 Kinetics of anthocyanin accumulation in the açai fruit according to fruit weight and ripening time.

changes in mineral content, particularly in the levels of iron and manganese, which increase gradually throughout the high season (Rogez, 2000).

Because soluble sugars represent a particularly low proportion of the pulp (see point 1.1.6), Brix cannot be used to evaluate the maturity stage of the fruits. As already mentioned, it seems that the anthocyanin content is the best criterion to confirm the full maturity of the fruits. Quantification of the anthocyanin content can be very quick for the manufacturer, requiring a simple extraction with alcohol and HCl and a simple photometer in the visible spectrum at approximately 515 nm.

As discussed above, anthocyanin accumulation is mainly influenced by the ripening time, and the wax cuticle covering the fruits may be used as an indicator to achieve a maximum concentration of these phenolic compounds.

Rogez (2000) also found that the smallest fruits contain more anthocyanins than the largest fruits in terms of content per kilo of fruit (Fig. 1.1). In fact, a significant and negative correlation could be observed between the anthocyanin content and the weight of the fruits. As these pigments are mainly present in the first cellular layers and smaller fruits have a higher surface to volume ratio, a higher proportion of cells are exposed to light, and produce anthocyanins.

1.4 Preharvest factors affecting fruit quality

1.4.1 Genetic factors of variation

For an allogamous species (i.e. a species that reproduces by mating), the açai palm presents a high degree of variation in many parameters of interest, such as the earliness of fruit production, fruit productivity, pulp output, and production time. Different kinds of açai palm were defined according to their inflorescence forms

and bunches, the numbers of fruits per rachillae, and the diameters of the trees. Based on these different agronomic varieties, Bovi (1998) concluded that the genetic variability within a population is, for the most part, greater than the variation between different populations.

Rogez (2000) found similar results when analyzing pulp composition (see section 1.1.6). Based on these results, one can conclude that no single sample can be considered as representative of a population. The absence or presence of springs, the speed of palm growth and the morphological characteristics of the leaves are the main vegetation features that allow us to distinguish between different populations. Nevertheless, Bovi (1998) also observed significant differences between populations in terms of the length of the sheath and spadicea, as well as in the number and length of leaflets.

Rogez (2000) also observed that the average weight of the fruit varies between plants (*shrubs*). Some plants produce larger fruits than others in the same population.

1.4.2 The soil factor: solid ground versus floodplains

The açai palm grows mainly in floodplains or in areas near tributaries of rivers with running water. Productivity typically varies between 7 and 9.3 kg of fruit per stem. It is preferable to grow açai palms in areas with medium humidity of soil, such as in medium and high floodplains. It can grow in highly humid soils (e.g. areas that flood twice a day at high tide), although its productivity is reduced by approximately one-half. The average number of bunches per plant in less humid soil is five, whereas it is only three in more humid areas. Rogez (2000) found that the most productive variety was the *black* variety when planted in less humid soils.

1.5 Postharvest handling factors that affect quality

The amount of time that elapses between harvest and consumption affects açai quality. It influences direct variables, such as the loss of water, as well as indirect variables such as the loss of aroma and nutritional quality.

1.5.1 Temperature and relative humidity management

The ideal temperature for the transportation and storage of açai fruit is between 10 and 15°C. If the temperature increases by 10°C, the rate of deterioration increases by a factor of two or three. According to Pompeu *et al.* (2009b), the temperature of açai fruit in the harvesting baskets increases significantly ($p < 0.001$) – by approximately 4°C – in the first few hours after picking. Because the açai fruit is non-climacteric, the elevation of temperature that occurs after picking may be due to the impacts suffered by the fruit during harvest and the compression that occurs during transportation and storage. In spite of low levels of available sugars, açai fruits present an intensive respiration just after picking, leading to a rapid decrease

in oxygen levels in the baskets, and prefiguring optimal conditions for a subsequent fermentation (Aguiar, 2010). The temperature increase is not desirable, as it significantly reduces the fruit's shelf life.

1.5.2 Physical damage

Lesions are the main cause of açai fruit quality deterioration. They allow micro-organisms to access the fruit and oxygen to directly access the oxidizable substances contained in the fruit. They also accelerate water loss and rotting. Just after picking the bunches, açai fruits are immediately separated from the spadices; thus, it is likely that lesions in the apex of each fruit can cause rapid deterioration. Every surface that is in contact with the fruit after harvest is a potential source of infection and all surfaces must, therefore, be extremely hygienic. In the case of açai fruit, the three most significant contaminating surfaces are:

- The baskets used by growers to transport the fruits to the cities. They are made of plant material that cannot be cleaned, and are used for 4 to 6 months.
- The wooden surfaces of the boats used for transportation, which may come into direct contact with the fruits through the baskets.
- The ground that can come into contact with the baskets (e.g. the floor of the market or harbor, etc.).

1.5.3 Atmosphere

Açai fruit are transported in boat cargo to processing centers, with journey times varying from eight to 35 hours. It is thought that during the transportation of açai fruits in boat cargo holds, the fruits respire for hours, air circulation is low, and they begin to ferment. Fermentation is facilitated by high microbial levels, substrate availability, high temperature, and high humidity. Conditions are anaerobic, generating volatile compounds such as lactic acid, acetic acid and short-chain fatty acids (Aguiar, 2010). Bacterial multiplication in açai fruits reaches the first logarithmic order only 12 hours after harvest, and reaches the second order after 32 hours. The abundance of fungi increases 10- and 100-fold after 20 and 60 hours, respectively. Such fast growth of micro-organisms is exceptional for a fruit (Rogez, 2000). In non-acidic products, fungi multiply very slowly in comparison to bacteria, whereas in açai fruit, fungi multiply much faster than bacteria. This indicates that the fruit has become more acidic and suggests that a fermentation process could be occurring.

1.6 Microbiological and physiological disorders

1.6.1 Microbiological contamination and quality deterioration

The açai fruit has a high basal level of mesophylic bacteria, fungi, and total coliforms (Rogez, 2000). In 48 hours of storage at the ambient temperature of the

region (approximately 30°C), mesophylic bacteria, fungi and total coliforms increase logarithmically (section 1.5.3), which affects the quality of the açai. Forty percent of the anthocyanins present in the fruit are oxidized during this time (an average of 660 mg of anthocyanins kg^{-1} of fresh fruit decreases by 380 mg kg^{-1} of fruits after 48 hours). The fruit also shrivels and the pulp sticks to the core, reducing pulp yield during the depulping process (Pompeu *et al.*, 2009b).

1.6.2 Physiological disorders

Rogez (2000) found that two enzymes of great importance are abundant in the açai fruit: peroxidase (POD), and polyphenoloxidase (PPO), which are vegetal tissue enzymes that belong to the oxidoreductase group. In the cases of açai fruits and fresh açai juice, the color change in the presence of oxygen – from red/purple to brown – is directly associated with the activity of PPO on the anthocyanins as well as changes in its sensorial and nutritional properties. In fact, it is well known that PPO oxidizes monophenolics, leading to the formation of *o*-diphenol compounds and to the oxidation of *o*-dihydroxy compounds to quinones. The quinones subsequently undergo polymerization, producing characteristic yellow to brown colors in the product (Nunes *et al.*, 2005). POD is distinctive because it is a thermo-resistant enzyme that is used by the agro-industry as an indicator of efficiency in thermal treatments.

Rogez (2000) determined high levels of POD and PPO activities in fresh açai juice. POD activity has also been found to increase significantly with postharvest time, especially more than 24 hours postharvest, whereas PPO activity was notably constant in the three days postharvest when the study was conducted.

1.7 Pathological disorders, insect pests and their control

Insect prevalence is an important factor compromising the production of açai palm. Between 2000 and 2010, areas under cultivation have expanded significantly, and practices have become less sustainable in terms of their impact on biodiversity (there has been açai palm plantation as monoculture that involves the destruction of other species). As a result of monoculture, blights have appeared more frequently, which is a cause for concern considering the potential damage to the crop. Several insects can attack the açai palm, from the seed phase to the adult plant. Blights remain little understood, which is why we highlight them herein.

1.7.1 Main pests according to Homma *et al.* (2005)

Cerataphis lataniae

(Heteroptera: Aphididae), or the palm aphid, mounts intense attacks on the açai palm at the nursery during the first three years of life, as well as in the field.

Symptoms: This insect retards the development of açai palm seedlings, making them weak, and turning the leaves yellow, because both immature and adult aphids feed on the sap.

Control: Control in the nursery is established by separating the infected plants from the healthy ones, and by removing the insects. The damaged plants are isolated from the nursery, and observed until confirmation that the blight has been completely eliminated. There is no known method of controlling this blight in the field, and therefore, care must be taken not to introduce damaged plants in the final plantation.

Rhynchophorus palmarum
(Coleóptera: Curculionidae), or the palm weevil, attacks the açai palm in the field, from 3 years old onward, when the plant's stem is sufficiently developed.

Symptoms: The damaged açai palm decreases in size. It has yellow leaves with tanned petioles, a smaller number of leaves or an absence of bunches, aborted inflorescences, and a stipe with black holes in the wreath.

Control: The use of traps is the safest way to control this parasite.

Mytilococcus (Lepidosaphis) bechkii
(Heteroptera: Diaspididae), or comma scale, attacks the açai palm at the nursery and in the first years of life in field.

Symptoms: This organism becomes fixed along the main nerve, in the ventral part of the leaflets. Due to the insects' constant sucking of the sap, the plant displays yellow leaves. Its development and fruit production are also delayed.

Control: As there is no registered insecticide that can control this blight in açai palm, control relies on preventive measures.

Aleurothrixus floccosus
(Heteroptera: Aleyrodiae), or wooly whiteflies, attack the açai palm at the nursery, and young plants in the field.

Symptoms: Due to depletion of the sap, the leaflets turn yellow, after which the plant becomes weak, and exhibits delayed development, and production.

Control: As there is no registered insecticide that can control this blight in açai palm, certain preventive measures can be adopted.

Eutropidacris cristata
(Orthoptera: Acridiae), or the coconut tree grasshopper, attacks the açai palm at the nursery, and young plants in the field.

Symptoms: This organism impedes the development of the plant and, consequently, delays the initiation of the productive phase due to the voracity with which young, and adult insects feed on the plants.

Control: Control requires the use of bait placed in the vegetation among the palms.

Synale hylaspes
(Lepidoptera: Hesperidae), or simply Synale, damages the açai palm at the nursery, and in the first years of life.

Symptoms: The caterpillar eats the leaf blades, tearing them, and making them dry and brown.

Control: There is no method yet available to control this blight in the field.

It is important to remember that the açai product produced in the Amazon Region, commercialized and exported to other states and countries is considered 'organic' because, as outlined in this section, no pesticides are used in its production.

1.7.2 'Trypanosoma cruzi'

One of the big problems of concern to Amazonian authorities is infection by *Trypanosoma cruzi*, a protozoan that causes Chagas disease, and is transmitted by insects of the Triatominae sub-family (intermediate hosts). In the Amazon region, the triatominae do not live inside houses but in the canopies of palms, and in trees; only the females can fly, and enter houses, drawn by light (IEC, 2007). Once inside a house, they are further drawn by the CO_2 exhaled by humans, and domestic animals. As infection of several groups has occurred in the region, it cannot be justified by triatomine bites alone. Thus, in the 1990s, there was increasing suspicion that transmission was not only due to direct contact of triatomines with humans. Progressively, the oral route was shown to be a major mode of transmission for Chagas disease, with infection occurring by the ingestion of crushed infected insects or their stool (Barghini, 2008).

1.8 Postharvest handling practices

1.8.1 Harvest operations

After the fruit that is to be picked has been selected, the reapers climb to the top of the stems to remove the bunches of fruit. That tiring physical activity is performed with the help of a 'peconha', which is a sort of handicraft belt that is wrapped around the feet to provide support when climbing, allowing the reapers to use their arms around the stems to maintain balance. After climbing to the top of the tree, the reapers cut the bunch at its base using a butcher's knife, and then

pull out the stem. If a second bunch on the same plant is mature enough, the reaper goes directly from one stem to another, without going down. The bunches are brought to the ground by hand, and then laid on the ground or on a plastic sheet in order to avoid direct contact with the soil. The harvest time begins in the morning (frequently between 6 and 10 am due to the low temperatures) or after 3 pm, according to business requirements, but it rarely occurs at high temperatures.

Separating the seeds

This phase consists of passing the fingers through the bunches and pressing to force the fruit to fall down. It is performed right after the harvest, generally at the same place, and the fruits are then placed in baskets. Full baskets are brought home, and are later taken to the port storage facility for trading. The duration of transport on foot may be 1 hour. In some cases, the growers put leaves at the bottom, and on top of the baskets to preserve the fruit. Rogez (2000) evaluated the evolution of temperature in the center of seven baskets of fruit during the postharvest period. The temperature increased significantly ($p < 0.001$) in all of the lots of fruit that were evaluated, especially during the first 15 hours, when it increased from 26 to 31°C.

Transportation

The means of transportation most frequently used in the Amazon estuary is boats. The açai palm grows mainly in floodplains, and therefore, 90% of the crop is transported by boat for commercialization.

Distribution

The main commercial centers where the fruits are transported are in Belém city, where the majority of the crop is traded among street market vendors or small businessmen, who extract the pulp from the fruit using traditional machines.

1.8.2 Recommended storage and shipping conditions

The conditions between harvesting and obtaining the final product are very important because they play a role in the loss of water, aroma, and bioactive compounds. Pompeu *et al.* (2009b) evaluated the effects of refrigeration during storage of the fruit. Refrigerated fruit presented little loss of mass, a minor proliferation of mesophilic bacteria, and fungi, and a slight degradation of anthocyanins, even when stored at only 15°C (Fig. 1.2).

A mass loss of 3 to 6% may negatively impact the nutritional, and sensorial properties of fruit in general. In açai, the problem is even more significant because the edible portion of this fruit consists of the external thin surface of epicarp and the mesocarp, which accounts, on average, for only 12% of the fruit's weight. This loss of mass is due to the elimination of water and CO_2 during the metabolic process of respiration. In environments with low temperatures, there is a reduction of metabolism in the fruit and, consequently, little mass loss.

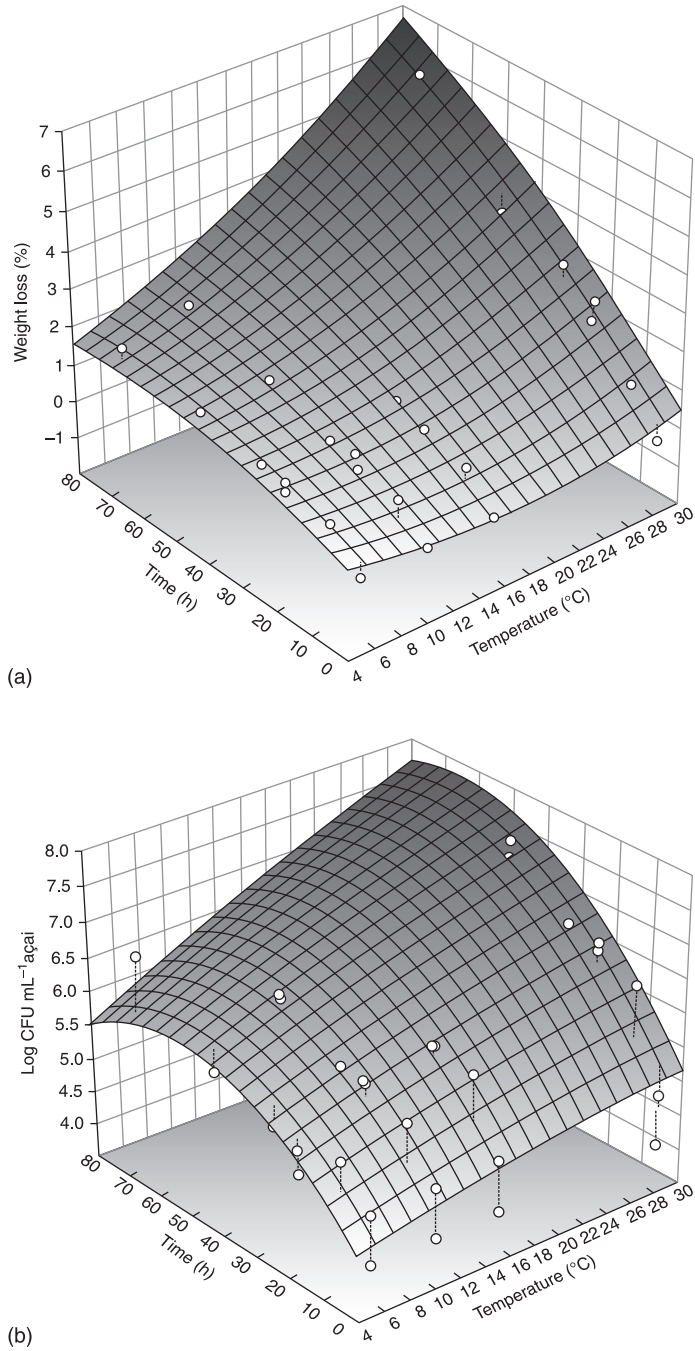

Fig. 1.2 Mass loss (a), evolution of total mesophilic bacteria (b), and evolution of anthocyanin concentration (c) in açai fruit as affected by duration and temperature of storage.

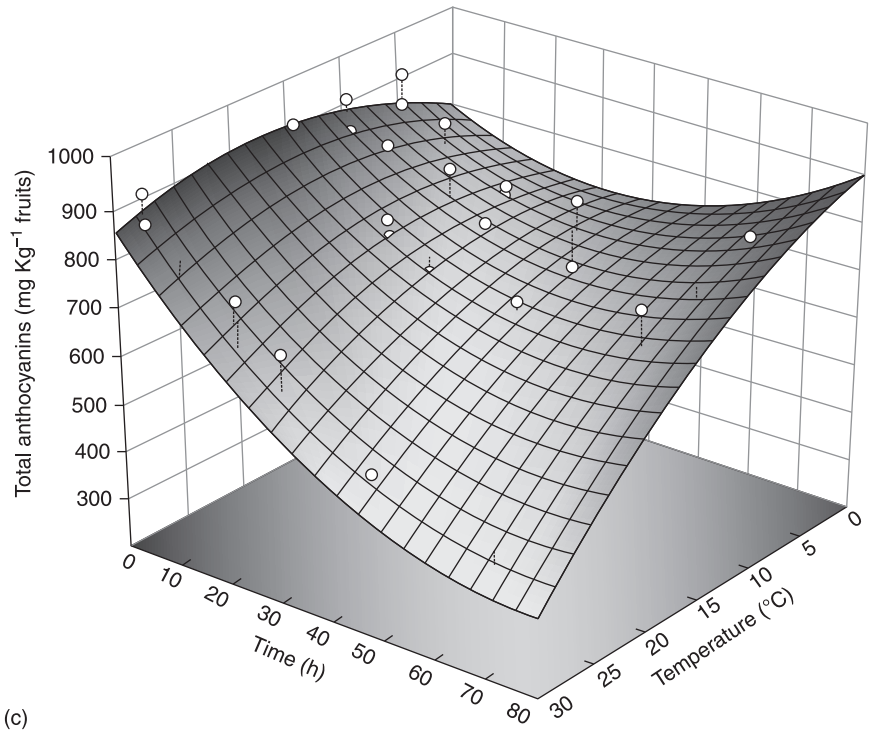

Fig. 1.2 Continued.

1.9 Processing practices

As açai has a high level of microbial contamination, it has a short shelf life, which limits its value and hinders its commercialization. To reduce levels of microbial contamination, it is necessary to improve harvesting, packaging, and transportation practices, and reduce the time taken for the harvested fruit to reach the market. This would improve the quality of the fresh fruit raw material without the use of chemical agents or technology, ensuring lower production costs.

1.9.1 Fruit reception

Açai fruits are transported to processing units packaged in baskets or plastic boxes, which are weighed before the selection process.

1.9.2 Selection

Manual selection of the fruits is conducted on stainless steel tables, using baskets that retain the fruit, but allow small contaminating elements, such as sepal and rachillae fragments, soil, and shrunken fruit, to pass through. At this phase, the

green fruits that are in a dubious phytosanitary state, or that have other types of problems that make them unsuitable for processing, are removed from the lot.

1.9.3 Washing

The fruits are immersed in water to remove contaminating elements. The cleaning process is repeated three times, with chlorinated water used for the second wash.

1.9.4 Blanching

Açai blanching is optional, and is only performed when the juice production process does not include a pasteurization stage. Blanching can be done by plunging the fruit into hot water (~80°C) for 10 seconds; these conditions reduce the microbial content of the fruit, and eliminate the majority of air present in the fruit, without fully denaturing the PPO, and POD enzymes. High temperatures of 80°C for more than 10 seconds alter the juice emulsion, and cause partial separation of the lipids.

1.9.5 Softening

The fruits are immersed in lukewarm water to soften the epicarp and mesocarp, which facilitates the crushing of the pulp. The variables affecting the softening process include water temperature, and immersion time, which are altered by the processors according to the fruit's provenance, and its level of maturity. The water used in this process is generally at room temperature or at an average of 40 to 45°C. The softening time is varied from 10 to 60 minutes: the greater the degree of maturation, the shorter the time of fruit immersion.

1.9.6 Depulping

At this stage, traditional machines commonly known as beaters are used. Açai juice is prepared in vertical stainless steel models that crush the açai fruit while adding water. The process of depulping of the fruit begins with the blade action; the movement of the blades promotes rubbing of the fruit, which is followed by progressive addition of water. The processed product goes down the machine, passing through a filter, and it is then stored in stainless steel bowls.

1.9.7 Clarification

Pulp clarification is a method used to improve the aesthetic properties, and market acceptability of the fruit by eliminating most of the lipids and fibers. Pacheco-Palencia *et al.* (2007) evaluated the effects of clarifying the açai pulp, and observed that the use of diatomaceous earth had a detrimental effect on the quantity of anthocyanins and other phenolic compounds, and reduced the antioxidant capacity

of the fruit. However, this process was efficient in removing polymeric compounds, resulting in pulp with a low level of insoluble solids, and a bright purple color.

1.9.8 Pasteurization

Pasteurizing natural açai juice allows it to be conserved at +4°C for ten days. Treatment at 90°C for ten minutes completely eliminates molds, and yeasts, guaranteeing adherence to official quality standards (BRASIL, 2000), and also causes total denaturation of PPO and POD. However, this treatment also causes considerable loss of anthocyanins. To conserve açai at −20°C for several months, industrial producers use temperatures of approximately 80 to 85°C, for 10 to 30 seconds. The residual activity of POD is an indicator of pasteurization success. It is important to remember that treatments at temperatures of greater than 80°C or durations of longer than ten seconds provoke the separation of fatty matter. A green-colored oil layer forms at the surface, because the emulsion has not formed correctly. The addition of the citric acid to decrease the pH of açai is permitted up to a concentration of 5%. This causes the destruction of bacteria and enzymes during the pasteurization process, and helps to conserve particularly the phenolic compounds in the product.

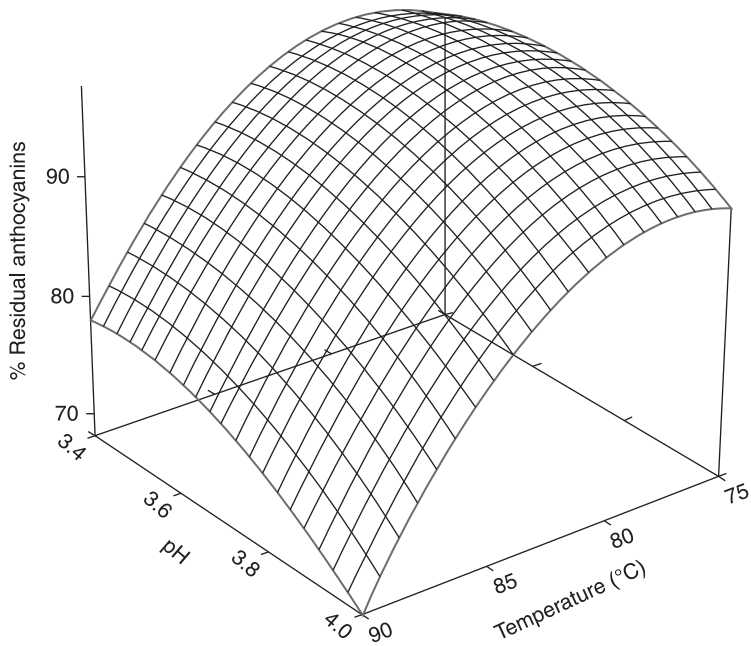

Fig. 1.3 Quadratic evolution of residual anthocyanins (percent) as a function of temperature of pasteurization and pH of the açai (constant time of 60 s).

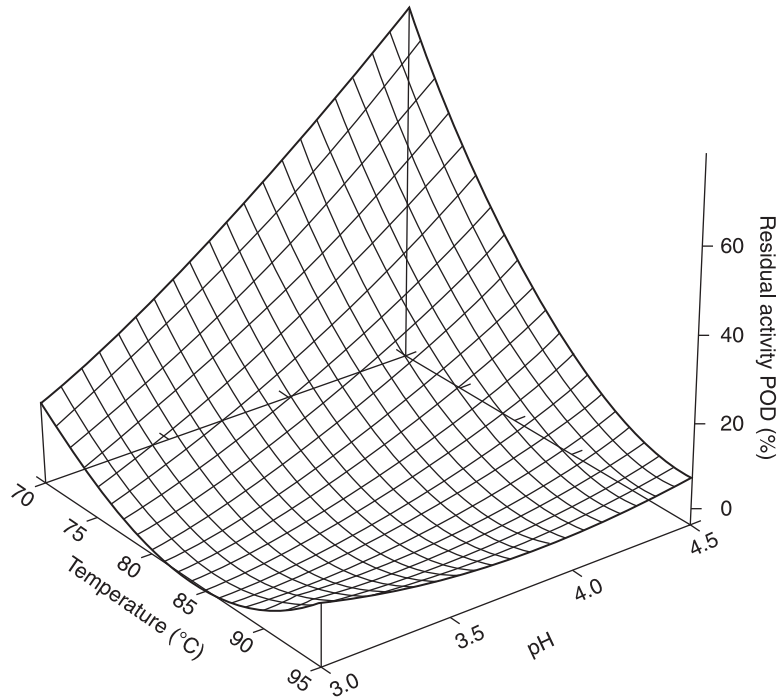

Fig. 1.4 Quadratic evolution of the residual activity (percent) of peroxidase according to the pasteurization temperature and pH of the açai (constant time of 60s).

1.9.9 Dehydration

The technology most commonly used to obtain dried açai is atomization (spray drying). This produces açai powder with high anthocyanin content. In this process, the drying time is short (between 1 and 10 seconds). When using a spray dryer (Mobile Minor Unit AS0340D model) to obtain the açai powder, the following operational conditions may be applied: an entering air temperature of 135 to 140°C; an exiting air temperature of 85 to 90°C; and a pressure of 4.9 to 6.2 kg cm^{-2}. The açai powder, once obtained, has a longer shelf life when packaged in aluminum and plastic (Melo *et al.*, 1988). Silva *et al.* (2008) evaluated the adsorption and desorption isotherm of açai powder. They concluded that açai presents a typical type-III adsorption isotherm. As the variation in desorption heat is low, the product is not very hygroscopic, with the final product presenting a monolayer value of 7.1 g H_2O per 100 g DM. Tonon *et al.* (2010) evaluated the anthocyanin stability and antioxidant activity of spray-dried açai juice produced with different carrier agents for 120 days, and concluded that anthocyanin degradation exhibited two phases of first-order kinetics: the first, with a higher reaction rate, occurring in the first 45 to 60 days of storage, and the second, with a slower reaction rate, occurring after 60 days. An increase in water activity also resulted in higher anthocyanin degradation, due to the greater molecular

mobility, which allows for greater oxygen diffusion, thus accelerating oxidation reactions.

1.9.10 Extraction of anthocyanin from açai fruits

An important technique nowadays is the extraction of anthocyanins from several different fruits using organic solvents; this anthocyanin can be used in natural dyes and natural supplements. Studies on the extraction of phenolic compounds from açai fruits are minimal; there is one report on the effect of methanol and ethanol on the phenolic extraction (Rodrigues *et al.* 2006), and this study did not investigate any other factors. To expand upon these studies, Pompeu *et al.* (2009a) studied the optimization of the extraction of antioxidant compounds using the proportion of ethanol, the concentration of hydrochloric acid, and the temperature of the process as variables. The optimized conditions that maximized the yields of phenolic compounds were as follows: an ethanol proportion between 70% and 80%; a hydrochloric acid concentration between 0.065 and 0.074 mol L^{-1}; and a temperature of 58°C. The three variables investigated in the present study could be ranked as follows in terms of their impact on extraction performance: temperature > ethanol proportion >> hydrochloric acid concentration.

1.10 Conclusions

Several studies have been conducted to elucidate the benefits of açai for human health. The biggest problems observed in açai production today are related to the conditions used to obtain açai, which still need improvement. Handling, harvesting, and transportation methods are still very rustic, and are undertaken without the necessary care, and hygienic precautions that these practices demand. Açai growers are resistant to new technologies or even to the application of basic knowledge, such as good manufacturing practices. Because it is a potential source of phenolic compounds, particularly anthocyanins, açai should be further examined in future research. This research should aim to apply, develop and optimize technologies for the extraction and purification of phenolic compounds. However, few studies regarding the stability of these compounds when used in the nutrition, pharmaceutical or cosmetic industries have been conducted to date.

1.11 References

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(a)

(b)

(c)

Plate I *Euterpe oleracea* palm tree (a), a bunch of açai fruits (b) and cross-section of a fruit (c). Photo: H. Rogez

2

Acerola (*Malpighia emarginata* DC.)

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Abstract: The Acerola, or West Indian cherry, which belongs to the Malpighiaceae family, is native to the West Indies and tropical South America. Fully ripe fruits have the highest vitamin C content of all fruits, ranging from 1,000 to 2,000 mg $100g^{-1}$. Processing the fruit into juice results in little loss of vitamin C; consequently, the juice is used to improve the ascorbic acid content of other fruit juices. Fruits are ready for harvesting when they turn pink or red. They should not be allowed to ripen fully on the trees because they deteriorate rapidly. The fruits are highly perishable after harvest. Postharvest losses are mainly due to physical injuries arising from abrasion, puncture and compression. Shelf life is also limited owing to pests and diseases. The fruits have a very thin skin and lose moisture very rapidly when stored at high temperatures and low relative humidity. Fruits are also susceptible to chilling injury during low temperature storage.

Key words: *Malpighia emarginata*, acerola, Barbados cherry, processing, postharvest.

2.1 Introduction

2.1.1 Origin, botany, morphology and structure

The acerola, which is also called 'Barbados cherry', 'West Indian cherry', 'cereza', 'cerise des Antilles' and 'sweet kersie' belongs to the genus *Malpighia*. In the past, according to Carrington and King (2002), the plant was known by the synonyms *Malpighia glabra* L. and *Malpighia punicifolia* L., but recent taxonomic work has resulted in the acceptance of *Malpighia emarginata* DC. as its scientific name. It is native to the West Indies and tropical America, but is now cultivated throughout the tropics and in subtropical areas such as Florida, Australia and Israel. Acerola can be found from South Texas, through Mexico and Central America and more recently, it has been introduced in subtropical areas throughout the world such as parts of Asia, India and South America. Some of the largest plantations are in Brazil, particularly in the Northern region of the country, and currently, Brazil is the largest producer of acerola in the world (de Assis *et al.*, 2008).

The plant is either a large, bushy shrub or a small tree that can attain an average height of 3 to 5 m. It has a short, slender trunk that is 0.5 to 1 m high and 7 to 10 cm in diameter. The branches are erect to spreading, forming a dense canopy, and the bark of the tree is slightly rough and grey-brown in colour. The evergreen leaves are hairless, glossy and dark green when mature and are generally small: 2 to 7 cm long and 9.5 to 40 cm wide. The flowers are borne in inflorescences that are sessile or have short peduncles, and are pink with five-fringed petals.

It is a hardy plant capable of growing in both tropical and subtropical climates. It can resist temperatures close to 0°C (Neto and Soares, 1994) but is well adapted to temperatures around 26°C. It grows and produces well when rainfall is between 1200 and 1600 mm per year. Irrigation is required in areas with little rainfall. Plants can be grown in sandy soils as well as clay soils: a soil with average fertility composed of a mixture of sand and clay seems to be optimal for its cultivation.

Flowering and concomitant fruiting can occur throughout the year, but typically occur in cycles associated with rainfall. Usually, they take place in 25-day cycles, up to eight times per year. Plants grown in dry areas with an annual rainfall around 1480 mm in irrigated fields produce between 2.01 and 27.11 kg per tree in four crops in a year. The plant has also been cultivated as an ornamental in subtropical areas where it flowers from April to November (Johnson, 2003).

The fruit is a thin-skinned, three-lobed drupe, globose, up to 2.5 cm in diameter and weighing 2 to 10 g. It ripens to a bright red colour and the pulp is orange, very juicy and acid to sub-acid in flavour. The three small seeds bear wings that give them a triangular shape.

2.1.2 Worldwide importance and culinary uses

The West Indian cherry is consumed fresh as a dessert, either whole or cut into halves and either served by itself or in combination with other fresh-cut fruits as a fruit salad. It adds colour and flavour to fruit salads and also prevents discolouration in other fruits such as bananas, due to its high vitamin C content. Fruits at the ripe and full-ripe stages of maturity can also be deseeded and eaten sprinkled with sugar or salt to modify the acidity of the particular cultivar available. Due to its highly perishable nature it is also processed into a range of value-added products such as juice (integral, concentrated and lyophilized), juice blends, fruit punches, nectars, soft drinks and fruit conserves (although the pasteurized canned juices do not keep well, are unattractive and rapidly lose their nutritional value). It is also used as an ingredient in yoghurts, sodas, jellies, ice-cream and bakery products, sold as a nutraceutical and consumed for medicinal purposes (Mezadri *et al.*, 2006).

Owing to the wide range of uses identified above, demand for the fruit outstrips supply. Demand for the pulp in Caribbean and Western European markets is particularly promising. Acerola is attractive to customers who prefer natural products over synthetic ones (for example it is a popular natural source of vitamin C). As it can be sold in both fresh and processed forms, the fruit is an excellent source of income to producers and agro-processors. The fruit is also a perennial, producing all year

long when cultivated in irrigated fields. Harvesting and marketing of the fruit provide employment as well as continuous income throughout the year.

2.1.3 Composition, nutritional value and health benefits

The West Indian cherry is rich in vitamin C, pectin and pectolytic enzymes, carotenoids and fibre, and contains small amounts of vitamins and several bioactive substances, such as thiamin, riboflavin, niacin, proteins and mineral salts, mainly iron, calcium and phosphorus according to de Assis *et al.* (2008), as shown in Table 2.1. Porcu and Rodriguez-Amaya (2006) investigated the variation in the carotenoid composition of acerola fruits and found that neoxanthin, violaxanthin, lutein, β-cryptoxanthin, α-carotene and β-carotene were present.

When fully ripe the ascorbic acid content of the fruit ranges from 1000 to 2000 mg $100g^{-1}$ and the pulp of partially ripe fruit can have values as high as 4500 mg $100g^{-1}$ (de Assis *et al.* 1998). Therefore, this fruit is recognized as the best natural source of vitamin C. In comparison with synthetic ascorbic acid, the vitamin C produced by this fruit is better absorbed by the human body. In fact, humans can only absorb 50% of synthetic vitamin intake compared to that of natural vitamins (Byrne, 1993). The high vitamin C content of acerola fruits enables it to be used for the production of vitamin C concentrate for pharmaceutical purposes or enrichment of industrialized foods. Vitamin C plays a key role in the biosynthesis of collagen, carnitine, neurotransmitters, corticoids and catecholamines as well as in the synthesis and maintenance of tissues including the formation of bones, teeth and muscles (Araujo and Minami, 1994; Naidu, 2003). In a study reported by Johnson (2003), it was found that infants consuming apple juice supplemented with acerola showed average or above average growth and development for their age and weight. Vitamin C levels in the blood were

Table 2.1 Food value of acerola fruit

Proximate composition (g 100 g^{-1})

	Energy	Water	Protein	Total lipid	Ash	Carbohydrate	Total dietary fibre	Total sugars
Fruit	32	91.41	0.40	0.30	0.20	7.69	1.1	–
Juice	23	94.30	0.40	0.30	0.20	4.80	0.3	4.50

Minerals (mg 100 g^{-1})

	Calcium	Iron	Magnesium	Phosphorus	Potassium	Sodium	Zinc	Copper	Selenium
Fruit	12	0.20	18	11	146	7	0.10	0.086	0.6
Juice	10	0.50	12	9	97	3	0.10	0.086	0.1

Vitamins (mg 100 g^{-1})

	Thiamin	Riboflavin	Niacin	Pantothenic acid	Vit. B-6	Folate	Vit. A
Fruit	0.020	0.060	0.400	0.309	0.009	14	767
Juice	0.020	0.060	0.400	0.205	0.004	14	509

Source: de Freitas *et al.*, (2006).

higher for all infants after the acerola/apple juice was introduced in the diet. No allergic reactions occurred, suggesting that acerola mixed with apple juice is an acceptable alternative to orange juice for obtaining vitamin C from the diet.

Acerola is a remarkable functional food resource. Santini and Huyke (1956), in their pioneering study, identified polyphenols as a colour-changing agent in acerola juice. According to Hanamura *et al.* (2008), though, it is only recently that the physiological effects of polyphenols and other functional constituents of acerola have become the subject of investigation by the scientific community. Hanamura *et al.* isolated three polyphenols from acerola fruits: cyaniding-3-*α*-*o*-rhamnoside (C3R) and pelargonidin-3-*α*-*o*-rhamnoside (P3R) as anthocyanin, and quercetin-3-*α*-*o*-rhamnoside (quercitrin; Q3R). These acerola polyphenols have an antiperglycemic effect, the mechanism of which was considered to be both the suppression of intestinal glucose transport and inhibition of *α*-glucosidase and thus beneficial to human health. The high antioxidant content of acerola extracts has contributed to their use for the prevention of age-related diseases such as hypertension and cancer (Filgueiras *et al.*, 2007). Filgueiras *et al.* (2007) evaluated the antioxidant capacity of fruits from five clones of ascerola. They stated that although the anthocyanin content measured was 2.7 to 7.8 mg $100g^{-1}$ FW (fresh weight), much lower than that of berry fruits, the phenolic content was about three times as high, that is, 3300 to 4400 mg $100g^{-1}$ FW and the vitamin C content varied from 1100 to 1400 mg $100g^{-1}$ FW. They concluded that the ORAC (oxygen radical absorbance capacity) value of acerola was 239 to 383 f.1M TE/g DW (Trolex equivalent per gram dry weight). This is significantly higher than that of strawberry and blackberry. The same authors reported that acerola extracts diluted 1:100 and 1:200 significantly inhibited the relative activity of carcinogenesis related Activator Protein-1 (AP-1) and nuclear factor kappa-light-chain-enhancer of activated B cells (NF-kB) transcription factors induced both by tissue plasminogen activator (TPA) and Ultra Violet B type rays (UVB) (Filgueiras *et al.* 2007). In addition, Johnson (2003) reported that in the presence of acerola cherry extract, soy and alfalfa phytoestrogen extracts prevented the oxidation of low-density lipoproteins, thus reducing an important risk factor in coronary heart disease: an extremely beneficial outcome for the health of postmenopausal women. Acerola is also reported to have anti-fungal properties (de Assis *et al.*, 2008).

2.2 Fruit growth and development

2.2.1 Fruit growth, and maturation

Carrington and King (2002) provided a comprehensive account of growth, development and ripening of West Indian cherries. According to these authors fruit growth is biphasic: the majority of the size increase occurred during the initial 14 days post-anthesis; a second limited phase of growth followed over the subsequent ten days. This double sigmoid pattern of growth articulated by Carrington and King (2002) was confirmed by measurements of fresh weight and dry weight.

According to Carrington and King (2002), Monselise's (1986) theory that the biphasic growth curves obtained for blueberry and peach are indicative of resource diversion to develop a substructure (such as the endosperm or endocarp) during the transition period between the two growth phases is not relevant for acerola fruits for two reasons. First, the embryonic development 3 days after pollination in acerola fruits attained morphological maturity around the time of the transition period, and secondly, the growth of the pyrene (comprising the seed and endocarp) mirrored the growth of the whole fruit on the basis of fresh and dry weight (Carrington and King, 2002). Carrington and King (2002) also contradicted the histological study by Miyashita *et al.* (1964), which suggested that the pericarp in acerola grew solely by cell enlargement. Rather, Carrington and King (2002) provided evidence to show that cell division occurred in the exocarp and mesocarp, but was limited to the earliest phase of fruit development where cell numbers increased exponentially up to eight days post-anthesis, and ceased thereafter.

Full-sized, green fruit turned cream at the distal end about 18 days post-anthesis (Carrington and King, 2002). According to these authors, fruits at this stage do not ripen off the tree, so this colour break is a useful index of horticultural maturity. Carrington and King (2002) further stated that by 20 days post-anthesis fruits changed to a peach colour and by 22 days fruits were orange-red. This is comparable with the 21 to 25 days development period articulated by Miyashita *et al.* (1964).

Changes in skin colour correlate with chemical changes in the fruit. Guadarrama (1984) and Alves *et al.* (1992) associated the degradation of chlorophylls at the early stages of fruit maturity with a concomitant rise in carotenoids, with trans-β-carotene being the main carotenoid. Towards the later growth stage coinciding with physiological maturity, anthocyanins were dominant, and therefore the full red skin colour developed. At this stage the anthocyanins increased strongly to become the major polyphenols (Hanumura *et al.*, 2008). Other chemical changes associated with advancing fruit maturity were investigated by Vendrami and Trugo (2000), who indicated that while titratable acidity, soluble solids and sugars increased, vitamin C and proteins decreased as fruit matures. The same authors identified the emission of volatiles at different stages of maturity. They identified 31 compounds in the mature red fruits, such as acethyl-methyl-carbinol, 2-methyl-10-propyl-acetate, limonene, E-Z-octenol, ethyl hexanoate, isoprenyl butyrate and acetofenone; 23 in the intermediate yellow stage, such as methyl hexanoate, 3-octen-1-ol and hexyl butyrate; and 14 in the immature green stage, such as methyl-propyl-ketone, E-Z-hexenyl-acetate and 1-octadecanol. Despite this, fruit aroma according to Carrington and King (2002) was considered too subtle to be used as maturity indices in acerola.

2.2.2 Respiration, ethylene production and ripening

Carrington and King (2002) and Alves *et al.* (1995) investigated the respiratory pattern of acerola fruits and confirmed its climacteric responses. Carrington and King (2002) reported that respiration rose dramatically as fruits turned orange-red and peaked around 3 days postharvest. They also indicated that ethylene evolution

followed a similar pattern with the climacteric peak occurring two to four days postharvest. Based on carbon dioxide production acerola fruits can be said to have an extremely high respiratory rate, which is consistent with its very perishable nature. In contrast, relatively low rates of ethylene were measured (Carrington and King, 2002). Fruit ripening in acerola is accompanied by major physicochemical changes. Weight, thickness and height increased during maturation and ripening, as well as levels of carotenoids, soluble sugars and total sugars and the soluble solids/titratable acidity ratio (Table 2.2). Chlorophyll, titratable acidity and vitamin C decreased, while pH showed few changes.

Hanamura *et al.* (2008) investigated ripening changes in five cultivars. For the purposes of the study, they classified the different stages of maturity as follows: green (under ripe), yellow (ripe), red (fully ripe) and purple (overripe). They concluded that the amounts of total polyphenols, malic acid and sugars, as well as total water-soluble solid, increased with the development of fruit ripening in cultivars 'BOK' and 'NRA309'. In the latter cultivar, sugar contents significantly increased from green to purple stages of fruit maturity (total sugar contents: 6.8 g kg^{-1} for green immature fruits, 23.2 g kg^{-1} for purple overripe fruits) compared to the former cultivar, where total sugar contents were 16.0 g kg^{-1} for green immature fruits and 31.1 g kg^{-1} for fully ripe fruits. On the other hand, the rate of increase of malic acid content was more significant in cultivar 'BOK' (2.7g kg^{-1} for green fruits and 9.7g kg^{-1} for red fruits) than in cultivar 'NRA 309', which gave 4.5 g kg^{-1} for green fruits and 8.4g kg^{-1} for red fruits. Vitamin C content, on the contrary, decreased with the development of fruit ripening in both cultivars, from

Table 2.2 Average values of some physical parameters in fruit of acerola genotypes studied in Brazil

Genotype	°Brix(TSS)	% Titratable acidity(TA)	TSS: TTA	vit. C mg/100 g^{-1}
Acer-1	6.35de	0.63g	9.97b	665.22de
Acer-2	6.65cde	0.72efg	9.20bc	887.61abcd
Acer-3	6.90abcd	0.73efg	9.46bc	1028.95ab
Acer-4	6.80bcd	0.69fg	9.87b	772.51bcde
Acer-5	6.40de	0.73efg	8.95bc	888.39abcd
Acer-6	6.90abcd	0.80def	8.57cd	751.44cde
Acer-7	5.80efg	1.05ab	5.53e	1141.21a
Acer-8	5.40fg	0.97bc	5.59e	967.59abc
Acer-9	7.55ab	0.75ef	10.03b	758.85cde
Acer-10	7.75a	0.82de	9.43bc	731.54cde
Acer-11	6.85bcd	0.78ef	8.76bc	800.21bcde
Acer-12	5.25g	0.90cd	5.81e	880.16abcd
Acer-13	6.25def	1.15a	5.44e	928.57abcd
Acer-14	7.35abc	0.37h	19.39a	723.74cde
Acer-15	6.55cde	0.73efg	8.95c	575.48e
Acer-16	5.80efg	0.78ef	7.38d	1127.55a

Source: Cavalcante *et al.*, 2007.

25.7 to 23.5 g kg^{-1} for cultivar 'BOK', and from 26.0 to 20.0 g kg^{-1} for cultivar 'NRA309'. In the same investigation, the two cultivars showed a similar pattern of change in the contents of individual polyphenolic compounds during maturation and ripening. Accordingly, the amount of anthocyanins (C3R and P3R) and Q3R increased with the development of fruit ripening in both cultivars. In particular, the amount of both anthocyanins dramatically increased from yellow to red fruits in both cultivars. In fruits of the cultivar 'NRA309', the amount of both anthocyanins further increased more than two times from fruits at the red stage of maturity to those at the purple stage of maturity. On the contrary, phenylpropanoids decreased with the development of fruit ripening in both cultivars from 61 to 24 mg kg^{-1} for 'BOK' and from 111 to 51 mg kg^{-1} for 'NRA309'.

2.2.3 Maturity indices

Physicochemical parameters are important indicators of fruit maturation and fruit internal and external quality. They are also significant for customer satisfaction. Change in skin colour is a major criterion used to assess acerola maturity. A classification of maturity and ripening stages is presented in Plate IIa (see colour section between pages 244 and 245; Mohammed, 1996). Stage 1 consists of immature fruits with a bright glossy green colour, stage 2 has 95% light yellow and 5% peach skin colour, stage 3 fruits has 85% peach and 15% shade of pink colour, stage 4 has 60% pink and 40% red skin colour, stage 5 has a uniform red skin colour and stage 6 has a darkish-red or purple skin colour. As already mentioned, full-sized, green fruit turn cream at the distal end about 18 days post-anthesis (Carrington and King, 2002). According to these authors, fruit at this stage do not ripen off the tree, so this colour break is a useful index of horticultural maturity. Although fruits are round at all stages of maturity, fruit size varied according to genetic lines, growth and environmental conditions and therefore is not a consistent and reliable maturity index. Fruits harvested at the pink stage of maturity have at least 6.5% soluble solids. Vitamin C loss during maturation can be 33% up to the pink stage and reach as much as 45% when dark red.

2.3 Preharvest factors affecting fruit quality

The genetic potential of the acerola plant along with the edaphoclimatic conditions strongly influence the productivity of the tree and characteristics of the fruit it produces. The quality of fruits prior to harvest depends on the cultivar, climatic conditions, soil type, irrigation, level of sunlight, way in which the plants are spaced and pruned and pest and disease control. Significant variation in fruit quality can be observed among different production areas.

Acerola fruit fresh weight and size vary according to cultivar and location (Table 2.3). Strong evidence of this can be found in the investigations conducted by Cavalcante *et al.* (2007), Semensato and Pereira (2000), Nogueira *et al.* (2002) and Roberts-Nkrumah *et al.* (1994). The lowest average fruit weight observed by

Table 2.3 Average values of some chemical parameters in fruit of acerola genotypes studied in Brazil

Genotype	Width (cm)	Length (cm)	Weight (g)	Pulp (%)
Acer-1	1.99bcd	2.34bcd	6.35c	50.02bcdef
Acer-2	1.94bcde	2.24d	6.02c	48.42cdef
Acer-3	2.07abc	2.35bcd	6.82c	46.54defg
Acer-4	1.92bcde	2.36bcd	7.25bc	50.48bcdef
Acer-5	2.06bcd	2.42bcd	6.42c	45.57defg
Acer-6	1.99bcd	2.33bcd	6.29c	49.72bcdef
Acer-7	1.88cde	2.32bcd	5.80cd	44.44efg
Acer-8	1.97bcde	2.40bcd	6.56c	52.41abcde
Acer-9	1.81de	2.28cd	7.12bc	42.26fg
Acer-10	2.00bcd	2.53ab	8.62ab	42.89fg
Acer-11	1.73e	1.99e	4.24d	38.58g
Acer-12	2.00bcd	2.43bcd	6.39c	54.36abcd
Acer-13	2.32a	2.70a	9.94a	61.21a
Acer-14	1.94bcde	2.43bcd	6.04c	41.44fg
Acer-15	2.17ab	2.47abc	7.08bc	57.52abc
Acer-16	2.07abc	2.50abc	7.28bc	57.83ab

Source: Cavalcante *et al.*, 2007.

Cavalcante *et al.* (2007) was 4.24 g (cv. Acer-11). This was above the 3.52 g reported by Semensato and Pereira (2000) and Roberts-Nkrumah *et al.* (1994), but below the 7.81 g and 6.59 g averages, respectively, for the cultivars UFRPE-7 and UFRP-8 mother plants obtained by Nogueira *et al.* (2002).

Cavalcante *et al.* (2007) found significant differences in length, width and pulp percentages between 16 acerola genotypes (Table 2.3). According to this analysis, fruit length was greater than fruit width, thereby characterizing the fruit as subglobose in shape. The cultivar Acer-11 had the smallest fruits (1.99 cm in length and 1.73 cm in width) while genotype Acer-13 had the largest fruits (2.70 cm in length and 2.32 cm in width). Fruit lengths were generally greater than 1.62 to 2.07 cm, the range reported by Semensato and Pereira (2000) but compatible with the UFRPE-7 mother plant, which has a 2.3 cm average (Norueira *et al.*, 2002). In any case, all the genotypes evaluated by Cavalcante *et al.* (2007) had fruit length above the minimum (1.5 cm) demanded by the industry. Genotype variations for pulp percentage are also given in Table 2.3 (Cavalcante *et al.*, 2007). The pulp percentage ranged from 38.58% for Acer-11 to 61.21% for Acer-13 which is close to the 47.8 to 58.9% range accounted for by Gomes *et al.* (2000) and the 40.83 to 65.63% obtained by Semensato and Pereira (2000) but lower than the 59 to 75% shown by Arostequi and Pennock (1995) and higher than the 30% average reported by Lopes *et al.* (2001).

The changes associated with the composition in acerola fruit in relation to cultivar, growing region and maturity were also articulated in the study reported by Hanamura *et al.* (2008). Thus, in terms of growing regions, cultivar 'Vietnam', vitamin C and polyphenol concentrations were lower in this fruit compared to

those found in fruits from other growing regions. Noteworthy, was the amino acid composition in this cultivar, which showed an extremely high concentration of proline (858 mg kg), almost half of the total amino acid content (1,733 mg kg). Also, this fruit contained a high level of phenylpropanoids, amounting to 30% of total polyphenols. The distinct compositional profile so obtained, including high sugar and low vitamin C contents as well as exceptionally high proline content, which is associated with a sweet taste, appeared to be strongly correlated with the organoleptic characteristics of this fruit. It has been reported that the taste threshold value of proline is 3.0 g L^{-1} at pH 6 to 7 and 875 mg L^{-1} at pH 4.3 (Schoenberger *et al.*, 2002). 'Vietnam' cultivar fruit contained approximately 800 mg kg^{-1} (edible portion) of proline whereas the pH value of acerola juice was 3.3, thereby confirming that proline contributes to the sweet taste of this fruit.

High variability in fruit quality has been reported in Brazilian acerola crops, especially those propagated by seeds. Fruit size and composition quality are not only affected by lack of orchard uniformity, but also by environmental factors such as excessive rain, and by preharvest factors such as irrigation, fertilization, pest and disease control. Variations in soluble sugars in acerola fruits can vary from 5 to 12 °Brix due to excessive rain or irrigation, which could dilute cell juice thereby reducing the amount of soluble solids and vitamin C (Alves *et al.*, 1999). Preharvest factors could also account for the variation in vitamin C in acerola fruits from 0.8 to 3.5%. A peak is reached approximately 16 to 18 days after anthesis and the concentration falls to nearly 50% of the peak amount when maturation is completed. Fruits from seed propagated plants for example have lower amounts than those from asexually propagated plants. In the shaded side of fruits there was a significant reduction in vitamin C content before harvest, whilst exposure to solar radiation for more than four hours after harvest resulted in substantial losses (Alves and Menezes, 1994; Alves *et al.*, 1992, 1995; Nakasone *et al.*, 1966).

Fruits and flowers at different stages of development are present simultaneously on the acerola plant. Therefore there is the risk that chemicals used for pest and disease control to improve plant health and productivity increase levels of pesticide residues in fruit.

2.4 Postharvest factors affecting quality

2.4.1 Temperature management

Postharvest temperature management, to minimize the rate of respiration and ripening in acerola, is very important. Maciel *et al.* (1999) reported that acerola fruits harvested at the pink stage of maturity stored at room temperature maintained marketable quality for two to three days when wrapped in PVC (polyvinylchloride) film. However when fruits were stored in PVC wrapping at 7 to 8°C and 80 to 90% relative humidity, shelf life advanced to a week without any losses in vitamin C (Maciel *et al.*, 1999; Mohammed, 1996) The storage temperature should not be too low, though, as acerola fruit are susceptible to chilling injury

when stored at temperatures below 5 to 6°C, with the damage becoming more visible when they are stored in air where the relative humidity is below 85% (see section 2.5.1).

2.4.2 Physical damage

Acerola fruits have a very thin skin, which offers little resistance against most types of physical injury. Fruits are particularly susceptible to abrasion caused by the fruit rubbing against each other. Physical injuries which are significant sources of postharvest losses are: punctures caused by fingernails during harvesting and other postharvest operations and compression of fruits packed in deep containers caused by the weight of the fruit in the layers above them. If the fruit skin is damaged then the fruit pulp deteriorates rapidly.

2.4.3 Water loss

When the types of physical damage outlined above occur, the level of transpiration increases. Despite the fruits having a natural gloss due to deposition of cuticular wax on the fruit skin, if fruits are stored in less than 85% relative humidity, moisture loss is high leading to shrivelling and a deterioration in appearance and therefore marketable quality. A 3-minute dip in a cassava starch suspension reduced moisture loss. The effect is more pronounced if the dipped fruits are stored at a refrigerated temperature of 7 to 8°C in an atmosphere of at least 85 to 90% relative humidity (Maciel *et al.*, 2004).

2.4.4 Atmosphere

Cerqueira *et al.* (2009) investigated the suitability of novel galactomannans as edible coatings for several tropical fruits including acerola. Edible coatings act by creating a modified atmosphere surrounding the commodity, similar to that achieved by controlled atmosphere or modified atmospheric storage conditions. Accordingly, the modified atmosphere created by the edible coatings protects the fruit from the moment it is applied until it reaches the final consumer. However, the effectiveness of edible coatings for fruit preservation depended on the control of the wettability of the coating in order to ensure a uniformly coated surface, permeability and mechanical properties in order to decrease the water loss in the fruit, to decrease oxygen permeability (since lower oxygen concentration prolongs the shelf life by delaying the oxidative breakdown of complex substrates) and also to reduce the production of ethylene, which is a key element of the ripening and maturation process. In their study they used coatings of galactomannans from two plant species, *Adenanthera pavonina* and *Caesalpinia pulcherrima*, both from the *Leguminosae* family to determine their impact on the fruit surface properties using different galactomannan solutions at 0.5, 1.0 and 1.5% respectively with glycerol at 1.0, 1.5 and 2.0% respectively to test their wettability status. For solutions with a better wettability status, films were casted and water vapour

permeability, oxygen permeability, carbon dioxide permeability, tensile strength and elongation at break were determined. Taking into account the surface and permeability properties of the films obtained the best formulation for acerola fruits was 0.5% *Adenanthera pavonina* galactomannan and 1.0% glycerol. The authors (Cerqueira *et al.*, 2009) recommended that the formulation should be applied either by immersion or sprayed on the fruits and allowed to dry at room temperature for 3 hours.

Storage of acerola fruits coated with 1 and 2% cassava starch edible film at 10°C resulted in fruits with an increased shelf life of up to 15 days with acceptable quality characteristics. It was also found that fruits subjected to prestorage coating of a 1% cassava starch biofilm maintained the highest ascorbic acid content. Cassava starch, according to Maciel *et al.* (2004), improved the fruit's appearance. They dipped different replicates of orange-red acerola fruits at 1, 2, 3 and 4% (w/v) in a cassava starch suspension for 3 minutes and examined quality attributes during storage at 10 and 22°C and at 85% relative humidity for up to 15 days. Their results showed that the use of cassava biofilm at 1% on acerola fruits maintained the highest ascorbic acid content and the temperature of 10°C extended storage life compared to their counterparts stored at 22°C. Fruits coated with 1 and 2% cassava biofilm had acceptable quality characteristics after 15 days at 10°C (Maciel *et al.*, 2004).

The use of PVC film to reduce transpiration and the creation of a suitable modified atmosphere at 7 to 8°C and 85 to 90% relative humidity extended shelf life of fruits more effectively than fruits stored in air. Under these conditions and packaging, acerola fruits did not experience a significant reduction in juice quality yield. Also, ascorbic acid retention is higher in a modified atmosphere, compared to ambient temperature, and this was attributed by Alves *et al.* (1995) to lower oxygen availability inside the package. The effect of controlling or modifying atmosphere on ascorbic acid content depended on the crop, temperature and atmospheric gas levels and, although low oxygen helped to reduce losses, high carbon dioxide inside the package could hasten losses as reported for other fruits like bananas and apples (Watada, 1987).

2.5 Physiological disorders

2.5.1 Chilling injury

As already mentioned, fruits are susceptible to chilling when stored at temperatures below 5 to 6°C with symptom expression becoming more visible when stored in air where the relative humidity is below 85%. Major symptoms of chilling injury damage include pitting, surface discolorations and occurrence of secondary infections. The randomly scattered pits eventually coalesced upon prolonged storage below 7 to 8°C to form more distinct larger depressions characterized with dark brown discolorations on the fruit surface (Plates IIb, IIc: see colour section between pages 244 and 245). These symptoms were visible after 4 to 5 days at 4 to 5°C when stored in air, and become more severe when fruits were transferred

for an additional day at 20°C. However, under similar storage conditions, fruits sealed in low-density polyethylene bags, these symptoms were not visibly apparent and this is undoubtedly related to the saturated microenvironment and modified atmosphere created within the sealed bags (Mohammed, 1996).

2.5.2 Other physiological disorders

Other physiological disorders affect acerola fruits. They can become malformed due to damage by sucking insects or nutritional imbalances. They are also susceptible to heat injury, which can be caused by overly dense canopies on the trees, trees spaced too close together or inadequate pruning. Heat-injured fruit usually have poor colour development, scalds and are smaller than usual.

2.6 Pathological disorders and pests and their control

Fruits are susceptible to fungal diseases such as anthracnose caused by *Collectotrichum gloeosporioides*, as well as bacterial diseases such as bacterial soft rots. Leaf spotting by the fungus *Cercospora bunchosiae* is a major disease in Florida, Puerto Rico, and Hawaii. Green scurf, identified by the algae, *Cephaleuros virescens*, occurred in Puerto Rico. Sooty mould is common where the plants are not effectively spaced and pruned.

A major obstacle in the cultivation of acerola is the tree's susceptibility to the root-knot nematode, *Meloidogyne incognita* var. acrita, especially in sandy soils (Morton, 1987). The nematode can be controlled by soil fumigation, mulching and regular irrigation. The burrowing nematode *Radopholus similis* can also affect healthy trees, significantly reducing fruit yield. A number of other pests has been identified, including the wax scale insect, which attacks the foliage, and the mango scale insect, whiteflies, the leaf roller and aphids. In Guatemala, the aphid *Aphis spiraecola* attacks the leaves and young, tender branches. In Puerto Rico, the tree is also damaged by the blue chrysomelid of acerola, *Leucocera laevicollis*. Some fruits may become misshapen due to the stinkbug. The major pest in Florida is the Caribbean fruit fly, *Anastrepha suspensa*, which attacks more acidic fruits. In Guatemala, a fruit worm, *Anthonomus florus*, deposits its eggs in the floral ovary and also on the fruits. The larvae then usually feed inside the fruits causing them to become deformed. Measures taken against this predator include incineration of all fallen, infested fruits and the elimination of all related species that serve as hosts (Morton, 1987).

2.7 Postharvest handling practices

2.7.1 Harvest operations

Acerola plants originating from asexual or seed propagation begin fruiting in the first and second years respectively after planting. Fruiting occurs three to four

times a year (Alves *et al.*, 1999). In Puerto Rico, up to seven production peaks were reported (Simao, 1971). In other places such as in North East Brazil, noted for its high light intensity and temperatures, irrigated plants are known to fruit in less than a year, to produce almost continuously throughout the year.

When selecting a harvest date for acerola fruit, their intended purpose must be taken into account. When they are to be eaten as a dessert, acerola fruit should be harvested at the ripe or fully ripe stage of maturity. When they are to be processed into pulp or juice, the fruit can be harvested when they are turning from yellow to red. Red fruits are preferable since at this stage of maturation they should have reached their maximum sugar content and lowest acidity, however care needs to be taken as fruits at this red stage are more prone to physical injury and also contain less vitamin C. When fruits are to be used in the manufacture of powdered products such as pharmaceuticals or concentrates for food enrichment, for which vitamin C content is the most important characteristic, fruit should be harvested at the beginning of the period of maturation.

The tree is well known for its ability to fruit continuously over prolonged periods. Therefore harvesting can be scheduled either daily, every other day or even every three days in order to minimize losses from fallen fruits. Harvesting is usually manual and is preferably carried out in the cooler parts of the day, such as in the early morning, late evening or even during the night. Contact between the fruit and the palm of the harvesters' hands should be avoided because the heat generated from the hand may increase fruit temperature and its rate of metabolism. Fruit destined for processing can be shaken from the trees and then caught on sheets above the ground.

Maintaining the cool chain to minimize the rate of respiration is of paramount importance. Direct exposure of fruit to the sun's radiation can also result in significant losses of vitamin C (Nakasone *et al.*, 1966) and also water loss. Fruit can be protected from the sun by placing it under the canopy of the plants or in a ventilated shed until transportation to the packinghouse. Ideally, fruits should be transported in refrigerated trucks where the temperature is set at 7 to 8°C and the relative humidity is at 90 to 95%, and later subjected to room cooling to remove field heat. In the absence of such facilities fruit should be transported in covered vehicles, preferably with a light coloured canvas with adequate free space between the cover and the fruit for ventilation. Mohammed (1996) recommended transporting the fruit within 3 hours of harvest in shallow plastic crates covered with a light coloured damp cloth to minimize water loss and vitamin C loss. Transportation of fruit filled containers in the early morning or late evening or night should be encouraged in order to take advantage of cooler ambient conditions. It should also be remembered that fruits should not be stored in refrigerated rooms or in reefer containers at temperatures below 5°C because chilling injury would occur.

When mature fruits are to be sold in distant markets, they need to be packed in cartons no more than 15 cm deep, so that the weight of the upper layer does not damage the lower layers. The cartons need to be constructed with a shoulder strap so that their transfer, loading and unloading is as comfortable for the worker as

possible so that fruit damage due to excessive handling can be avoided. Whatever type of harvesting container is used, the use of plastic foam is recommended to avoid compressing fruit against the edges of the containers. Fruit containers should be stacked so that the bottom of a container is not in contact with the fruit inside the container underneath, and the boxes or crates must be arranged so that ventilation is not impaired.

2.7.2 Packinghouse practices

Upon arrival at the packinghouse, fruit should be emptied in tanks containing cold sanitized water (5 to 10 ppm of free chlorine) to remove dust, pesticides residues and debris (Mohammed, 1996). Fruits are then placed on conveyor belts and are inspected to eliminate defective fruits, such as those that are misshapen, immature, decayed or physically damaged. In the inspection procedure fruits are also graded according to uniformity in size and skin colour. Alternatively, tanks with cold water (7 to 8°C) may be used to hydrocool graded fruits. At all times the water must be chlorinated (5 to 10 ppm free chlorine) to prevent infection by fungi such as *Alternaria* spp., *Fusarium* spp., *Aspergillus* spp. and *Penicillium* spp.

2.7.3 Control of ripening and senescence

In general, ripening leads to the production of an attractive, ripe, seed-bearing fruit. The ripening stage is characterized by active cell division and expression leading to the formation of a mature fruit. Koura *et al.* (2002) provided valuable insight on hormonal influences on fruit set and control of ripening when they investigated the effects of aminoethoxyvinylglycine (AVG), an inhibitor of ethylene biosynthesis, gibberellic acid (GA_3), 4-Chloro-Phenoxy-Acetic acid (4-CPA) and 2-chlorophosphonic acid (Ethephon) on fruiting and fruit ripening of acerola fruits (Table 2.4).

Their study indicated that the untreated control fruit attained a deep red colour (a* value >30) rapidly after 2 days and fruit drop was completed after 4 to 7 days.

Table 2.4 Effects of 2-aminoethylvinylglycine (AVG) and 2-chloroethylphosphonic acid (Ethephon) applied at the start of coloration on the quality attributes of acerola fruit

Treatment	ND*	Fruit wt (g)	Juice yield/ fruit (%)	°Brix	Diameter (cm)	Colouring (%)
Control	4.8 ± 0.3	5.86 ± 3.3	46.1 ± 3.3	7.1 ± 0.6	2.46 ± 0.05	90.0 ± 8.4
Ethepon (100 ppm)	3.1 ± 0.4	5.61 ± 0.06	39.5 ± 3.1	7.4 ± 0.6	2.19 ± 0.06	72.5 ± 6.8
AVG (100 ppm)	6.4 ± 0.6	5.77 ± 0.08	45.0 ± 4.4	8.3 ± 0.07	2.29 ± 0.06	97.5 ± 1.2

Note: *The number of days from treatment day to natural fruit drop day.

Source: Koura *et al.*, 2002.

Ethephon (100 ppm) accelerated colouration and abscission: treated fruit turned a deep red colour in one to two days and abscissed completely after about three to five days. By comparison, AVG (100 ppm) delayed colour change in the fruit: treated fruit attained a deep red colour two to three days later and dropped completely after six to nine days. These results indicated that ethylene was instrumental in ripening of acerola and that AVG delayed ripening by one to two days. Furthermore, fruits treated with ethephon (100 ppm) had an 'L' value (brightness) that decreased rapidly while the 'a*' value (red) did the opposite. Accordingly, AVG (100 ppm) delayed the expression of 'a*' value compared to non-treated control fruits, and also decreased the 'L' value. Ethephon (100 ppm) in this study showed acceleration in fruit drop before ripening but increased the concentration of total vitamin C. Differences were also observed in the number of days to 50% fruit drop in relation to the degree of colouration at the time of treatment. Thus, after treatment with AVG (100 ppm) at 0 to 10% colouration, it took eight to 11 days for 50% fruit drop to occur compared to an application of 10 to 20% colouration, where six to seven days were required; and when applied at 30% colouration, four to five days passed to attain 50% fruit drop. Likewise, duration to acquire an 'a' value of more than 30 required two to three days when treated at 0 to 10% and one to two days when treated at 10 to 20 or 30% colouration. In addition, the number of days to bring the 'L' value lower than 35 was eight to nine when treated at 0 to 10% colouration, therefore, AVG treatment at an earlier stage of maturation, that is, at a lower percentage fruit colouration, also lowered the 'L' value. The three major conclusions from the study by Koura *et al.* (2002) indicated firstly, that application of AVG alone failed to achieve fruit set, and by inhibiting ethylene evolution during this period, it did not improve fruit setting nor did it prevent the formation of an abscission layer. Secondly, ethylene played an essential role in rapid fruit ripening while AVG delayed fruit ripening by one to two days. Thirdly, AVG enhanced fruit setting when combined either with 4-CPA or GA_3 and addition of AVG prior to fruit harvesting at 0 to 10% colouration increased shelf life and marketability of fruits.

The aforementioned discussion by Vendramini and Trugo (2000) and de Assis *et al.* (2001) of a decrease in vitamin C content as acerola fruits ripened, which contradicts earlier work by Davey *et al.* (2000), was in fact supported by Badejo *et al.* (2007) in their pioneering investigations at the molecular level where they examined molecular cloning and expression of GDP-D-Mannose-3", 5"-Epimerase (GMEase) during fruit ripening in acerola fruits. The high rate of cell division during fruit ripening articulated by Carrington and King (2002) may have accounted for the transcript abundance of MgGMEase (amino acid sequences of GMEase from *Malpighia glabra*) in the green unripe fruits (Badejo *et al.*, 2007). Badejo *et al.* (2007) argued that the substrate for GMEase, and GDP-mannose, available in the fruit during cell division, may not all be channelled to vitamin C biosynthesis because other mechanisms within the plant such as cell wall and L-fructose biosynthesis also required GDP-mannose, and this could lead to a reduction in the expression of MgGMEase and consequently a low vitamin C content in acerola fruit during ripening. They also provided evidence to prove that

as fruit ripening progressed, MgGMEase transcript is reduced along with vitamin C content, emphasizing that vitamin C biosynthesis in acerola may indeed follow the D-Mannose/L-galactose pathway as previously hypothesized by Wheeler *et al.* (1998). However, it is also possible that the molecule is also synthesized through the D-galacturonic acid pathway, in view of the fact that the substrate is abundant in the cell walls of all plants (Badejo *et al.*, 2007).

2.7.4 Recommended storage and shipping conditions

As fresh acerola fruits are highly perishable, it is recommended that air shipments be undertaken under refrigerated conditions at 7 to 8°C and 90 to 95% relative humidity. Fruits should be placed in low-density polyethylene bags, then in shallow cardboard cartoons and precooled at 7 to 8°C prior to loading in refrigerated containers. Shipping containers must be properly cleaned to remove decaying fruit and vegetables from previous shipments, which would release ethylene gas, promoting ripening and senescence and shortening the fruit's shelf life. Care must be taken not to mix acerola cherries, which have a climacteric pattern of respiration, with incompatible commodities during transport, particularly to overseas markets. They should ideally be shipped in separate units. Shipments in the same containers as climacteric fruits such as passion fruit, banana, plantain, mango and papaya should be avoided. Likewise, they should not be placed in containers with green leafy vegetables such as shado benni, parsley, spinach and thyme; and root crops should also be avoided because the volatiles produced by the cherries would accelerate senescence in these commodities (Mohammed, 1996).

2.8 Processing

2.8.1 Fresh-cut processing

The thin skin of acerola, the presence of a winged-type seed and, to a lesser extent, its small size limits its use as an industrial fresh-cut commodity. Enzymatic browning does not occur once it has been sliced and deseeded due to its intrinsically high vitamin C content. Porcu and Rodriguez-Amaya (2006) found that peeling of fruit reduced the level of β-carotene. Peeling also reduced the level of violaxanthin (another carotenoid) whereas levels of other carotenoids identified, including neoxanthin, lutein, β-cryptoxanthin and α-carotene, remained virtually unchanged (Porcu and Rodriguez-Amayo, 2006).

2.8.2 Other processing practices

As acerola is highly perishable, researchers have investigated many market opportunities for a diverse range of value-added, processed products. The process for production of frozen acerola is outlined below. After the fruits are washed and sorted, the selected fruits are diverted from the packaging line to a forced air

tunnel to be frozen. The duration of freezing should be as short as possible, as slow freezing can cause large ice crystals to form. These cause cell membranes to rupture, reducing compartmentalization in the fruit. The resulting increase in interaction between enzymes and substrates leads to undesirable changes such as softening and yellowing. Yellowing of frozen fruits can be avoided by forced air or hydro-cooling prior to freezing at −18°C. Fruits should be packaged immediately after the fruits have been frozen, preferably with an automatic packing machine that weighs and seals thermoplastic bags. Polyethylene bags may contain 0.5, 1, 2, 14 or 16 kg frozen fruit, according to market requirements, and are arranged inside water and compression resistant cardboard boxes (Alves *et al.*, 1999). For prolonged storage frozen fruits must be kept at −20°C. Physical, biochemical, microbiological and nutritional changes can still occur in the frozen fruit during storage depending on the duration of storage and temperature. The physical changes that begin during the initial freezing process may continue during storage, in particular water recrystallization due to the temperature fluctuations that arise from excessively frequent door opening or incoming loads with elevated temperatures. These temperature fluctuations favour the growth of the undesirable larger ice crystals at the expense of smaller ones, emphasizing the need to maintain the cold chain throughout distribution.

Maciel *et al.* (2004) assessed the effects of storage conditions on the nutritional and organoleptic properties of frozen acerola fruit, fruit pulp and jelly. Their results showed that low temperature (−18°C) storage effectively retained the vitamin C level of frozen acerola fruits and pulp. The total acidity and pH of frozen jelly (49% sucrose, 1% pectin and 50% acerola juice) remained practically constant during 180 days of storage and the product's quality remained the same. However the authors cautioned that frozen storage of acerola fruit other than those required for further processing for a period longer than 30 days should be discouraged because its sensory characteristics can be altered.

Marques *et al.* (2006) investigated the effect of freeze-drying on several quality parameters of acerola fruits such as water activity (*a*w), glass transition temperature (*T*g), vitamin C content, shrinkage and rehydration capacity. They observed that freeze-dried acerola fruits can easily be reconstituted and important parameters, such as vitamin C content, are well preserved, even in fruits processed at an intermediary stage of ripening. De Freitas *et al.* (2006) evaluated chemical, sensory and microbiological changes in non-sweetened glass-bottled acerola tropical fruit juice processed by the hot fill method and stored for 350 days under simulated retail conditions (28°C). They reported that over this period the juice maintained good microbiological stability and retained total soluble solids and SO_2 levels throughout storage. However, the juice browned slightly and increased in pH, while total carotenoids, anthocyanins and vitamin C decreased slightly.

Acerola fruits have a pectin content of 0.5 to 4.0% fresh material weight. This macromolecule is currently used in the candy industry and in the enrichment of food as dietary fibre. Pectins extracted from acerola fruits can also be used to enhance the turbidity, consistency and appearance of fruit juices (Alkorta *et al.*, 1996). In fruits, the pectin substances account for about 0.5 to 4% of the fresh

material weight. When the tissue is ground, the pectin is found in the liquid phase (soluble pectin) causing an increase in viscosity and the formation of pulp particles, whereas other pectin molecules remain bound to cellulose and this facilitates water retention (Kashyap *et al.* 2001). The enzyme pectinmethylesterase (PME) from acerola fruits can be used in the preparation of low methoxyl pectin and in the destabilization of cloud in fruit juices. However, studies reported by de Assis *et al.* (2008) showed that a PME from acerola (characterized after partial purification by filtration in Sephadex G-100) had a variety of PME isoforms, with high thermal stability. Acerola PME displayed high catalytic activity at relatively high temperatures, which induced changes in juice flavour, thereby compromising the use of PME for juice clarification.

2.9 Conclusions

Though acerola is widely accepted as having a diverse range of health, pharmacological and nutritional benefits both in its fresh and processed forms, not enough studies have yet focused on improving fundamental knowledge for rational cultivar selection, improving fruit yield, size and skin thickness and reduction in or elimination of seeds via biotechnology. Especially as marketing is strongly based on its high vitamin C content and abundance of carotenoids, there needs to be further research into the stability of these antioxidants in fresh-cut fruit, in bottled juice and even in nutraceuticals and products where acerola juice is combined with other fruit juices and manufactured into energy beverages, sport drinks and other functional food products. Existing research suggests its antifungal potential for the treatment of dermaphytic infections, its capacity to bolster immunity, to prevent formation of blood clots and to reduce the risks associated with cancers, heart diseases and other degenerative diseases, but its medicinal benefits require further exploration. Other important medicinal benefits that need further research include: the ability of its copper content to facilitate the absorption of iron in the body; the ability of acerola juice to act as a powerful solvent for inorganic calcium deposits in the body, thereby assisting in maintaining the elasticity of the body; the fruit's dietary fibre content which can provide relief from constipation by providing roughage for the enhancement of colon health, not to mention its low calory, fat and sodium content and lack of cholesterol, making it a perfect fruit for health conscious individuals.

Quality indices for acerola fruit need to be better specified, as the quality of the raw material varies and processed products are available in many forms. The pesticide residues found in acerola have not been sufficiently investigated. Maximum permitted levels of pesticides that are acceptable for local markets and for international trade must be established. Improved methods of harvesting, packaging, storing, precooling and enhancing quality and shelf life are warranted.

Research, extension and development studies on the above will expand existing markets in Japan, Germany, France, Belgium, Hungary, in the US and in Latin America especially in Chile, Uruguay and Argentina where there is growing

demand for acerola fruit for juice enrichment and where there are product development opportunities in the pharmaceutical industry. In particular, research to avoid deterioration of bioactivity must be undertaken. Particularly noteworthy is the well-established fact that acerola fruits at the immature green and green stages of maturity could be exploited as a source for pectin, a macromolecule currently used in the candy industry and in dietary fibre enrichment of foods.

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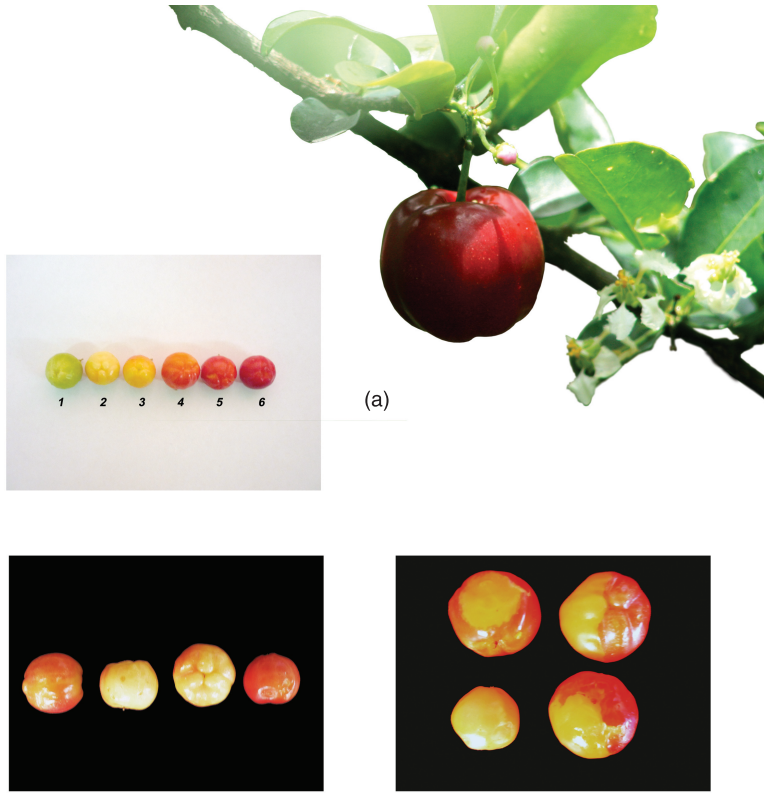

Plate II Ripening stages 1–6 of acerola cherries (a), Chilling injury symptoms of acerola fruits (b), Chilling injury with pigment degradation in acerola fruits (c). Source: Mohammed (1966).

3

Achachairú (*Garcinia humilis* (Vahl) C. D. Adam)

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Abstract: Achachairú is a Guttiferae native to oriental Bolivia, formerly *Rheedia laterifolia* L. Herzog, and now named *Garcinia humilis* (Vahl) C. D. Adam. This fairly large tree produces very good tasting fruit with a white, juicy and sweet pulp that normally contains one fairly large seed and two aborted ovules. Its weight is around 40 g. The seed is apomictic, and more than one plant can arise from it. The peel, of an orange-brown colour at maturity, is thick but somewhat brittle. The fruit is non-climacteric and fairly resistant to transport and storage. Adequate storage temperature is 12°C while 6°C results in chilling injury. Few studies have been done on its postharvest physiology and handling requirements. The success of small export quantities has raised interest in expanding production, since most of the fruit comes from wild or backyard trees, with little coming from technically conducted orchards.

Key words: Achachairú, postharvest, non climacteric, chilling injury, thick peel, apomixes.

3.1 Introduction

3.1.1 Origin, botany, morphology and structure

Rheedia laterifolia L. Herzog belongs to the Guttiferae family and grows wild in the Eastern parts of Bolivia, where it is very popular. This species has been included recently in the genus *Garcinia* of the Old World as *Garcinia humilis* (Vahl) C. D. Adam, although the flowers generally have only four sepals. According to Morton (1987) this genus comprises about 45 species that have not yet been fully defined. In Spanish it is called *achachairú*, *shashairú*, *ibaguazú*, *cachicheruqui* or *tapacuari*. Wild plants are harvested to sell the fruit in nearby towns, mainly in the city of Santa Cruz de la Sierra. There are backyard trees, many of them spontaneous, in rural areas and small plantations. Larger orchards have been started in recent years, because this fruit, that has a flavour resembling that of mangosteen, seems to have a market potential outside Bolivia. Some air

shipments of fruits from wild or semi-cultivated trees have been sent to Europe and this has created interest in starting commercial plantations (Duarte and Paull, 2008). At the 2011 fruit logistica in Berlin fruit coming from Australia was shown under the name of 'achacha'. In this region there are several relatives of this species including *Rheedia achachairú*, *R. brasiliensis*, *R. gardneriana*, *R. macrophylla*, *R. madruno*, *R. spruceana*, *R. rogaguensis*, etc. with edible fruits. These are in less demand, though, except for ocoró (*R. acuminata*), which according to Ardaya *et al*. (1995) is marketed in similar volumes.

The pyramidal canopy of the achachairú tree can grow to 6 to 12 m in height and the trunk can reach a diameter of 40 cm. The opposite, lanceolate leaves, measuring 15 to 25 by 4 to 7 cm, are shiny and slightly darker green on the upper side, with an acute apex, entire margins and a prominent central vein, while the lateral parallel veins are not very conspicuous. The developing leaves are pinkish-bronze or reddish and turn yellowish-green before maturing. Young leaves can be severely burnt by the sun or deformed, so during the initial years semi-shade has to be provided using tall annual plants such as castor bean or pigeon pea or small trees. There are about 200 hermaphrodite flowers (17 to 36 mm long, 20 to 34 stamens, 3 to 5 mm ovary, two sepals, four petals, a pedicel of about 2 cm), to each male flower (9.6 to 12.5 mm long, 26 to 28 stamens that can have a vestigial ovary and a pedicel of about 4 cm). Hermaphrodite flowers come in groups of two to five. Some trees have only male flowers. Anthesis occurs in the morning until noon and honey-bees and other insects seem to play an important role in pollination. About 57% of the flowers are self-fertilizing. The remaining fruits come from cross-pollination, thus explaining the variability found among seedlings (Ardaya *et al*., 1995).

The fruit is a berry that has a smooth but hard 2-mm thick skin, that starts out a bluish-green colour (Plate III: see colour section between pages 244 and 245) and evolves to a yellow-orange colour before ripening, ending up orange-brownish when fully ripe (Plate IV: see colour section). The ovoid fruit can measure 4.0 to 5.2 by 3.0 to 4.0 cm in height and diameter, with an average weight of about 40 g (Duarte and Paull, 2008).

By weight the fruit is 40% edible pulp, 47% peel and 13% seeds (Duarte and Paull, 2008). The fruits are found inside the canopy. They contain normally one large seed and two aborted ovules. Seeds are cylindrical, brown-coloured measuring 3.0 to 3.4 by 1.5 to 2.0 cm. They can have one to three nucellar embryos plus the sexual embryo, and if split into two pieces each seed can give rise to a plant. Seed size and number are related to fruit size.

3.1.2 Worldwide importance and economic value

This species is grown basically only in Bolivia. Some small plantings have been started in Honduras, Guatemala, Colombia, among other countries, but they amount to very little area, so essentially Bolivia is the only important producer. Production still comes mainly from wild trees or small backyard plantings, although in recent years some commercial plantations have been started due to the potential of this fruit as an export product.

No exact statistics exist on production or planted areas. It is estimated that these new plantings amount to less than 1000 hectares. A 15-year-old tree can produce 2000 to 3000 fruits and some reports indicate production levels of up to 7000 to 8000 fruits for 50-year-old trees. It is estimated that an adult plantation can produce about 19.6 tons per hectare (Ardaya *et al*., 1995).

3.1.3 Culinary uses, nutritional value and health benefits

This fruit is basically eaten fresh out of the hand. The peel is split in two with the thumbnails and one half removed leaving the white flesh containing the seed(s) exposed, that can be removed with the fingers, a spoon or the teeth. Some of the pulp is used to make ice cream or juice. There are no other industrial uses for this fruit. The peel can be put in a blender with water and sugar to make a nice drink.

The fresh pulp, according to Ardaya *et al*. (1995) contains 83.9% water, 0.4% protein, 0.5% fat, 14.2% total carbohydrates, 0.6% fibre and 0.3% ash. There are no reports about the specific properties of the fruit or medicinal uses. There is no information on special nutritive elements either, but it is a very well-flavoured fruit.

3.2 Fruit development and postharvest physiology

3.2.1 Fruit growth, development and maturation

The fruit will grow to maturity in about five to six months depending on temperatures. The fruit starts out as a very small, round, green-coloured ovary that becomes ovoid and becomes a bluish-green colour. As already mentioned, as ripening approaches the colour turns yellow and later orange-brown, until it is almost light brown when overripe. Not much else has been studied about this fruit.

3.2.2 Respiration, ethylene production and ripening

The fruit is non climacteric since it will not continue to ripen properly after being harvested at the unripe stage. No data on ethylene or carbon dioxide production after harvest are available.

3.3 Maturity and quality components and indices

Maturity is normally determined by the colour of the fruit only, and coincides with the best flavour condition, although no formal maturity indices exist. The fruit should have passed beyond the yellow colour and become orange with a brownish tint in order to be harvested. No other maturity indices are currently taken into consideration.

3.4 Preharvest factors affecting fruit quality

Lack of soil moisture reduces the fruit size, although the fruit's flavour can be enhanced by the resulting higher concentration of sugars. Mechanical damage

caused by rubbing leaves or branches will also reduce quality, mainly because it affects the fruit's appearance.

3.5 Postharvest handling factors affecting quality

3.5.1 Temperature management

Storage at very low temperatures can damage the fruit. Storing the fruit at 6°C will result in chilling injury.

3.5.2 Physical damage

Mechanical injury will also result in blackening of the damaged area, and as a consequence rotting will follow.

3.5.3 Water loss

Although water loss does not happen very fast, the fruit will eventually shrivel and reduce in weight.

3.5.4 Atmosphere

Not many results have been published of studies in this area. Poly vinyl chloride (PVC) wraps had a positive effect on extending fruit life after harvest (Duarte and Castedo, 2005). More research is needed on plastic films, waxes and other liquid coatings. These may have a positive effect as atmosphere modifiers and in reducing water loss.

3.6 Physiological disorders

As already mentioned, chilling injury has been found in achachairú held at 6°C, which indicates that it behaves as a tropical fruit.

3.7 Pathological disorders

Rotting of the peel will eventually occur after harvest if damage has occurred (for example if the fruit was roughly handled before or after harvest) or if it has been stored when wet.

3.8 Insect pests and their control

Fruit flies can attack very mature fruits and therefore fruits should be harvested as soon as they reach the right colour. The usual fruit fly control measures should be

used, together with a lure like hydrolyzed protein or sweet solutions of molasses or brown sugar and a contact diptericide, to eliminate the flies that arrive to the treated areas of the trees attracted by the lure. Not many other pests are of importance.

3.9 Postharvest handling practices

Few studies have been conducted on the best handling practices for this fruit. Avoiding of bruises and rough handling will help prolong fruit life after harvest.

3.9.1 Harvest operations

Harvesting is normally done by hand. People climb the trees in order to pick the fruit with the hands. No special tools are normally used to detach the fruit and in many cases fruit are dropped onto the ground, which increases quality deterioration postharvest.

3.9.2 Packinghouse practices

Commercial packinghouse operations are not in place for this fruit. If fruits are muddy, they are washed or rubbed with the hands but they are not cleaned, sorted precisely or carefully packaged. Sometimes they are classified by size, normally into three or four categories, just by looking at the fruit. They are normally packed into wooden crates, cardboard boxes and even polypropylene sacs. On arriving at the place of sale no special storage conditions are usually available and in many cases street vendors keep the fruit in carts in full sun or under an improvised plastic shade in the streets.

3.9.3 Control of ripening and senescence

No coating, waxing or plastic wrapping is normally used. The fruit is not even refrigerated when selling to the local markets.

3.9.4 Recommended storage and shipping conditions

Duarte and Castedo (2005) found that storage at 12°C combined with packing in trays wrapped in poly vinyl chloride (PVC) film was the best treatment, extending storage life to three weeks, but they did not investigate the effect of varying the temperature. The use of different temperatures, wraps or coatings and their combination, as well as other techniques, should be investigated in the future.

The fruit can last at least one week in room conditions for fresh market use and two to three weeks for industrial use (ice cream, refreshments). Fruits will shrivel and lose firmness but will not rot, unless they are kept wet in plastic bags or have been previously damaged.

3.10 Processing

It would be difficult to prepare fresh-cut achachairú. Presenting the fruit peeled with the pulp around the seeds could be an interesting possibility, however, since peeling and removing the whole inner part is very easy and the pulp around the seeds stays firm. Oxidation could be a problem, though, and would need to be prevented.

Industrial processing is performed on a very limited scale. In terms of domestic processing, some people separate the pulp from the seeds to prepare juice in a blender or make ice cream. In some cases the fruit peel is put in the blender with water and sugar and a fairly tasty drink is prepared. The fruit is not normally canned. It is sometimes frozen at home or in cottage industries so that the pulp can be kept for juice or ice cream preparation after the harvest season is over.

3.11 Conclusions

This is a very flavoursome fruit that is starting to become known outside of its place of origin. It has been exported to Europe on a small scale over the last 20 years. The flesh is very tasty and the fruit peel is very tough and resistant but will shrivel and eventually rot. The main defect of this fruit is the large size of its seeds that comprise one-third to almost one-half of the fruit cavity. Its fine taste creates the potential to expand production, but a marketing campaign will be required to make the fruit well-known in new markets. The plant and the fruit are not attacked by many insects and diseases.

If exports are increased, commercial plantations will have to be started, appropriate plant materials selected, propagation methods revised and plantings managed adequately, as when growing any important fruit crop. This will improve quality and yield, and the interested markets could be satisfied and even grow in the future. Postharvest handling should be improved by avoiding rough handling of the fruit, keeping it shaded and wrapping it in PVC or using a coating agent. The use of refrigeration would markedly improve the storage life of this fruit.

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Plate III Young achachairú fruits showing their green-bluish colour, their position inside the canopy and typical leaves.

Plate IV Ripe achachairú fruits showing the sweet pulp, the thickness of the peel and the seed size.

4

Ackee fruit (*Blighia sapida* Konig)

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Abstract: The ackee (*Blighia sapida*), a tropical fruit belonging to the *Sapindaceae* family, has its origin in West Africa but has traversed the Atlantic Ocean, making the Caribbean (where it grows wildly and is also cultivated) its home. The colloquial name Ackee is derived from the terms 'anke' and 'akye-fufuo', which are used to describe the fruit in West Africa. It was named *Blighia sapida* in honour of the infamous Captain William Bligh who transported the fruit from Jamaica to England in 1793. Although Ackee fruit was first known for its poisonous properties, it is nowadays considered one of the major fruits consumed in Jamaica and is an ingredient of the national dish Ackee Saltfish. Extensive literature exists on hypoglycin A, the toxic compound of unripe Ackee, while no referenced data are readily available on its physiology and reports are very limited on its biochemistry. The aim of this chapter is to fill this gap moderately, and give an overview on the fruit as fresh and commercial produce.

Key words: *Blighia sapida*, ackee, maturity, biochemistry, composition.

4.1 Introduction

4.1.1 Origin and history

The Caribbean region accounts for not more than 0.03% of the total world's lands, however, the region is rich with a wide range of species and varieties of plants. More than 2% of the total number of plant species in the world is endemic and found in this region, and some species are found only in Jamaica (Adams, 1972). It is established that ackee is indigenous to the forests of the Gold Coast of West tropical Africa where it is not consumed much, but various parts of the Ackee tree have been put to domestic use. In Ghana, for example, the fruiting tree is considered ornamental, and trees are planted for shade. The ackee fruit was brought to Jamaica in 1778 to furnish food for slaves. In 1793 the fruit was brought to England by the renowned Captain Bligh, and named *Blighia sapida* in 1806 by Koening in honour of Captain Bligh. It was readily adopted and became commonly grown in dooryards and along

roadsides and, to some extent, naturalized. The arils still constitute a favourite food of the island and the fruit is featured in a calypso despite the health hazards associated with it. Ackee trees are found throughout Jamaica: however, most of the trees grow in the Clarendon and St Elisabeth parishes.

The ackee was planted also in Trinidad and Haiti and elsewhere in the West Indies and the Bahamas, and apparently was carried by Jamaican slaves to Panama and the Atlantic Coast of Guatemala and Costa Rica. In 1900 it was outlawed in Trinidad after it had caused some fatalities. There are scattered trees in Surinam, Venezuela, Colombia, Ecuador and Brazil, quite a number maintained as curiosities in southern Florida, and some are planted around Calcutta, India. The tree has been tried in the warm, moist climate of Guyana and Malaya but when planted at Lamao in the Philippines in 1919, the trees did not bear fruits in the first fruiting season although they did so in the following years.

4.1.2 Botanical description

The ackee tree is tropical evergreen with a yellow-red fruit that is about 10 cm wide and weighs 100 g. As the ackee fruit ripens, the colour of the fruit changes from green to yellow, to yellow-red, and then to red when the fruit is fully open showing the yellow arils and black seeds. When ripe, the fruit splits longitudinally into three sections to reveal glassy black seeds in each section surrounded by a thick yellow oily, fleshy portion. This is the aril, which is edible and has a nutty flavour (Barceloux, 2008).

Ackee fruit belongs to the family *Sapindaceae*, and is also known as the ackee apple, or vegetable brain (*seso vegetal* in Spanish) (Plate V: see colour section between pages 244 and 245). Other Spanish names for ackee are also used such as: *arbol de seso* and *palo de seso* (in Cuba); *huevo vegetal* and *fruto de huevo* (in Guatemala and Panama); *arbol del huevo* and *pera roja* (in Mexico); *merey del diablo* (in Venezuela); *bien me sabe* or *pan y quesito* (in Colombia) and *akí* (in Costa Rica). In Portuguese, ackee is called *castanha* or *castanheiro de Africa*. In French, it is named *arbre fricassé* or *arbre à fricasser* (in Haiti); *yeux de crabe* or *ris de veau* (in Martinique), while in Surinam it is known as *akie*. In Africa, from where it is supposed to have originated, ackee is called *kaka* or *finzan* (in Côte d'Ivoire), *abd finza* (in the Sudan), while in other African regions ackee is generally known as *akye*, *akyen* or *ishin*, because of the many dialectal names. The colloquial name, ackee, is derived from the terms *anke* and *akye-fufuo*, which are used to describe the fruit in West Africa. It was named *Blighia sapida* in honour of the infamous Captain William Bligh, who transported the fruit from Jamaica to England in 1793.

In Jamaica, two types of ackee are recognized – 'cheese', or hard, and 'butter', or soft. The 'cheese' ackee aril is hard, cream coloured and retains its shape when cooked, while the 'butter' ackee aril is soft and yellow, losing its shape easily during cooking. The ripe fleshy ackee aril is widely consumed by Jamaicans. It is one of the national dishes, and is considered as one of the national symbols in Jamaica. The unripe fruit contains a water-soluble toxin, hypoglycine A (L-aminomethylenecyclopropylpropionic acid), and the less toxic hypoglycine B.

The latter compound is the -glutamyl conjugate of hypoglycine A. Unripe akee fruit also contains glutamate analogs that are carboxycyclopropylglycine compounds (Natalini *et al.*, 2000). To prevent toxicity, the seeds and husk of the ackee fruit must be carefully removed and the aril thoroughly washed and cooked before consumption. Cooking arils of unripe ackee fruit does not destroy the toxins, whereas cooking effectively arils of ripe fruits eliminates the toxicity by leaching hypoglycine A (McTague and Forney, 1994; Golden *et al.*, 1984).

4.2 Toxicity of ackee fruit

Although ackee fruit was first known for its poisonous properties, it is nowadays considered one of the major fruits consumed in Jamaica. The toxicity of ackee fruit has been associated with the consumption of unripe fruit since the late nineteenth century (Scott, 1916). Between 1880 and 1955, a variety of case reports associated the ingestion of ackee fruit with vomiting, generalized weakness, altered consciousness and death, including an epidemic of 151 cases and 32 deaths during 1954 near Montego Bay, Jamaica (Feng and Kean, 1955; Feng, 1969). Hassall and Reyle (1954) first isolated the two toxic constituents (hypoglycine A and B) from the arils and seeds of unripe ackee in 1954 (Fig. 4.1). In 1976, Tanaka *et al.* confirmed the ingestion of hypoglycine A from unripe ackee fruit as the cause of Jamaican vomiting sickness. An extensive literature exists on the toxicity of hypoglycine A (Billington *et al.*, 1978; Henry *et al.*, 1998; Joskow *et al.*, 2006; Sherratt, 1986).

A number of other metabolites have been isolated from the ackee fruit. While not as biologically interesting, the compounds are unusual in their structure. Blighinone, a sparingly soluble quinone was isolated from the arilli of the fruit (Garg and Mitra, 1968). Vomifoliol, has been isolated from the leaves and stems of the plant and has been implicated in the endogenous regulation of stomatal aperture (Stuart *et al.*, 1976). More recently, another non-proteinogenic amino

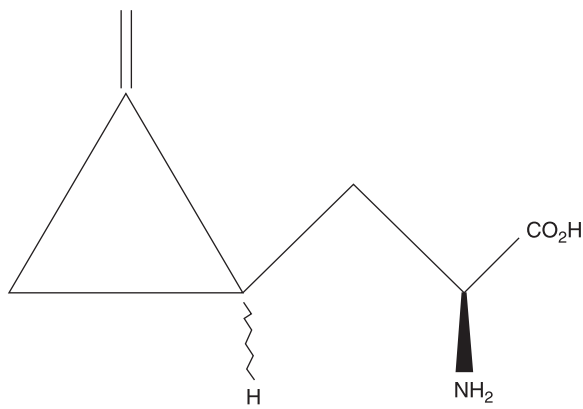

Fig. 4.1 Structural composition of hypoglycine A.

acid (2S, 1'S, 2'S)-2-(2'-carboxycyclopropyl), glycine (CCG 1), was isolated from the fruit (Natalini *et al.*, 2000). It is similar in structure to hypoglycine A with respect to the presence of a cycopropane ring structure, which is a rare occurrence in nature.

From the toxicological point of view, metabolism of hypoglycin yields methylenecyclopropylacetyl-CoA (MCPA-CoA). The Acyl-CoA dehydrogenase accepts MCPA-CoA as a substrate, removing a proton from the a-carbon to yield an intermediate that irreversibly inactivates acyl-CoA dehydrogenase by reacting covalently with FAD on the enzyme (Corredor *et al.*, 1967; Schulz, 1991; Yasuyuki and Tanaka, 1990). However, other research reported that methylenecyclopropylacetyl-CoA severely inhibits not only acyl-CoA dehydrogenase I (butyryl-CoA dehydrogenase, EC 1.3.99.2) but also acyl-CoA dehydrogenase II (octanyl-CoA dehydrogenase, EC 1.3.99) (Kunau and Lauterbach, 1978).

Moreover, the effect of methylenecyclopropane-pyruvic acid (a toxic amino acid occurring in the ackee and a metabolite of hypoglycine) on gluconeogenesis *in vitro* was studied. It was noted that glucose production from a variety of precursors was found to be markedly inhibited, the agent being active at low concentrations (0.1 mM). The site of the block was located specifically at the fructose 1,6-diphosphatase reaction; however, the mechanism by which this effect is achieved is not known (Kean and Rainford, 1973).

4.3 Fruit maturity

The ackee takes seven to eight weeks to attain full maturity. During weeks two to three of fruit development, the fruit doubles in size, after which it increases at a much slower rate (Stair and Sidrak, 1992). At full maturity the fruit are pear-shaped and acquire a red or yellow tinge with red colouration. The pods then open revealing the seeds and three fleshy arilli, and fruits are considered safe for consumption only at this stage of maturity (Plate VI: see colour section between pages 244 and 245) as reported by Kean and Hare (1980) and described below (see section 4.4). It has been hypothesized that during fruit maturity hypoglycine A is translocated from the arils to the seeds of the fruit (Plate VI: colour section), where it is converted to the dipeptide hypoglycine B. As the fruit matures the concentration of hypoglycine B in seeds increases from 0.40 mg g^{-1} to 3.30 mg g^{-1}. (Kean and Hare, 1980). Hypoglycine B is found only in the seeds of the fruit. It also possesses hypoglycemic activity but is less potent than hypoglycine A. Brown *et al.* (1991) analyzed ackee fruits with different range of maturities, and found that hypoglycine A contents in the arils dropped from over 1000 ppm to undetectable (<0.1 ppm) as the fruit matured (i.e., pod coloured up, split and opened fully). However, at all stages the seed contained appreciable levels of hypoglycin A (~1000 ppm). Yet there is no available reference reporting whether ackee fruit is climacteric or not. Thus, and in practice, ackee fruit is always harvested at the ripe stage when the pods open and the arils are well visible.

4.4 Biochemical composition

Despite its importance in the local diet, there are few data reporting the biochemical composition of ackee fruit. As shown in Table 4.1, ackee fruit contains high proportions of fatty acids, carbohydrates and proteins, and is quite rich in fibres and other vitamins and minerals. Mitchikpe (2007) reported close values and found that ackee arils contain 12.1, 46.2, 20.0 and 17.4 g 100 g^{-1} dry matter of proteins, fats, carbohydrates and fibres, respectively.

Recently, some physiological and biochemical studies have been conducted on ackee, and it was reported that total sugars increased during the first four stages of ripening and decreased during the last stage of ripening (Fig. 4.2a). However, reducing sugars increased progressively during the five investigated ripening stages (Fig. 4.2b) (Emanuel and Benkeblia, unpublished data).

Recent research also reported that the level of total phenolic compounds is somewhat high in the arils of green ackee fruits, but decreases by 30% during the ripening. The level of total phenolic compounds ranged from 10.59 mg g^{-1} fresh weight at stage 1 to 7.38 mg g^{-1} fresh weight at stage 5 (Fig. 4.3a). The level of anthocyanins in arils showed a similar pattern, decreasing by 95% during ripening. Levels ranged from 2.30 mg g^{-1} fresh weight at stage 1 to 0.10 mg g^{-1} fresh weigh at stage 5 (Fig. 4.3b) (Emanuel and Benkeblia, unpublished data).

Oladiji *et al.* (2009) analyzed the physicochemical properties of the oil from ackee fruit. They found that the fruit oil yield was 20.02%, and consisted of 22.22% saturated, 56.43% monounsaturated, and 21.35% polyunsaturated fatty acids. They also noted that oil is rich in behenic, palmitoleic, oleic, gadoleic, erucic, and 9,12-eicosanoic acids. Odutuga et al. (1992) analyzed the fatty acid composition of arils at four different stages and found that lipid content was

Table 4.1 Nutritional value of raw edible arils of Ackee fruits

	In 100 g fresh weight
Moisture	57.60 g
Protein	8.75 g
Fat	3.45 g
Fibre	9.55 g
Carbohydrates	1.87 g
Ash	83 mg
Calcium	98 mg
Phosphorus	5.52 mg
Iron	–
Carotene	0.10 mg
Thiamine	0.18 mg
Riboflavin	3.74 mg
Niacin	65 mg
Ascorbic acid	

Source: Anon., 1990.

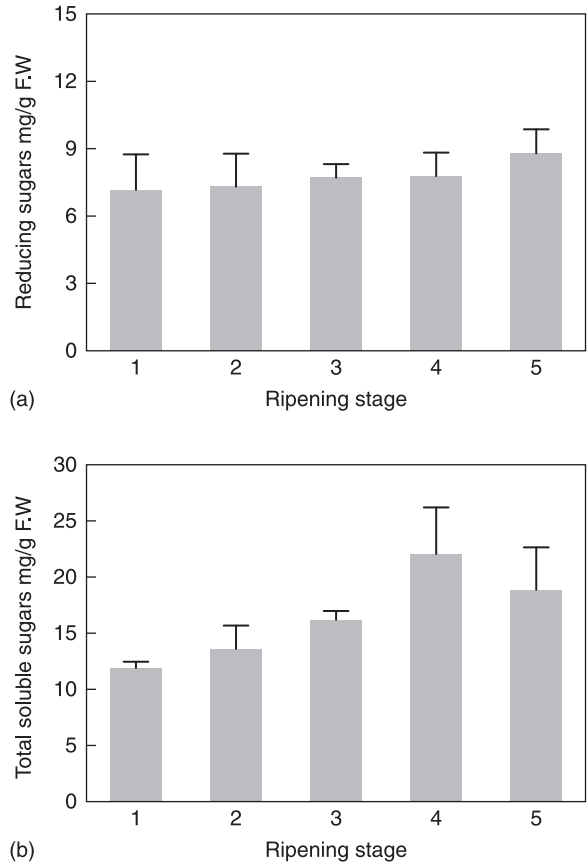

Fig. 4.2 Variation of total (a) and reducing sugars (b) in arils of ackee fruits during the five ripening stages. Source: Unpublished data.

higher in arils of fruit opened in sun. Palimitc (16:0), stearic (18:0), and linileic (18:1) acids were the predominant fatty acids. They also analyzed the content of total proteins and noted that a high content (31.8 g $100g^{-1}$ dry weight) was measured in arils opened on the tree.

4.5 Food and other uses

Although cooked in different ways, the most common method of cooking arils is as follows. The ackee must be 'yawned' (seed and internal median pink tissue removed), then the seeds are discarded and the arils, while still fresh and firm, are best parboiled in salted water or milk and then lightly fried in butter. The arils are also cooked with codfish, onions and tomatoes and are also added to a stew of

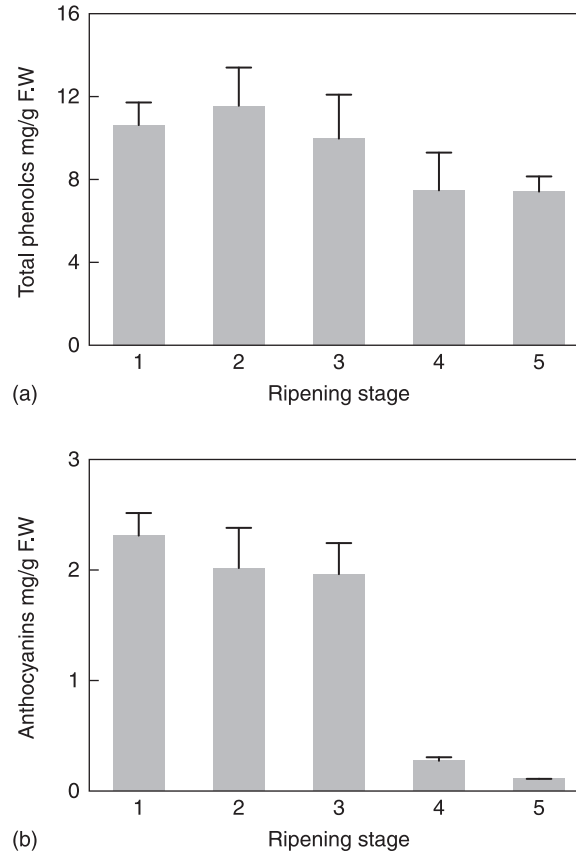

Fig. 4.3 Variation of total phenolic compounds (a) and anthocyanins (b) in arils of ackee fruits during the five ripening stages. Source: Unpublished data.

beef, salt-pork and scallions, thyme and other seasonings, after parboiling. In addition, they are sometimes curried and eaten with rice.

Beside these culinary uses, ackee fruits are also used for other purposes. The green fruits producing a lather in water are used for laundering, while crushed fruits are employed in fishing and used as fish poison. Because the seeds have high oil content and their jackets contain potash, they are burned and the ashes are used in making soap. In Cuba, volatiles are extracted from flowers and used in making perfume and appreciated as cologne. The bark is pulverized and mixed to ground hot peppers, and the mixture is rubbed on the body as a stimulant. From the tree, the sapwood is white or light greenish-brown. The heartwood is reddish-brown, hard, coarse-grained, durable, and immune to termites. It is used locally for construction and pilings and has been recommended for railway sleepers. It is also fashioned into oars, paddles and casks.

In traditional medicines, Brazilians use repeatedly administered small doses of an aqueous extract of the seeds to expel parasites, and the treatment is followed by a saline or oily purative. Cubans blend the ripe arils with sugar and cinnamon and use this mixture as a febrifuge and as well as a treatment for dysentery. In Côte d'Ivoire, the bark is mixed with pungent spices in an ointment and used as pain reliever. The crushed new foliage is applied on the forehead to relieve severe headache, while leaves crushed with salt are poulticed on ulcers. Moreover, the leaf juice is also employed in ophthalmia and conjunctivitis as eye drops. In Colombia, the leaves and bark are considered stomachic, and various preparations are made for treatment of epilepsy and yellow fever. More recently, a feeding trial to evaluate the potential of *Blighia sapida* leaves as a dry-season feed resource for West African dwarf goat in the derived savannah zone of Nigeria was carried out. The results showed that the animals did not show any negative reaction to the experimental diets; therefore, *Blighia sapida* leaves could be used as a major feed resource during this dry season to reduce the effect of feed shortage and enhance the poor quality of available grasses and crop residues (Aderinola *et al.*, 2007).

4.6 Processing

Because of its content of the toxic compound hypoglycine A, ackee arils were subjected to marketing and export restrictions. However, following recent toxicological and biochemical studies, which demonstrated that toxicity of ripe ackee is extremely low should the arils be consumed, a technological process of arils canning was developed (US Patent 1982967B1). The process consists of mixing 26 to 36 whole or diced arils with 1.5% brine and then canning and sealing the product. The cans are sterilized at 210°C for 15 min. The temperature should be strictly below the boiling point so that the canned arils remain firm and retain good flavour (Fig. 4.4). The canned arils are exported to the United Kingdom and USA, where they are welcomed by Jamaican immigrants and autochtons.

4.7 Economic importance

The canned arils of ackee fruit are a major export product from Jamaica. In 2005 the ackee industry on the island was valued at J$ 400 million (c. US$ 6.5 million). The importing of canned ackee into the USA has at times been restricted due to unripe ackee arils being included. However, it is currently allowed, provided that the amount of hypoglycine A present meets the standards of the FDA. The FDA considers a concentration of 100 $\mu g.g^{-1}$ (or 100 ppm) as the public health 'level of concern' (LOC) for evaluating Ackee imports. In 2006 the FDA, which issued the original recalls, approved the resumption of imports under new screening procedures starting in July. Jamaica seeks to find a niche in growing exotic foods such as the savoury ackee fruit to market in the USA and continues to export ackee to the United Kingdom and Canada, where there are large communities of Jamaicans (Anon., 2006).

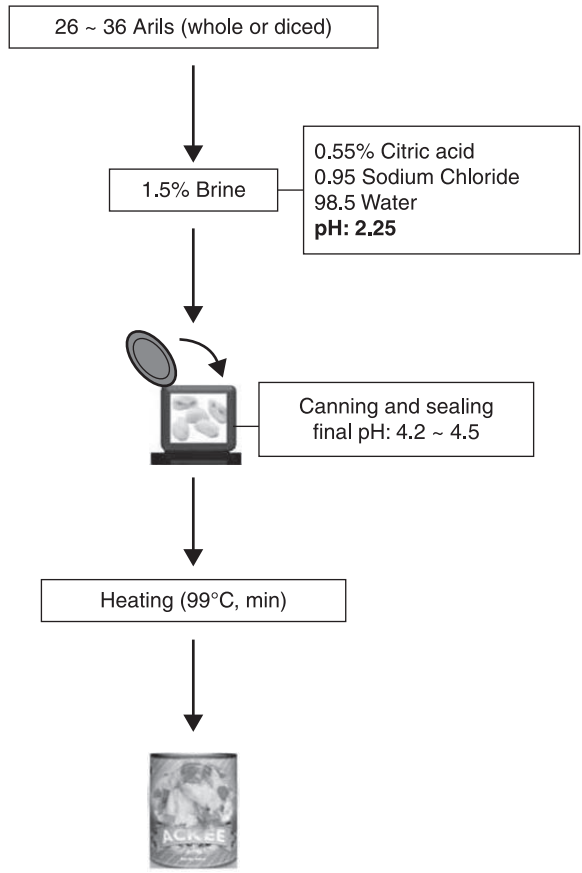

Fig. 4.4 Technological process of canning and sterilization of ackee arils. Source: US Patent.

4.8 Conclusions

Jamaica is the only place where the ackee fruit is generally recognized as an edible crop, although this tree grows in most of the other Caribbean islands, where it is known by different names and does not thrive in economic quantities. Ackee has the potential to be a valuable crop and to generate a consistent income for small farmers and the rural population. Due to its high yield, the lack of disease reported on trees or fruits, its long and multi-fruiting seasons, and its simple processing technique, the development of canned ackee for both local and international markets would be beneficial for the local population and the Jamaican economy. Because this fruit is not only associated with Jamaican cuisine, but also with the history of the country, it should attract further interest. It also has the potential to compete with other 'exotic' fruits on the basis of quality rather than quantity, as

does Jamaica's famous Blue Mountain coffee. However, much work needs to be undertaken to understand its physiology, biochemistry and postharvest features.

4.9 Acknowledgements

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(a)

(b)

Plate V Ackee fruits on tree (a), and ripe open ackee showing husk, arils and seeds (b).

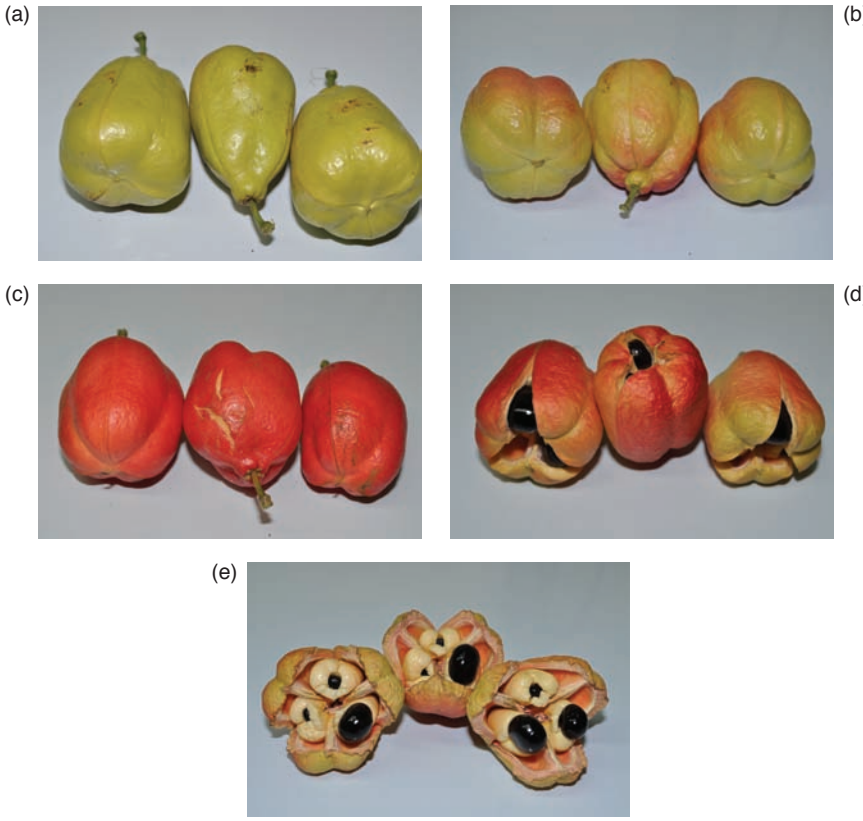

Plate VI The ripening stages of ackee fruits.

Plate VII Aonla tree.

5

Aonla (*Emblica officinalis* Gaertn.)

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Abstract: This chapter presents and reviews the medicinal, chemical and physical properties of aonla fruit and its wide range of uses. Fruit growth and development, preharvest factors affecting postharvest quality, postharvest handling, physiology, postharvest disorders, insect pests and diseases of aonla fruit are described and discussed. Finally, information on processing and food, medicinal and cosmetic processed products of aonla fruit is provided.

Key words: *Emblica officinalis*, postharvest, physiology, technology, processing.

5.1 Introduction

Aonla or Indian gooseberry (*Emblica officinalis* Gaertn.) is one of the most important traditional and underutilized fruits of Indian origin, having immense potential for cultivation on marginal or wastelands. It belongs to the family Euphorbiaceae and sub-family Phyllanthoidae. Aonla trees thrive throughout the tropical and subtropical parts of India, found either growing wild or cultivated. Aonla is quite hardy, a prolific bearer and highly remunerative even without much care. It can be grown easily on calcareous and slightly saline as well as alkaline soils where common fruit crops do not thrive.

Aonla is regarded as sacred by Hindus and has great mythological significance. According to Hindu mythology, a meal should be taken beneath an aonla tree during *Kartik* (October) when trees are laden with fruits. The Hindu religion also prescribes that ripe fruits of aonla be eaten for 40 days after fasting in order to restore health and vitality, known as *Kaya Kalp* (Benthal, 1946).

The fruit is highly nutritious and it is the next richest source of vitamin C among fruits after Barbados cherry (Asenji, 1953). The edible fruit tissues of aonla contain about three times more protein and 160 times more vitamin C than apple (Barthakur and Arnold, 1991). Normally, a single aonla fruit contains 20 times more vitamin C

in terms of antiscorbutic value as two oranges, containing 500 to 1500 mg of ascorbic acid per 100 g of pulp. The fruit contains leucoanthocyanin or polyphenols, which retard the oxidation of vitamin C and presence of astringency (Sastry *et al.*, 1958; Singh *et al.*, 1993). Hanif *et al.* (1966) noted a marked antioxidant effect of gallic acid present in aonla fruits.

The fruit also contains a considerably higher concentration of minerals and amino acids than apple. Glutamic acid, proline, aspartic acid, alanine and lysine are 29.6, 14.6, 8.1, 5.4 and 5.3%, respectively, of the total amino acids. The main constituents of aonla are tannins, polyphenolic compound 1,3,6-trigalloylglucose, terehebin, corilagin, phyllantnic, beta siotostural, linolic acid, ellagic acid, and lupeol. Aonla is a rare example of an edible material that is rich in tannins as well as ascorbic acid (Pathak, 2003).

Tannins containing gallic acid, elagic acid, and glucose retard the oxidation of vitamin C and renders its value as antiscorbutic in the fresh fruit as well as in dried products. Aonla is also a source of carbohydrates, carotene, thiamine, riboflavin, and minerals like iron, calcium and phosphorus. It is valued for its antiscorbutic, diuretic, laxative (Nadkarni, 1954), antibiotic (Ray and Majumdar, 1976), acidic and cooling properties (Singh *et al.*, 1993). Dried fruit is considered useful in treating haemorrhage, diarrhea, chronic dysentery, diabetes, jaundice, dyspepsia and cough. Aonla is the main ingredient in the popular Ayurvedic medicines *chavanprash* and *triphla*.

Aonla may be an important fruit of the future due to its high medicinal and nutritional value, high productivity per unit area and suitability for production even in areas considered to be wastelands, particularly in salt-affected soils. It has immense scope for processing and value addition as the fruits are not consumed fresh or in the raw state, as they are highly acidic and astringent.

5.1.1 Origin, botany, morphology and structure

Aonla (*Emblica officinalis* Gaertn syn. *Phyllanthus emblica* L.) also known as Indian gooseberry, is one of the traditional fruits indigenous to India. Of the related species *Phyllanthus acidus* Skeel syn. *P. distichus* Mnella, popularly known as otatheite gooseberry, star gooseberry or country gooseberry, is mostly grown for ornamental purposes, whereas the wild species, *Emblica fischery* Gamble, syn. *P. fischery*, found in the forest of South India, bears fruit suitable for traditional pickle making. It belongs to Euphorbiaceae family and includes about 350 (Hooker, 1937) to 500 species (Bailey, 1917). *Emblica* is highly branched, grows to 9 to 12 m high, with seedling trees capable of growing to a height of more than 20 m (Plate VII: see colour section between pages 244 and 245). It is deciduous under north Indian conditions, however, it is considered as evergreen in the tropics (Bajpai, 1968). Its bark is usually light brown to black with thin strips or flakes exposing the fresh surface of a different colour underneath the older bark. The average girth of the main stem is about 70 cm and in most cases, the main trunk is divided into 2 to 7 scaffoles very near the base. The leaves are 10 to 13 mm long, 3 mm wide closely set in pinnate fashion, making the branches

feathery in general appearance. Aonla trees bear two types of shoots, i.e. long or indeterminate and short or determinate (Ram, 1971). Flowers are unisexual, pale green, 4 to 5 cm in length, born in the leaf axis of clusters of six to ten staminate flowers, tubular at the base having a very small stalk. They are gamosepalous with six lobs at the top, one to three stamens, polyandrous with 2-mm long filaments. The pistillate flowers are fewer, with a gamopetalous corolla amid a two-branched style. Both staminate and pistillate flowers are born on the same branch, but staminate flowers occur towards the apices of small branches.

Physical characteristics

Aonla fruits are round, ribbed and pale green, divided into six segments. The surface of the fruit is shiny, the size varies from that of a marble to a large plum, and it is quite hard with a thin and translucent skin (Plate VIII: see colour section between pages 244 and 245). The raw fruit, due to its high acidic nature and astringent taste, is considered unacceptable for fresh consumption. The average fruit weight and seed weight varies from 22 to 25 and 1.5 to 1.8 g, respectively among 'Krishna', 'NA-7' and 'Chakaiya' cultivars (Goyal *et al.*, 2007). The seed:pulp ratio is reported to vary from 1:15 to 1:22 (Kalra, 1988).

Goyal *et al.* (2007) studied the physical and mechanical properties of aonla fruits of three cultivars, 'Krishna', 'NA-7' and 'Chakaiya', and concluded that the average length, diameter and sphericity of the aonla fruits ranged from 3.12 to 3.24 cm, 3.44 to 3.60 cm and 1.04 to 1.10 cm, respectively. Mass, volume and true density of the fruits from the cultivar 'Chakaiya' was higher than the other fruits. The rolling resistance of the fruits in radial orientation was less than in the vertical orientation. The size of the seeds ranged from 1.3 to 1.5 cm. The initial surface hardness ranged from 12 to 17 Newton.

5.1.2 Important cultivars

'Banarasi', 'Chakaiya', 'Francis', 'Kanchan', 'Krishna', 'NA-6', 'NA-7', 'NA-8', 'NA-9', 'NA-10', 'Gujarat-1', 'Gujarat-2', 'Laxmi-52', 'BSR-1' and 'Goma Aishwarya' are important cultivars developed at various institutes in India (Pathak *et al.*, 1993; More *et al.*, 2008). The salient features of some of these cultivars include:

1. **Banarasi:** The tree has a spreading growth habit. The fruits are large in size (48.2 g), conical at apex, lobed. Skin is smooth, thin, semi-translucent and whitish-yellow or straw yellow in colour, and segments are raised in three parts with six strips. Flesh is whitish green, fibre content is 1.3 to 1.5%. Fruits have poor keeping quality. 'Banarasi' is a shy bearing cultivar with a high sex ratio, not suitable for commercial growing.
2. **Chakaiya:** It is a seedling selection with a tall, upright growth habit. Fruits are small to medium size (33.4 g), flattened and whitish-green in colour. Segments are six in number and intact. Flesh is whitish-green, fibre content is high (2%), ascorbic acid content is 750 to 800 mg 100 g^{-1} and pectin content averages 3.4%. The fruits have strong attachment, so premature dropping is

not a problem in this cultivar. Keeping quality is moderate. Very suitable for making pickles and shreds for drying.

3. **Krishna:** This cultivar was developed as a chance seedling of Banarasi. Fruits are large, triangular, skin smooth, whitish-green to apricot yellow in colour with red spots on exposed surfaces. There are six segments, easily separated; the flesh is pinkish-green, less fibrous than other cultivars. 'Krishna' matures early, with no evidence of fruit necrosis. Keeping quality is moderate, TSS averages 11.00%, acidity 2.32% and vitamin C 549 mg 100 g^{-1}.
4. **Kanchan:** This is believed to be a chance seedling originated from the cultivar 'Chakaiya'. Fruits are small sized (averages 30 g), with a flattened shape and yellowish-green in colour. Fibre content is about 1.5%, and it is moderate in ascorbic acid content. Fruits of this cultivar are highly susceptible to russeting (corking).
5. **Francis (Hathi Jhool):** Fruits are large (averaging 46 g), a flattened oblong, and greenish-white in colour. Segments are six in number and distinct, solid and thick. 'Francis' is considered moderate in fibre content (1.5%). It is a mid-season variety and matures in mid-November to mid-December. Ascorbic acid content is lower than in the early maturing group, while this one is rich in iron content. Fruits of this cultivar are highly susceptible to internal browning (necrosis) and hence fruit is not suitable for preserve making.
6. **NA-6:** This is a chance seedling of cultivar 'Chakaiya'. Fruits are small to medium in size (averages 39 g), oval to round, smooth, semi-translucent, and light green in colour. Flesh is fibrous and semi-hard. Segments are six, paired, difficult to separate and the cavity shallow to absent, ridges on stem end less prominent. Fruits mature in mid-November to mid-December. Fibre content is low (0.8%), ascorbic acid content average (788 mg 100 g^{-1}), while low in phenolics. Keeping quality of fruit is good and it is suitable for making preserves, candy and jam. Fruits are free from internal necrosis.
7. **NA-7:** This is a seedling selected from the open pollinated strain of 'Francis'. Fruits are medium to large (44 g), conical in shape with pappilate apex at the pea stage, while at maturity it appears as a flattened oval. It is heavy yielding, as the number of female flowers per branchlet is high (10.05). Fibre content is 1.5%. 'NA-7' is moderate in ascorbic acid content (527.0 mg 100 g^{-1}), TSS is 10.33 % and acidity is 2.15%. It is free from fruit necrosis and can be used successfully for processing.
8. **NA-8:** This is a chance seedling developed from the 'Chakaiya' cultivar. Fruits are small, a flattened round shape with slightly rough skin, thick and light green in colour. Fruits have six segments, which are paired and difficult to separate. 'NA-8' is a late maturing variety. The keeping quality of the fruit is good but it is susceptible to fruit necrosis.
9. **NA-9:** This is a chance seedling of the 'Banarasi' cultivar. Fruits are large in size (50.3 g), with a flattened oblong shape. Segments number six to eight, and are distinct and solid. Fibre content is low (0.9%). Ascorbic acid content

is high (881 mg 100 g^{-1}). This is an ideal variety for making preserves, candy, jam and jelly.

10. **NA-10:** A chance seedling developed from the 'Banarasi' cultivar, and also known as Agra Bold. Fruits are a flattened round shape and are moderate in size, rough skinned, yellowish-green with a pink tinge. Segments are six in number, paired and easily separated. Flesh is slightly fibrous, whitish-green, soft, juicy and highly astringent. It is moderate in bearing and an early cultivar. Fruits have good keeping quality but are mildly susceptible to fruit necrosis.
11. **Lakshmi 52:** This is a seedling selection from the 'Francis' cultivar, and has a profuse bearing habit with an average yield of 200 to 250 kg $tree^{-1}$ from a full-grown tree. Fruits are large with six ridges, are light pink in colour during the early stages, which colouring then disappears on full maturity. The fruit have excellent processing potential and are suitable for preparing segments in syrup, preserves and candy.
12. **Goma Aishwarya:** Average yield potential is 103 kg $tree^{-1}$. It has low fibre content and is suitable for processing and export. Fruit size is medium (45 g) and contains 47% juice. Pulp:stone ratio is about 26. TSS averages 10°Brix, and ascorbic acid content averages 555 mg 100 g^{-1}.

5.1.3 Importance

India ranks first in the world in area and production of aonla. Naturally growing aonla trees are also found in Sri Lanka, Cuba, Puerto Rico, USA (Hawaii and Florida), Iran, Iraq, Pakistan, China, Malaysia, Bhutan, Thailand, Vietnam, Philippines, Trinidad, Panama and Japan. The information on different aonla species and their status of prevalence in different parts of the world, particularly in South and Southeast Asia, is shown in Table 5.1 (Pathak, 2003). The major aonla growing states in India are Uttar Pradesh (UP), Maharashtra, Gujarat, Rajasthan, Andhra Pradesh, Tamil Nadu, Karnataka, Haryana, Punjab and Himachal Pradesh. One of the oldest commercial plantations in India was established in 1936 in Pratapgarh, UP and is still in production.

Although mention is made of Indian gooseberry in different countries, systematic data on area and production volume are not available. In India it is estimated that aonla is cultivated on about 65000 ha with a production of 250 000 tonnes.

5.1.4 Culinary uses

Aonla may be used in many ways, including as a vegetable, for medicinal purposes, and in many processed products (Thakur, 1985; Yadav, 1987; Dhir *et al.*, 1990, 1991; Asmawi *et al.*, 1992; Jose and Kuttan, 1995; Ghosal *et al.*, 1996; Jose *et al.*, 1997; Nandi *et al.*, 1997; Clixto *et al.*, 1998; Kaur and Kapoor, 2002; Saxena, 2003). In general, aonla fruits are utilized for three purposes:

- As food items: Jams, preserves, candy, dehydrated shreds, drinks (squash, nectars), syrup, pickles, sauces, and chutney.

Table 5.1 Aonla distribution in South and Southeast Asia and other parts of the world

Region	Country	Species	Cultivated in orchards (>10 plants)	Cultivated in house stead (1–2 plants)	Collected wild for human consumption
Southeast	China	*Phyllanthus emblica*	*	*	*
Asia	Hong Kong				
	Thailand	*Phyllanthus acidus*	*	*	
		P. acutissimus			*
		P. albidiscus			*
		P. amarus			*
		P. angkorensis			*
		P. chamaepeuce			*
		P. clarkei			*
		P. collinsae			*
		P. Columnaris			*
		P. elegans			*
		P. emblica			*
		P. geoffrayi			*
		P. gracilipes			*
		P. Kerrii			*
		P. lingulatus			*
		P. mirabilis			*
		P. oxyphyllus			*
		P. reticulates			*
		P. roreus			*
		P. sikkinensis			*
		P. virgatus			*
	Taiwan	*P. acidus*		*	*
		P. emblica		*	*
	Philippines	*P. acidus*			*
	Malaysia	*P. acidus*		*	*
		P. emblica		*	*
	Indonesia	*P. emblica*		*	*
		P. javanicus (Ceremai)		*	*
South Asia	Sri Lanka	*P. acidus*	*	*	*
		P. emblica	*	*	*
	India	*P. acidus*	*	*	*
		P. amarus (Bhonya amali)	*		*
		P. emblica	*	*	*
		P. emblica	*	*	*
Others	Australia	*P. acidus*		*	
	Brazil	*P. acidus*		*	
	Venezuela	*P. acidus (Grosella)*	*		
	Honduras	*P. emblica*		*	
	Costa Rica	*P. emblica*		*	
	Reunion Island	*P. emblica*			*

- As Ayurvedic (Indian system of medicine) preparations: Chavanprash, trifla, trifla pash, trifla mashy, trifla churn, madhumeh (diabetic) churn, and bavasir nashak mahaushdhi.
- As cosmetic and industrial products: Hair oil, shampoo, tooth powder and in the tanning industry.

5.1.5 Medicinal uses

Several investigators have determined the efficacy of aonla as an anti-atherosclerotic (Thakur *et al.*, 1988), antidiabetic (Tripathi *et al.*, 1979), antimutagenic (Sharma *et al.*, 2000) and anticancer agent (Jose *et al.*, 2001). Rawat and Uniyal (2003) reported that aonla root bark, stem bark, leaf, fruit and seed possess medicinal properties. The root bark is astringent and is useful for treating ulcerative stomatitis and gastric ulcer. The bark is astringent and used in treating gonorrhea, jaundice, diarrhea and myalgia. The leaves are used to treat conjunctivitis, inflammation, dyspepsia, diarrhea and dysentery. The fruits are astringent, cooling, anodyne, carminative, digestive, stomachic, laxative, alterant, alexeteric, aphrodisiac, diuretic, antipyretic, tonic and trichogenous. They are used for treatment of diabetes, cough, asthma, bronchitis, headache, ophthalmic disorders, dyspepsia, colic, flatulence, hyperacidity, peptic ulcer, erysipelas, skin diseases, leprosy, haematemasis, inflammations, anaemia, emaciation, hepatic disorders, jaundice, strangury, diarrhea, dysentery, intringic haemorrhages, leucorrhoea, menorrhagia and prevention of greyness of hair. Seeds are reported to be useful in treating asthma, bronchitis and biliousness.

Aonla is an important ingredient of *triphala*, which consists of *harer* (*Terminalia chebula*), *bahera* (*Terminalia bellirica*) and aonla (*Emblica officinalis*) in equal proportions. *Triphala* is an appetite stimulant and carminative, considered beneficial for eyes and alleviates *kapha, pitta*, leprosy, constipation anomalies or urinary secretion and malarial fever. *Triphala* is an important component of muskakadiganal and mustadigana. In *Charaksamhita* (an ancient book on Ayurvedic medicine), aonla has been listed amongst the foods that are age-sustaining. *Emblica* fruit extract exhibits antioxidant properties, its aqueous extract being a potent inhibitor of lipoid peroxidation and a scavenger of hydroxyl and superoxide radicals *in vitro* (Scartezzini and Speroni, 2000).

5.2 Fruit development and postharvest physiology

5.2.1 Fruit growth, development and maturation

In North India, the aonla tree begins to shed its determinate shoots from February onwards, and its indeterminate shoots are devoid of foliage by the end of February to mid-March. The new determinate shoots, which emerge at nodes from the margins of the scars formed after abscission of determinate shoots in the previous seasons, begin to appear by the end of February and continue to appear until the first week of April. Blossom buds appear on the newly developed determinate

shoots but shoots that emerged after mid-April do not bear flowers and remain vegetative (Naik, 1949). The flowering period is affected less by temperature and more by day length (Ram, 1982). Male flowers appear first followed by female flowers in the axils of leaves on a determinate shoot. Anthesis of male flowers occurs between 16.00 and 17.00 hrs in 'Banarasi', whereas that in 'Chakaiya' occurs both in the morning (08.30 to 11.30 hrs) and afternoon (15.30 to 18.30 hrs) (Alleemullah and Ram, 1990). Dehiscence of pollen grains coincides with the anthesis of male flowers in different cultivars, and the majority of the pollen grains are fertile (Bajpai, 1957; Alleemullah and Ram, 1990). The stigma is receptive between the second and fifth day after anthesis. Wind, honeybee and gravity play important roles in pollination on which initial fruit set and ultimate fruit retention depends (Bajpai, 1968; Ram, 1983; Alleemullah and Ram, 1990). Pathak and Srivastava (1994) have observed self-incompatibility in initial studies in flowering and fruit set in aonla, where the number of female flowers varied from two to eight.

Fertilization takes place in about 24 hours of pollination (Bajpai, 1968; Ram, 1971). The ovary gets encased in a paper brown covering called 'cupule', signifying fruit set. Such fruit set remains dormant for about three to five months after pollination, and growth and development starts at the end of July and first week of August after the onset of the monsoon depending upon the location and climatic conditions. In general, fruit attains 5 to 6 mm diameter by the end of August. The pointed and tapering fruitlet assumes a spherical shape. The fruit grows rapidly from the middle of August to the first week of October and completes almost 75% growth during this period. The growth rate again slows between the second week of October and the first week of November and increases slightly thereafter in a double sigmoid pattern.

5.2.2 Respiration, ethylene production and ripening

Aonla is a non-climacteric fruit (Pareek, 2010a). Very little research has been done on aonla postharvest physiology, but it seems that respiration patterns and ripening behaviour vary among the different cultivars, and are affected by climatic conditions and geographical location where the fruit is grown. Respiration is high after fruit set and then declines and maintains low until the fruit starts to mature. Aonla fruit showed respiratory activity (measured as production of carbon dioxide) ranging from 72.00 to 82.10 mg CO_2 kg^{-1} h^{-1}. As a non-climacteric fruit, aonla cannot be ripened after harvest (Pareek, 2010b).

5.3 Maturity and quality components and indices

5.3.1 Determination of maturity indices

Being an under-utilized fruit crop, little attention has been given to establishing reliable maturity indices of aonla. However, commonly used parameters like specific gravity, total soluble solids (TSS): acid ratio, colour of fruit surface, fibre

content, seed colour, heat units, days from flowering to maturity can be used for determining the maturity index of particular cultivar of aonla in a particular region (Ojha, 1986; Singh, 1997; Singh *et al.*, 2004).

On the basis of season of maturity, aonla cultivars have been classified into three groups, i.e. early, mid and late season (Pathak *et al.*, 1993). The maturity seasons of selected aonla cultivars are described in Table 5.2. However, the maturity period is affected by various factors such as location, climate, soil type, and other cultivation practices. In the north Indian arid climatic conditions of Rajasthan and Gujarat, fruits of 'Agra Bold', 'NA-7' and 'Banarasi' mature during the last week of October; 'Francis' and 'Krishna' mature during the first week of November; 'Gujarat-1' and 'Gujarat-2' by middle of November and 'Kanchan' and 'Chakaiya' during the last week of November (Singh *et al.*, 2006).

At the time of maturity specific gravity should be 1.02 in 'Chakaiya'; 1.03 in 'NA-7', 'Krishna' and 'Kanchan'; 1.06 in 'Gujarat-2'; 1.07 in 'Agra Bold' and 1.08 in 'Banarasi', 'Francis' and 'Gujarat-1'. Fibre content at maturity is 0.37% in 'Krishna', 0.38% in 'Banarasi', 0.54% in 'NA-7', 0.58% in 'Gujarat-1', 0.60% in 'Gujarat-2', 0.65% in 'Agra Bold', 0.72% in 'Francis', 0.81% in 'Chakaiya' and 0.84% in 'Kanchan' (Singh *et al.*, 2006).

Fruit colour ranged from dull greenish-yellow to translucent in various cultivars. Fruit skin characteristics of various cultivars at maturity is described in Table 5.3.

Table 5.2 Maturity seasons of selected aonla cultivars

Early	Mid	Late
Banarasi	Francis	Chakaiya
Krishna	NA-7	
NA-10	Kanchan	
	NA-6	
	NA-9	

Table 5.3 Fruit skin characteristics of aonla cultivars at maturity

Cultivar	Fruit skin characteristics
Banarasi	Thin, smooth, semi-translucent, whitish-green to straw yellow
Krishna	Smooth, whitish-green to apricot yellow in colour with red spots on exposed surface
Francis	Smooth, thick at upper side and thin at basin, light green in colour
Kanchan	Smooth, light green, strips deep red at pea stage which disappear later on
NA-6	Smooth, semi-translucent, light green in colour
NA-7	Smooth, semi-translucent, yellowish-green
NA-8	Slightly rough, thick and light green in colour
NA-9	Smooth, semi-translucent, light green in colour
NA-10	Rough, yellowish-green with pink tinge

Growing Degree Days (GDD) can also be taken into consideration for determination of fruit maturity. The average GDD for aonla is 5000 hours (Singh *et al.*, 2005d; Shukla *et al.*, 2007).

5.3.2 Quality components

The chemical composition of aonla fruits is influenced by cultivar, management practices and environmental factors. The chemical composition of fresh fruit with respect to moisture, protein, fat, crude fibre, starch, sugars, minerals and vitamins is shown in Table 5.4.

The total sugar content of aonla fruits varies from 7 to 9.6%: reducing sugars from 1.04 to 4.09 % and non-reducing sugars from 3.05 to 7.23 % among the various cultivars. Aonla is particularly rich in vitamin C. The pulp of fresh fruits contains 200 to 900 mg of vitamin C per 100 g (Kalra, 1988).

The fruit pulp contains moisture (81.2 %), fat (0.1 %), calcium (0.05%), potassium (0.02%), iron (1.2 mg 100 g^{-1}), nicotinic acid (0.02 mg 100 g^{-1}) and vitamin C (600 mg 100 g^{-1}) (Kapoor, 1990). The fruit contains trigalloylglucose, techebin, corilagin, ellagic acid, phyllembic acid (6.3%), lipids (6.0%), gallic acid (5.0%) and emblicol (Kapoor, 1990).

The seeds contain a fixed oil, phosphaides, and a small quantity of essential oil with a characteristic odour. The fixed oil (16%) is brownish-yellow in colour and contains linolenic (8.78%), linoleic (44.0%), oleic (28.4%), stearic (2.15%), palmitic (2.99%) and myristic (0.95%) acids (Kapoor, 1990). Tannins from aonla bark are found to have 2,3-cis configuration and to be a mixture of partially 3-o-gallated prodelphinidin and procyanidin (Gongye, 1987).

The fruits of aonla are reported to contain hydrolysable tannins, emblicannin A and emblicannin B, along with pedunculagin and punigluconin (Ghosal *et al.*, 1996). These fruits were to be considered rich source of ascorbic acid until Ghosal *et al.* questioned its presence in 1996. However, in 2006, Scartezzini *et al.* proposed a reliable HPLC-DAD (Fig. 5.1) for the identification and quantification

Table 5.4 Chemical composition of fresh aonla fruits

Characteristic	Composition
pH	2.45
TSS (°B)	13.50
Acidity (%)	2.25
Ascorbic acid (mg 100g^{-1})	590.00
Reducing sugar (%)	2.45
Non-reducing sugar (%)	0.79
Total sugar (%)	3.31
Pectin (% calcium pectate)	0.55
Tannin (% gallotannic acid)	0.50
Protein (%)	0.93
Moisture (%)	84.56

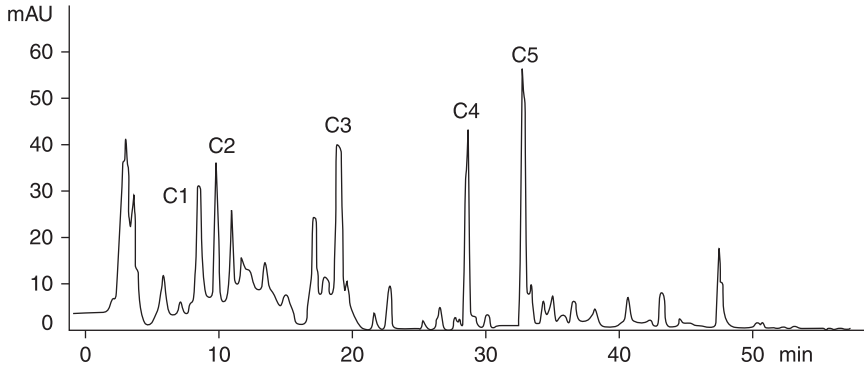

Fig. 5.1 HPLC profile of methanolic extract of emblica monitored at 280 NM.

of ascorbic acid and further indicated that high antioxidant activity is due to a large percentage of the presence of ascorbic acid (Scartezzini *et al.*, 2006). Recently, Raghu *et al.* (2007) compared ascorbic acid content of the fruits by conventional colorimetric estimation, specific enzymatic method and as the o-phenylene diamine derivative of dehydroascorbic acid and found contents of 34 to 38 mg of vitamin C equivalent to 100 g of fresh weight.

The free and bound phenolics of aonla fruits showed high content of phenolic compounds (126 and 3.0 mg g^{-1}). Gallic acid and tannic acid were identified as the major antioxidant components in phenolic fractions of aonla (Kumar *et al.*, 2006).

5.4 Preharvest factors affecting fruit quality

Many factors, especially cultural practices and environmental conditions, can influence the development of aonla and therefore influence its quality. Cultivar, fibre, tannin and vitamin C content are the important components of aonla fruit quality. Some of the cultivars ('NA-6', 'NA-7' and 'Banarasi') have low fibre content and are therefore preferred for processing. 'Hathijhool', 'Chakaiya', and 'Kanchan' are prolific bearers but contain high amount of fibre as well as tannins. Vitamin C and fibre content in different aonla cultivars vary from 500 to 1500 mg 100 g^{-1} and 0.35 to 1.50 %, respectively.

Although no systematic work has been done on nutritional requirement of aonla fruits, aonla trees need an adequate supply of nutrients for rapid growth, flowering and fruiting. Ten-year-old and older trees should get a fertilizer dose of 100 g N + 500 g P_2O_5 + 1000 g K_2O plus 1000 kg Farm Yard Manure. In sodic soil, 100 g of boron, zinc sulphate and copper sulphate should also be incorporated along with fertilizers as per the tree age and vigour. Two sprays of micronutrients during August-September containing B, Zn, Cu (0.4 %) along with hydrated lime is helpful in reducing fruit drop, improving fruit quality and reduction in fruit

necrosis particularly in 'Francis'. Boron deficiency affects the appearance of fruits and results in pinkish spots on the fruit surface (Pathak *et al.*, 2003).

Treatment with calcium nitrate, calcium chloride and borax increased shelf life, lowered physiological weight loss and reduced respiration rates (Yadav and Singh, 1999). Treatment with 1 % calcium nitrate resulted in lowest weight loss (11.09 %) and decay loss (14.43 %) and prolonged shelf life up to 20 days (Yadav and Singh, 1999). Three sprays of borax (0.6 %) in the month of September reduced the browning in fruits (Sharma, 2006). Postharvest application of calcium nitrate (1 %) minimized weight loss during the storage period and no pathological loss was observed with borax treatment (4 %) during up to nine days of storage (Nath *et al.*, 1992).

5.5 Postharvest handling factors affecting quality

5.5.1 Temperature management

Aonla fruit as the case for almost all subtropical fruits is very sensitive to improper temperature management. Chilling injury (CI) is manifested initially in aonla fruit as brown discolouration on the skin, often accompanied by pitting and water soaking lesions. In more severe cases the flesh is also affected. CI also can cause uneven ripening, poor colour and fruits more prone to decay. Generally, storage below 6°C results in CI in aonla fruits. Not much work has been carried out in cultivar differences for susceptibility to CI in aonla. The best control of CI is to avoid exposure to temperatures lower than optimum. The optimum temperature for aonla storage was found to be 12°C (Pareek, 2010b).

5.5.2 Physical damage

Aonla fruits are susceptible to surface abrasions at the time of harvesting. In India fruits are generally harvested by beating the twigs or shaking the plant, with fallen fruits being physically damaged. Fruits with scuffs or bruises on the surface make them unsuitable for processing, especially for making preserves. Damaged and wounded fruits are characterized by a high rate of respiration as well as a high rate of ethylene production. These fruits are more susceptible to microbial attack and postharvest decay. Therefore, careful harvesting, proper sorting, packaging and storage are essential requirements to maintain the postharvest quality of aonla fruits.

5.5.3 Water loss

Aonla fruits are harvested in India during November to March, when temperatures are high enough to cause high rates of water loss and to reduce the quality of the fruit if pre-cooling and low temperature storage are delayed after harvest. Exposure to sunlight adversely affects the quality as well as marketable quantity by weight. Therefore, harvested fruits should be transported to the packinghouse, processor or market as soon as possible.

5.6 Physiological disorders

5.6.1 Chilling injury

Chilling injury (CI) occurs in aonla fruit at temperatures below 6°C and the optimum temperature for storage is 12°C. Pitting, peel discolouration, water soaked lesions on the surface followed by irregular ripening with poor colour and increased susceptibility to decay are the symptoms of CI in aonla fruit (Pareek, 2010b).

5.6.2 Internal fruit necrosis

Internal fruit necrosis is characterized by browning of the innermost mesocarpic tissues at the time of endocarp hardening, followed by browning of the epicarp, resulting in the development of black areas on the fruit surfaces. In severe cases, the mesocarp of the affected fruits may turn completely black, becomes corky along with the development of gummy pockets on the fruit surface. The 'Francis' cultivar is highly susceptible to fruit necrosis, followed by 'Banarasi'. This disorder has been reported to be due to the deficiency of boron and can be corrected by three sprays of borax (0.6 %) during the months of September and October at fortnightly intervals (Sharma, 2006).

5.6.3 Pink colouration

In recent years, it has been noticed in many orchards in India that spots of pink colour appeared on aonla fruits. This disorder is due to boron deficiency. Fruit marketability is adversely affected. Two sprays of borax in September and October have been shown to reduce the pink colouration on fruit surface (Pareek, studies currently in progress).

5.6.4 White specks

The development of white specks on the surface and interior of the fruit is a major hindrance during curing and pickling. The white-specked fruits become very poor in appearance and mushy in texture. Studies to evaluate the effects of various pretreatments on the development of white specks were carried out (Premi *et al.*, 1998). The extent of white specks was lower in aonla fruit segments preserved in steeping solution containing 10 % salt and 0.04 % potassium meta-bi-sulphite than in those preserved by dry, salting with 10 % salt and 0.02 % potassium meta-bi-sulphite during one month of storage. The fruits that developed white specks were poor in texture and brownish in colour. These white specks were isolated and extracted with water, then purified as white solid matter. This was found to be insoluble in water and other common organic solvents but soluble in alkali solutions. The white solid matter was mucic acid (D-galactaric acid). Its mineral analysis indicated the formation of an unknown complex of this compound with calcium and potassium (Premi *et al.*, 1998).

5.7 Pathological disorders

Aonla is a hardy crop and there are few known effects of diseases during production in India. However, aonla rust and postharvest diseases are major constraints. In China, brown spot (*Phyllostica emblica*), false anthracnose (*Kabatiella emblica*), *Pestalotiopsis* leaf spot (*P. heterocornis*) and powdery mildew (*Oidium sp.*) were reported. The first two species are described as new species and *Pestalotiopsis* leaf spot was a newly reported pathogen for China (Zhang and Qi, 1996).

5.7.1 Rust

Rust is a major and economically important disease in aonla. A maximum disease incidence of 21% was noted in the last week of December and the development was higher when relative humidity increased and temperature decreased (Anonymous, 1989). Black pustules develop on fruits, which later develop in a ring pattern. In an advanced stage, many pustules coalesce together and cover a large area of the fruit surface. A papery covering covers these pustules at the initial stage and black spores are exposed when the covering ruptures.

Aonla rust is caused by an obligate parasite (*Revenelia emblica* Syd.), which requires the live host for infection and establishment under favourable conditions.

Integrated approaches should be followed for effective control of aonla rust, which involves cultural methods, chemical control and use of resistant cultivars. Clean cultivation is essential and infected fruits and leaves must be collected and destroyed. Proper pruning to maintain optimum canopy density and avoiding humidity build-up results in less incidence and intensity of infection of the pathogen. Three sprays of 0.5% wettable sulfur or Zineb (0.2%) at intervals of one month starting from the month of July can be useful to control rust (Tyagi, 1967). The commercially cultivated cultivars 'Chakaiya', 'Krishna', 'Kanchan', 'NA-7', and 'NA-10' are relatively susceptible to rust. Out of nine cultivars screened under Faizabad (India) conditions, 'NA-6' was found to be resistant. No cultivar was found to be immune to rust (Anonymous, 2002).

5.7.2 Anthracnose

Anthracnose is the second major disease in aonla fruits. The causal organism of the disease is the *Colletotrichum* state of *Glomerella cingulata*. It appears on leaflets and fruits during August to September. Initial symptoms of the disease appear in the form of minute, circular, brown to grey spots with yellowish margin in leaflets, and severely affected leaves dry up. In fruits, the initial symptoms are pin head sized spots, which are dark brown to pink to red. As the pathogen proliferates, spots change colour, eventually becoming dark brown spots with red margin and yellow halos (Misra and Shivpuri, 1983). To control the disease, infected fruits and leaves have to be removed at the initial stage of disease appearance. Spraying with 0.1% Carbendazim or 0.2% Difolatan can help control the disease (Nallathambi *et al.*, 2007).

5.7.3 Fruit rots

Other diseases causing fruit rots can cause considerable economic losses in aonla. Thirteen types of different fungi have been isolated from stored fruits of aonla (Mishra, 1988). *Phoma* rot, *Alternaria, Cladosporium, Pestalotia, Penicillium* and *Aspergillus* are the common rots associated with aonla.

Among all types of rots, *Phoma* rot is most widespread in India. Different species of *Phoma* cause different fruit rots in aonla. Dry rot of aonla is caused by *Phoma emblicae* (Jamaluddin *et al.*, 1975) or *Phoma putanium* (Pandey *et al.*, 1980) and soft rot is caused by *Phoma phyllanthi* (Lal *et al.*, 1982). Small pinkish-brown necrotic spots extending towards both ends of the fruit, forming an eye-shaped spot, are the characteristic symptoms of this disease. Infected fruit appears dark brown and crinkled with softening of underlying tissues. In severely infected fruits, lesions coalesce forming bigger pustules (Nallathambi *et al.*, 2007). Not many studies have been made on physiological changes in fruits due to *Phoma* infection, however, it is known that postharvest infections of aonla fruits by *Phoma exigna* result in a very rapid decrease in vitamin C content compared with the slow decrease during storage of healthy fruits (Reddy and Laxminarayana, 1984).

Alternaria alternata (Fr.) Keissler is responsible for *Alternaria* rot. Slightly depressed, brown to dark brown circular necrotic lesions appear on the fruit. Sometimes concentric rings are also present on these spots. The smaller spots coalesce to form larger spots. The centre portion of the infected tissue becomes soft and pulpy. The fungus survives in debris and soil. Dropped fruits and fruits touching the soil become infected and the disease spreads later by dissemination of spores through the air.

Cladosporium rot is also known as dry rot and caused by *Cladosporium tenuissiumum* in November to February and by *C. cladosporoids* in February to March. Disease starts as a colourless area, where slightly soft spots develop and later progress into a circular manner. The diameter of the lesions varies from 1.0 to 1.5 cm in a 1-week-old infection. Subsequently, light to dark brown necrotic lesions are the characteristic symptom (Jamaluddin, 1978).

Penicillium rot is also known as soft rot and caused by *Penicillium digitatum, P. citrinum*, and *P. isolandicum*. Initially water soaked lesions appear near brown patches on the fruit surface. As the rot progresses, three distinct colour zones of bright yellow, purple brown and bluish-green are observed on the infected fruits. In advanced stages of infection the fruits emit a foul smell.

Other less-reported rots are caused by *Aspergillus niger* (Jamaluddin *et al.*, 1979), *Penicillium digitatum* (Taneja *et al.*, 1983), *Aspergillus luchunensis, Fusarium acuminatum* (Sumbali and Badyal, 1990), *Cytospora sp.* (Tandon and Verma, 1964) and *Pestalotia cruenta* (Tandon and Srivastava, 1964).

Management of fruit rots

Decay control is accomplished with an adequate preharvest and postharvest integrated program. Postharvest wash water should contain 100 to 150 ppm of sodium hypochlorite plus fungicides depending on the source and extent of the

problem. Proper handling of the fruit during harvest, packaging, elimination of mechanical injury, rapid cooling, maintenance of optimum temperature and maintenance of hygienic conditions are essential for decay control.

Several chemicals are applied to aonla both pre- and postharvest for control of fruit rots. Two preharvest sprays of 0.01% calcium nitrate with 0.1% Topsin M were found to be effective for control of rot (Yadav and Singh, 1999). Treatment with Topsin M and Bayleton controlled *Penicillium oxalicum* and *Aspergillus niger* for two to three weeks. Four percent borax as a postharvest dip resulted in effective control of fruit rot (Nath *et al.*, 1992).

5.8 Insect pests and their control

The major pests of aonla are *Virachola isocrates, Betousa stylophora* Swinhae, *Gracillaria acidula, Celepa celtis*, and *Inderbela tetraonis* belonging to the order Lepidoptera, *Ceciaphis emblica, Nipaecoccus vastator* and *Oxyrhachis tarandus* of Homoptera, *Myllocerus discolor* of Cleoptera and termite *Odontotermes spp.* of Isoptera.

5.8.1 Fruit borer (*Virachola isocrates*)

Borers lay eggs on young fruits, and the caterpillars bore into the fruits and feed on developing seeds. The insects make holes in the fruit, which facilitates the entry of microorganisms resulting in decay of fruits. To prevent the spread of the insects, infested fruits should be collected and destroyed. A spray of Endosulphan (0.05%) is effective during July to August. Pomegranate cultivation should be avoided near aonla orchards.

5.9 Postharvest handling practices

5.9.1 Harvest operations

Careful harvesting is important in aonla fruit because damaged fruits are not useful for processed products. Fully developed fruits, which show signs of maturity, should be harvested in a timely fashion. Delay in harvesting results in heavy dropping of fruits particularly in cultivars like 'Banarasi' and 'Francis', and also adversely affects the following year's bearing. The recommended method of harvesting is hand picking of individual fruits. Shaking of twigs of the tree is a common practice in India, but fruits are damaged when they drop on the ground. These fallen fruits are the source of soil-borne microorganisms, which can cause rots during storage. Therefore, fruit harvesters should use long ladders and carry cotton or jute bags for collecting the fruits. Fruits should be harvested early in the morning or in the evening to avoid high field temperatures. Harvested fruits should be immediately moved under shade.

5.9.2 Packinghouse practices

Grading

Aonla may be graded according to weight or diameter. Grading has not been standardized in aonla, but the authors recommend that aonla fruits should be graded into three size grades as shown in Table 5.5. Fruits may also be graded on weight basis (A grade = 50 ± 5 g, B grade = 40 ± 5 g and C grade = 30 ± 5 g). Highest physiological loss in weight (PLW) was observed in C grade fruits followed by B grade and was least in A grade fruits during eight days of storage at ambient temperature. PLW in the 'Francis' cultivar was 12.50, 16.00 and 20.50 % in A, B and C grade fruits respectively on the eighth day of storage. PLW was 6.50, 11.30 and 14.50 % for A, B and C grade fruits in 'Chakaiya' (Pareek *et al.*, 2008) (Table 5.6).

Final destination or utilization of aonla fruits is based on the size, weight and fibre content of fruits. Large-sized fruits with 45 ± 5 g weight and low in fibre are used for preserves, candy and pickle making, while small-sized fruits with medium to high fibre contents are used in making of medicinal products, i.e. *chavanprash*. Misshapen fruits or fruits with necrosis and blemishes can be peeled, trimmed and used in making *trifla* and for drying or powder making.

Packaging

At present packaging is inadequate for aonla handled in India. Aonla fruits are packed in cloth sacks of 50 to 100 kg capacity. These fruits suffer vibration and

Table 5.5 Recommended grades for aonla fruits

Grade	Description
A	Large-sized fruit: diameter 4.5 cm and above, free from blemishes; weight 50 + 5g
B	Small-sized fruit: diameter less than 4.5 cm, free from blemishes; weight 40 + 5g
C	Defective fruits, i.e. blemished, scarred and necrotic fruits; weight 30 + 5g

Table 5.6 Water loss (%) during storage of aonla fruits in different size grades

Grades	Days after harvest			
	2	4	6	8
cv. 'Francis'				
A	3.20	7.50	11.30	12.50
B	4.50	8.75	14.50	16.00
C	6.00	13.80	16.00	20.50
cv. 'Chakaiya'				
A	1.50	3.50	5.20	6.50
B	2.80	7.25	9.50	11.30
C	4.75	9.00	12.50	14.50

compression injuries during stacking and transportation in these large sacks. Corrugated fibre boxes (CFB) of appropriate size (20 kg capacity) should be used. Lightweight paper liners should be used inside the CFB cartons to reduce abrasions. Minimum spoilage (16.0%) was reported in CFB with newspaper liners followed by CFB boxes with polythene liners (17.0%), and was highest in cloth sacks without any liner (30.19%) after 13 days of storage (Singh *et al.*, 2005b). The effects of cloth sacks, corrugated fibreboard box, pigeon pea basket, wooden crate and bamboo basket with polythene liner as packaging material were studied for the transportation and storage of aonla cv. 'NA 7' at an ambient temperature of 21 ± 2°C (minimum) and 33 ± 2°C (maximum) with a relative humidity of 65 ± 3%. Minimum spoilage loss was reported in fruits kept in CFB with newspaper liners. The same treatment also resulted in the lowest respiratory activity (81.1 mg CO_2 kg^{-1} h^{-1}) and exhibited 11 days of economic shelf life under ambient conditions. The highest respiration rate was reported for aonla handled in cloth sacks (90.0 mg CO_2 kg^{-1} h^{-1}) on the thirteenth day of storage (Singh *et al.*, 2009). Wooden crates of 40 kg capacity with polythene liners were also found to be suitable for packing and long distance transportation of aonla fruits. % weight loss and bruising were minimized in this sturdy container as compared to cloth sacks (Singh *et al.*, 1993).

5.9.3 Recommended storage and shipping conditions

The fruit availability period of fresh aonla is two to three months, and typically there is a seasonal glut during November to mid-January. Therefore, storage of aonla fruits at appropriate temperature is essential to extend the availability period and to stabilize the prices in the market. The fruits may be kept successfully in cold storage for seven to eight days at 12°C and 85 to 90 % relative humidity. Very little research has been done on low temperature, modified atmosphere or controlled atmosphere storage of this fruit.

The shelf life is very short at ambient temperatures and differs by cultivar. Pareek *et al.* (2009) reported the shortest shelf life in 'Francis' cultivar (6 days) and highest in 'Chakaiya' (8 days) at ambient temperature. Singh and Kumar (1997) stored fully mature aonla fruits using four different treatments: at room temperature, under modified storage conditions (packed in low density polyethylene pouches), in a zero energy cool chamber (which provides evaporative cooling conditions and very high relative humidity) and in a zero energy plus modified storage conditions. It was found that decay was at a minimum (26.56%) under modified storage conditions on the twenty-fourth day of storage, whereas it was at the maximum (48.70%) in a zero energy cool chamber.

Nath *et al.* (1992) studied the effect of postharvest treatments on shelf life of aonla fruits with calcium nitrate (1%), GA_3 (50 ppm) and borax (4 %) and found that the physiological loss in weight and pathological loss increased with the length of the storage period. Calcium nitrate (1%) treatment minimized weight loss during the storage period and no pathological loss was observed with borax treatment during up to nine days of storage.

To enhance the shelf life of aonla fruits of a local cultivar, Patel and Sachan (1995) studied the effects of calcium nitrate (1%), GA_3 (40 ppm), Cycocel (400 ppm) and kinetin (10 ppm). Fruits were dipped in these solutions, packed in perforated polythene bags and stored at ambient temperature. The physiological loss in weight and decay percentage increased with the increase in storage period. Calcium nitrate (1%) was the best treatment to minimize weight loss. No decay was observed during up to nine days of storage in kinetin (10 ppm) treated fruits. GA_3 (40 ppm) treatment resulted in better retention of vitamin C during storage of aonla fruits. Singh *et al.* (2005a) recorded the least physiological loss in weight (2.12 to 16.00% and 2.15 to 16.34%) and spoilage (2.40 to 15.00% and 2.50 to 15.60%) and storage duration of 11 days in fruits treated with calcium nitrate at 1.5% + perforated polythene bag, and GA_3 100 ppm + perforated polythene bag. The same treatments also resulted in low respiratory activity (72 to 82 mg CO_2 kg^{-1} h^{-1}). The untreated control in these studies had only 7 days of economic life under ambient conditions.

Singh *et al.* (2005a) assessed four aonla cultivars (NA-7, NA-10, Krishna and Chakaiya) for their shelf life at ambient condition (18 ± 2°C and 65 ± 5% RH). In general, the aonla fruits showed browning of skin followed by loss of glossiness during storage. 'Krishna' and 'NA-10' were more prone to browning than 'NA-7' and 'Chakaiya'. The cumulative physiological loss in weight, TSS, acidity and tannins increased, while ascorbic acid content decreased on prolonging the storage period in all the cultivars. 'NA-10' and 'Krishna' exhibited minimum loss in weight, TSS, ascorbic acid, and tannins in comparison to 'Chakaiya' and 'NA-7'. Greenness (a chromacity value) was maintained in cultivar 'NA-10' and 'Krishna' followed by 'Chakaiya' during storage. Contrary to this, maximum yellowness index (based on L, a and b values) was recorded in 'NA-7' and minimum in 'Krishna'. However, 'NA-7' exhibited the least browning compared to 'Krishna' during up to ten days of storage (18 ± 2°C and 65 ± 5 % RH). Therefore, 'NA-10' and 'Krishna' had better shelf life of ten days and retained high vitamin C content, glossy and green appearance compared to 'NA-7', which can be stored for only six to eight days under ambient conditions.

5.10 Processing

Aonla becomes ready for harvesting from mid-November to the first week of January. Aonla is not consumed fresh or raw, as it is acidic and astringent. The excellent nutritive and therapeutic value offers great potential for processing into several quality products, i.e. preserves (*murabba*), squash drinks, candy, jelly, jam, syrup, pickles, chutney, preserved pulp, blended beverage, carbonated drinks, Ready-to-Serve drinks, supari, churan, powder, barfi, laddoo and segments in sugar syrup.

The postharvest losses in aonla vary from 30 to 40% due to its perishable nature and gluts during harvesting time, and the resulting decline in quality reduces the market value of the fruit. Proper temperature management during

transport and short-term cold storage could reduce these losses, however, value addition through processing would be the most effective tool for economic utilization of the fruits during the peak of production.

5.10.1 Traditional and new methods of processing

Aonla has been in use for pickles and preserves for ages in India and the methods employed were based on traditional knowledge. Aonla has been an important ingredient for *chavanprash*, an ayurvedic health tonic. Traditional methods used for processing are unhygienic in nature, time consuming and nutritive losses can be high. The manual methods of processing are laborious, costly and cannot maintain the quality of the finished products. Minor accidents have been reported during manual operations such as pricking and shredding, and the shelf life of traditionally prepared products tends to be lower and the quality inferior.

Modern methods for preparing different aonla products are hygienic, and provide maximum retention of nutrients, especially vitamin C. There is an urgent need to design a full line of processing equipment including graders, segment separator, pricking machine, shredder, etc. The engineering of suitable machines will improve quality to international standards so that products can better compete in the international market (Goyal *et al.*, 2008).

5.10.2 Aonla products

Aonla fruits are normally used to make preserves. A preserve is made from fully matured aonla by cooking fruits whole or in the form of large pieces in heavy sugar syrup, until the fruit becomes tender and transparent. Freshly made preserves are wholesome and have an attractive appearance. When fruits are stored for a long period before processing, their natural colour and flavour deteriorate on account of oxidative changes. Preserves should therefore be made only during the season, unless there are adequate facilities to store the fruits properly so that they are available in the off-season as well.

No proper attention has yet been given to improving the preparation of other products like jam, jellies, squash, candy, toffee, barfi, laddoo, and the preserved pulp of aonla fruits. Candy is an intermediate moisture food that is prepared after shade drying of drained fruits impregnated with cane sugar or glucose. Like other fruits, aonla can also be processed into good-quality pulp. This can be used as base material for preparations of different products, i.e. squash, syrup, jam and nectar. Thus, there is an overriding need to develop and popularize several other value added products of aonla as fruit production increases.

Various studies suggest that many types of value-added products of aonla can be prepared, and a great potential exists for better utilization of aonla. However, more attempts are needed to standardize the procedures for preparation of various new value-added products and to assess the suitability of aonla cultivars for preparation of these products. Removal of astringency from aonla fruits is an important step prior to the preparation of various value-added products. At present

different ingredients or chemicals such as salt, alum and lime are used to counteract the astringency in aonla. However, very little information is available with regard to their comparative safety and effectiveness in the removal of astringency from different aonla cultivars.

5.10.3 Cultivar screening for aonla processing

Processed products of good quality can be made only from good quality raw material. Singh and Pathak (1987) evaluated five cultivars of aonla for processing based on their physico-chemical properties and organoleptic quality. Out of these five cultivars 'Kanchan' and 'Krishna' were suitable for candy and jam. 'Banarasi' was suitable for drying and 'Chakaiya' was suitable for pickles, chutney and syrup. Bhagwan (1992) observed that 'NA-9' was ideal for candy making. Singh *et al.* (1993) also reported that 'NA-6' is an excellent cultivar of aonla for making good quality candy. Nath and Sharma (1998) reported that 'Chakaiya' is good for making nectar, squash, syrup and jam products, whereas 'Banarasi' is better for candy and pickle preparation. Nath (1999) observed that 'Chakaiya' was suitable for beverages (nectar, squash and syrup) and jam whereas 'Banarasi' was better for candy and pickle preparation. Singh *et al.* (2004) evaluated five cultivars ('NA-6', 'NA-7', 'NA-10', 'Kanchan' and 'Chakaiya') for fruit processing. 'NA-6' recorded the lowest content of fibre, higher content of pulp and TSS with moderate fruit size and ascorbic acid content while 'NA-7' had a higher content of ascorbic acid. These cultivars have also higher productivity and fruits are free from necrosis or internal browning, hence they seem to be ideal for processing. The composition of selected aonla cultivars is provided in Table 5.7.

5.10.4 Effect of pricking, soaking and blanching treatments on quality of aonla products

The retention of nutrients such as ascorbic acid in the final aonla products depends on the methods of preparation. Pricking, soaking and blanching of aonla fruits are necessary to render the preserves and candies soft and to facilitate uniform

Table 5.7 Composition of selected aonla cultivars

Varieties	Average fruit weight (g)	Pulp (%)	Fibre (%)	Seed (%)	TSS (%)	Acidity (%)	Ascorbic acid (mg 100 g^{-1})
NA-6	41.40	94.27	0.87	4.86	11.12	1.80	641.27
NA-7	42.90	92.97	1.33	5.70	10.96	1.95	733.63
NA-10	44.84	93.57	1.30	5.13	10.14	1.82	626.82
Kanchan	30.92	92.36	1.40	6.24	10.86	1.72	603.64
Chakaiya	35.82	93.61	1.93	43.46	9.44	2.26	655.64
CD at 5%	4.26	0.97	0.51	0.96	1.04	0.52	86.38

Source: Singh *et al.* (2004)

absorption of sugar (Kalra, 1988). There are many reports on losses of nutrients during preparation of candy and preserves. The loss of ascorbic acid content during preparation of candy has been observed in aonla (Pathak, 1988; Tripathi *et al.*, 1988; Bhagwan, 1992; Singh *et al.*, 1993). Sastry and Siddapa (1959) found that prolonged brine treatments of aonla destroy the ascorbic acid content. The ascorbic acid content of aonla preserves decreases during preparation (Sethi, 1980). Sethi and Anand (1982) found that 55.5 % of the ascorbic acid content is lost during preparation of intermediate moisture food aonla preserves (including pricking, soaking and blanching) and only 45.5 % ascorbic acid was retained in the final product. Tripathi *et al.* (1988) reported that the aonla candy retained 108.6 mg 100 g^{-1} ascorbic acid as against initial value of 571.76 mg 100 g^{-1} in the fresh fruit.

Anand (1970), while studying the effect of certain pretreatments on the loss of tannins and vitamin C in aonla preserves, found that soaking and blanching of the fruit resulted in heavy losses of these constituents. Damame *et al.* (2002) reported that unblanched dehydrated products were found to be superior to all the blanched dehydrated products in terms of vitamin C retention over a 6-month storage period. Aonla candy and preserve were found to be the most unsuitable sources of vitamin C. Among the unblanched products, aonla pulp recorded the highest vitamin C content, followed by supari. Among the blanched products the aonla supari, treated with 2 % salt, was found to be superior in vitamin C content. Overall results indicate that aonla pulp, supari and juice are the most suitable sources of vitamin C due to minimum losses of this vitamin during storage.

Jain and Khurdiya (2002) observed that blanching of the aonla fruit prior to juice extraction significantly improved the juice recovery, increased the density and tannin content of the juice but reduced the vitamin C content by 12 %. Addition of water increased the juice volume but diluted the juice and reduced the water-soluble constituents. Higher water-soluble constituents and ascorbic acid contents were obtained by blanching the fruits and separating the segments.

The astringency in aonla fruits is due to the presence of polyphenols or tannins, which make them unpalatable but have therapeutic value (Sastry *et al.*, 1958). Astringency can be removed by curing with either salt or lime. Sethi (1980) recommended blanching of aonla fruits for 4 minutes in boiling water while Sethi and Anand (1983) found that 25 % of ascorbic acid and 24.4 % of tannins in aonla are lost during blanching. Geetha *et al.* (2006) observed that blanching done prior to processing of aonla preserve has a marked effect on all the physico-chemical constituents of aonla. Ascorbic acid content during the process of blanching was reduced significantly from 563.12 mg 100 g^{-1} (before blanching) to 434.95 mg 100 g^{-1} (after blanching) showing a loss of 19.20 %. Similarly, Total Soluble Solids, acidity, total sugars, reducing sugars, non-reducing sugars, moisture and pectin content showed a loss of 10.67, 30.78, 4.95, 5.83, 2.45, 2.20 and 21.60 %, respectively with blanching.

Phenolic compounds are important in determining colour and flavour of fruits. The losses of total phenolic compounds in finished aonla candy have been reported by Pathak (1988) and Tripathi *et al.* (1988) as compared to fresh fruit. Sethi and

Anand (1982) observed the loss of tannins during preparation of intermediate moisture foods of aonla as compared to initial values in fresh fruits.

Pathak (1988) reported that a 2 % salt solution for soaking of pricked aonla fruits was considered organoleptically ideal. Bhagwan (1992) and Singh *et al.* (1993) observed that organoleptically good quality aonla candy was prepared with 2% salt and alum soaking of pricked fruits, each for 24 hours.

5.10.5 Techniques for manufacturing processed products

The most suitable techniques determined by organoleptic evaluation by Pareek (2010a) for some of the important aonla products are described here.

Pulp extraction technique

Nath (1999) carried out a study on the extraction of aonla pulp and suggested a method for preparation of aonla pulp from fully matured fruits. In this process, the fruits are blanched in boiling water for about ten minutes to separate the segments from the seed. An equal quantity of water is added to the segments during pulping. If the pulp is to be preserved, it should be heated to 75°C and then cooled to room temperature. Potassium meta-bi-sulphite (2 g kg^{-1} of pulp) should be mixed thoroughly and the pulp should be packed in sterilized bottles and then sealed. Vitamin C losses can be minimized by using an improved pulp extraction technique, in which a shredder machine is used for removing seeds instead of the boiling water treatment.

Pickles

Small-sized aonla fruits, which are not suitable for preparation of preserves and other confectionary items, may be utilized for Indian pickle making. To improve upon the texture of the fruit and also to remove astringency, brining is important in pickling. When pickles are ready a few days after treatment, they can be stored at room temperature.

Premi *et al.* (2002) standardized the method for preparation of instant oil-less pickles from aonla. Two cultivars of aonla ('Desi' and 'Chakaiya') were used for the preparation of dehydrated oil-less pickles. The overall quality of dehydrated pickles made from pretreated segments of 'Desi' cultivar was better than those made from 'Chakaiya'. For curing aonla fruits for pickling, brining along with potassium meta-bi-sulphite treatment was found to be more effective for long-term storage than was dry salting or other pretreatments for the control of white specks, retention of texture and retention of nutrients in both cultivars. The drying rate was faster for pickles made from cured and steam blanched segments of 'Desi' than for other cultivars.

Juice extraction

Jain and Khurdiya (2002) standardized a procedure for the extraction of juice from aonla fruits. Blanching the fruits prior to juice extraction significantly improved the juice recovery, increased the density and tannin content of the juice

but reduced the vitamin C content by 12%. Higher soluble constituents and vitamin C content were obtained by blanching the fruits and separating the segments. Among the methods of juice extraction, centrifugal juice extraction recorded higher density, soluble constituents and higher vitamin C and tannin contents as compared to crushing and pressing whole or segments of aonla fruits.

Ready-to-serve (RTS) drinks

Ready-to-serve drinks can be prepared by using 10 % pulp with 12 % total soluble solids and 0.3% acidity. Juice is extracted separately and sugar syrup of the desired strength prepared separately by boiling sugar with water and adding citric acid towards the end of boiling. After cooling syrup to room temperature, mix the syrup and juice, homogenize, fill and crown cork the bottles. The bottles are then pasteurized in a boiling water bath for 20 minutes, air-cooled and stored for use.

Various workers have explored the possibilities of utilizing aonla fruit for the preparation of blended juice and beverages (Prasad *et al.*, 1968; Singh and Kumar, 1995; Nath, 1999; Deka *et al.*, 2001). If aonla juice is blended with other fruit juices for the preparation of ready to drink beverages, it boosts their nutritional quality. These fruit juices in turn improve the acceptability of aonla juice.

Deka *et al.* (2001) conducted various experiments to study the feasibility of blending juices and pulp from lime, aonla, grapes, pineapple and mango in different preparations for the manufacturing of a ready-to-drink fruit juice beverage. The highest sensory scores were obtained with a formulation comprising of 95% lime and 5% aonla juice.

Jain and Khurdiya (2004) conducted an experiment to develop vitamin C rich ready-to-serve beverages prepared from apple, lime, pomegranate, Perlette and Pusa Navrang grape juices fortified with aonla juice. For juice extraction, aonla fruits were blanched, seed removed manually, and segments were fed into a centrifugal juice extractor. The juice was strained and pasteurized at 90°C for one minute, poured into sterilized glass bottles, crown corked, and air-cooled. Juice from other fruits was extracted and pasteurized using standard methods. The aonla juice was mixed with each of the apple, lime, pomegranate, Perlette, and Pusa Navrang grape juices in the ratio of 0:100, 10:90, 15:85, 20:80, 25:75, 80:70, and 50:50. All the 40 blends were then adjusted to proportions of water, sugar, and citric acid in order to contain 10 % juice, 10 % TSS, and 0.22 % acidity except the lime–aonla blend which had 5 % juice, 10 % TSS, and 0.22 % acidity. All the blends were pasteurized at 90°C for one minute before packing in sterilized glass bottles of 200 ml capacity. On the basis of overall sensory quality and vitamin C content, the ready-to-serve beverage prepared by blending aonla and Pusa Navrang grape juice in the 20:80 ratio was reported to be the highest rated.

Squash and syrup

To prepare 15 litres of aonla squash drink, 3.75 kg juice/pulp should be mixed in sugar solution to prepare a final product with 45 % juice/pulp, 50 % Total Soluble

Solids, and 1% acidity (Fruit Products Order of India specifications). Syrup from the aonla pulp can be prepared according to Fruit Product Order specifications, i.e. 45% juice/pulp, 68% TSS and 1.2% acidity.

Nectar

Nectar can be prepared by using 10 % pulp with 12 % TSS, 0.3 % acidity and 350 ppm SO_2. To prepare 10 litres of aonla nectar, 1 kg pulp should be mixed in sugar solution. The syrup can be prepared by dissolving 1.2 kg sugar and 20 g citric acid in 7.6 litres of water by slow heating. Add the pulp after cooling the solution. Mix in the preservative (1 g potassium meta-bi-sulphite) and homogenize.

Jams

To prepare aonla jam, the pulp is extracted from the fruit, mixed with the desired quantity of sugar and citric acid and this mixture is cooked to desired consistency. The end point judged by hand refractometer (68°Brix) or by drop test or sheet test.

Herbal extracts added to aonla pulp for preparing jam improved medicinal quality. Fifty percent aonla pulp, 75 % asparagus + 2 % ashwagandha extract with 68 % Total Soluble Solids and 1 to 2 % acidity was reported to be the best combination (Singh *et al.*, 2005e).

Candy

Aonla fruit can be utilized for making excellent quality candies or intermediate moisture food (IMF). Pathak (1988) described the technology for preparation of aonla candy. Aonla candies are becoming popular because of minimum volume, higher nutritional value and longer storage life.

Tandon *et al.* (2003) found that candy prepared from lye-peeled fruits of aonla showed decreased content of ascorbic acid compared to blanched fruits. The candy prepared from 'Lakshmi-52', 'Kanchan' and 'Chakaiya' was found the best quality.

Singh *et al.* (2005e) prepared aonla candy with four different techniques (whole and segmented fruits with either sugar or pectin coatings). Candy prepared from segmented fruit with pectin coating recorded the highest organoleptic score because of its attractive colour and flavour, followed by whole fruit candy with pectin coating.

Preserves

Aonla fruits are normally used to make preserves. A preserve is made from fully matured aonla fruits by cooking them whole or in the form of large pieces in heavy sugar syrup, until they become tender and transparent. Preserves should be made from large fruits and dipped in 2 % common salt solution until the green fruit changes to a cream color, with replacement of the brine solution on alternate days. The fruits are thoroughly washed, pricked with a stainless steel pricker and then blanched in boiling water for 4 to 5 minutes. Sugar equal to the weight of

fruits is sprinkled over the fruit and the batch is stored overnight. The strength of sugar syrup should be increased by 10°Brix on at 2-day intervals until it reaches 75°Brix.

Chavanprash

Chavanprash is a health tonic described in the Indian system of medicine known as Ayurveda. It is prepared by mixing aonla pulp and sugar, then a variety of spices and medicinal plants extracts while cooking. The ingredients vary with the recipes and about 65 types of plant extracts are used to prepare this health tonic.

Shreds and drying

The osmo-air drying method was found to be the best method for drying aonla because of better retention of nutrients like ascorbic acid and sugars. The level of antinutrients like tannins was also found to be lower in osmo-air dried aonla compared to other methods of drying. Browning of the dehydrated fruits was also minimal in the case of osmo-air dried fruits. The nutrient content in osmo-air dried aonla was satisfactory after 90 days of storage (Pragati *et al.*, 2003). It was found that the aonla powder prepared from pretreated 'Chakaiya' variety and mechanically dried can be stored effectively in high-density polyethylene (HDPE) packages under refrigerated conditions for three months without much loss in vitamin C, and with better overall acceptability in terms of appearance, flavour and texture (Sharma *et al.*, 2002).

Processes for producing dehydrated aonla powder have been standardized by Alam and Singh (2005). The pricked aonla fruits were blanched for 5 minutes in 5 % boiling salt solution containing 0.15 % $NaHCO_3$ and 0.10 % MgO. The blanched aonla fruits were sulphited for 30 minutes in 0.5 % potassium meta-bi-sulphite. The treated fruits were sliced manually with a knife. For the dehydration of aonla slices, the mechanical dryer (50, 60 and 70°C), solar and cabinet dryers were used. They found that the mechanically dried slices contained higher in vitamin C content and were organoleptically superior to slices dried using the solar and cabinet dryers. Kavitha *et al.* (2003) studied the effect of osmotic dehydration on vitamin C content of aonla at different salt concentrations and different temperatures. The overall retention of vitamin C was found better in the unblanched osmotically dehydrated and air dried samples.

Alam and Singh (2010) studied the optimization of the osmotic dehydration process for aonla fruit in salt solution by using response surface methodology. The independent process variables for the osmotic dehydration process were osmotic solution concentration (5 to 25 % w/v salt), osmotic solution temperature (30 to 60°C), solution to fruit ratio (4 to 8 v/w), and process time (60 to 240 minutes). The osmotic drying process was optimized for maximum water loss, overall acceptability and minimum solute gain, colour change, and vitamin C loss. The optimum conditions were 22 % salt concentration, 44.5°C osmotic solution temperature, 6.5 solution to fruit ratio, and 60 minutes' process time. Among the process variables, salt concentration has the most significant effect on water loss, solute gain, and overall acceptability; solution temperature has the most effect on colour change; and process time has the most effect on vitamin C loss.

Murthy and Joshi (2007) dried aonla fruits under three different conditions: sun drying, hot air tray drying, and fluidized bed drying. Sun drying required the longest period of drying (660 minutes), while the shortest time of drying was for fluidized bed drying at 80°C with 115 m/minute air velocity (120 minutes). The retention of ascorbic acid in the samples dried using fluidized bed drying was greater as compared to those dried under the sun and in hot air trays. Methakhup *et al.* (2005) reported that aonla flakes subjected to vacuum drying at 75°C and at absolute pressure of 7 K Pa contains similar level of ascorbic acid retention compared to those dried by a low-pressure super heated steam at 65 and 75°C at absolute pressure of 7 to 13 K Pa.

Tea

Aonla tea is prepared from dried aonla flakes. Kongsoontornkijkul *et al.* (2006) investigated the effect of different drying methods, i.e. hot air drying, vacuum drying, and low-pressure superheated steam drying on the retention and degradation of vitamin C in dried aonla flakes. The effect of temperature of water used to prepare the tea on the release of ascorbic acid and on its later degradation was also investigated. Low-pressure superheated steam drying helped retain ascorbic acid in dried flakes better than did hot air and vacuum drying. Lower hot water temperature during tea preparation was recommended to retard ascorbic acid degradation.

5.11 Conclusions

Aonla fruit is one of the most nutritious fruits of India and its medicinal properties have long been known. Aonla cultivation is gaining popularity due to its commercial attractiveness to growers. It presents tremendous commercial opportunities for growers in difficult agroclimatic zones, such as dry regions of arid zones, salt affected soils and in ravines. Many processed products have been standardized for this fruit, but much of its basic biology, physiology and chemistry are not known. Some of the most basic postharvest information related to chilling injury, storage conditions, respiration and ethylene evolution rates are not well understood. The following are recommendations for future researchers.

Aonla, like many other herbs, has been in use for centuries in India, but it is important that traditional knowledge of aonla is documented and protected through patents.

The modernized and automated technologies used to produce certain aonla products need to be improved and patented. Scaling up the processing of selected products such as aonla pulp, powder or candy could attract investment by the international community.

Marketing the attributes of aonla fruit to the global community can generate interest in the benefits of regular consumption of aonla value-added products.

Documentation of respiration rate, ethylene evolution rate, pre and postharvest treatments, storage temperatures and relative humidity, packaging and transportation conditions, etc. are required for each commercial cultivar.

Shelf-life studies of fruit juices should be conducted, to better understand the effects of different temperature treatments, carbonation, additives and techniques such as modified atmosphere packaging.

The potential for extracting alkaloid and formulation of antioxidants tablets from aonla powder should be explored.

Standardization of processing factors related to detection of bacteriological contamination, preservation methods and protocols, use of additives, pesticide residues, etc. is required.

5.12 References

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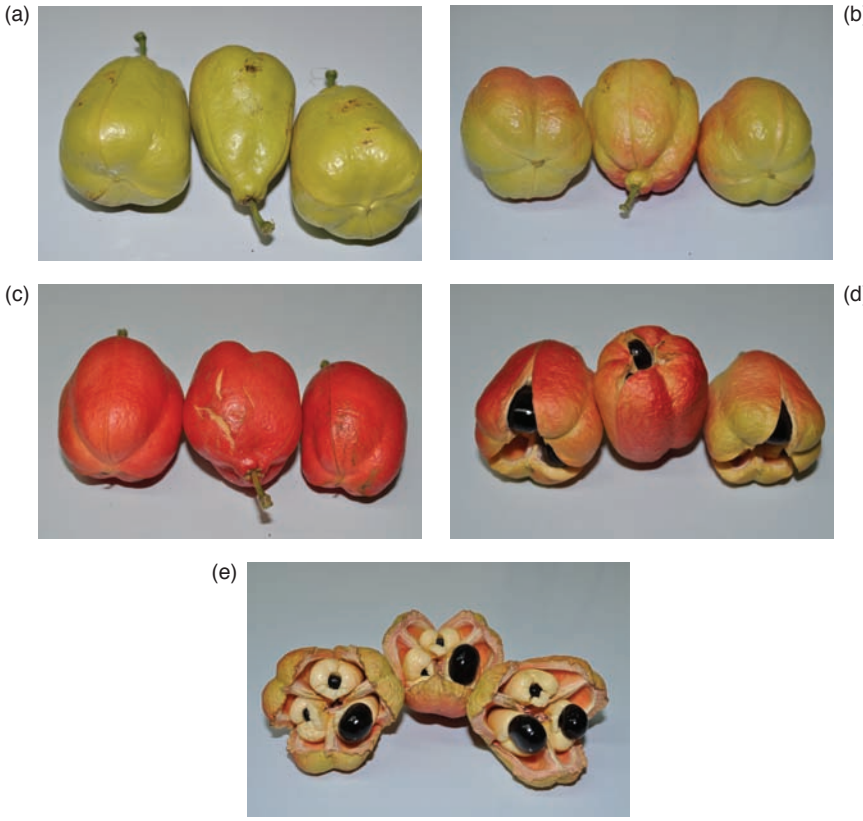

Plate VI The ripening stages of ackee fruits.

Plate VII Aonla tree.

Plate VIII Aonla fruits.

Plate IX Colour chart of the different classes of the six maturity classes of arazá fruit. 1. Mature-green; 2. Breaker; 3. Half-yellow (turning); 4. Yellow; 5. Fully mature; 6. Over-ripe.

6

Arazá (*Eugenia stipitata* McVaugh)

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Abstract: Arazá is an Amazonic fruit from the *Myrtaceae* family with a sigmoidal growth and a shelf life of less than four days at 20°C. The acidic pulp contains high levels of vitamin C, provitamin A, proteins and malic acid, and has a very pleasant aroma. The fruit is usually harvested in its mature-green stage of maturity, using skin colour, titratable acidity and fruit firmness as harvest indices. The fruit is very susceptible to mechanical damage, dehydration and shrivelling, anthracnose rot, softening and chilling injury at temperatures below 12°C. Postharvest treatments such as modified atmosphere packaging, intermittent warming, 1-methylcyclopropene and hot water dips, and use of adequate packaging may extend its shelf life up to two weeks at 12°C. The fruit is used fresh and processed (juices, frozen pulps, jams, sweets). This chapter describes basic recommendations for postharvest handling and maintaining quality, and suggests future research directions.

Key words: *Eugenia stipitata*, postharvest, climacteric fruit, vitamin C, shrivelling.

6.1 Introduction

6.1.1 Origin, botany, morphology and structure

Arazá (*Eugenia stipitata* McVaugh) is a perennial tree of the *Myrtaceae* family, *Eugenia* genus. Two subspecies were described by McVaugh (1956): *stipitata* from Brazil and Peru (also known as *araçá-boi* in Brazil or as *pichi* in Peru, the wild one), and *sororia* from Peru (also called *rupina caspi*, the domesticated subspecies). One landrace occurs in the Western Amazon (Gentil and Clement, 1997).

The arazá fruit is a fleshy berry with a fine, yellow, pubescent epicarp, and attractive flavor (Galvis and Hernández, 1993a). Fruit shape is different in both subspecies of arazá: round to oblate in sp. *stipitata* and ovoid in sp. *sororia*.

With regard to the arazá fruit's structure, the parenchyma is the predominant tissue, with rounded cells and a well-defined thin cell wall. A cross-section of

mature arazá fruit shows that cell growth stops in the last phase (S3), when the cell walls become thinner and deteriorate, while the seeds reach their definitive size and the fleshy mesocarp shows thin-walled cells. By the end of S3, the intercellular spaces are enlarged, while the cell wall becomes weaker as a result of hydrolysis, and the secretory channels have deteriorated. The pericarp of the mature arazá fruit includes the epidermis, a single external layer with thin-walled cells that divide anticlinally. The hypodermis, with small meristematic cells, lies below the epidermis. Secretor channels originate from the hypodermis. Several layers of parenchymatic cells form the mesocarp tissue. The pericarp increases at the beginning of fruit development as a result of cell division and later by cell expansion (Hernández *et al.*, 2007b).

6.1.2 Worldwide importance

Arazá is grown in countries of the Western Amazon basin (Peru, Brazil, Colombia, Bolivia, and Ecuador) and also in Costa Rica. Arazá seeds have been distributed to grow trees for ornamental purposes (e.g. Florida, Brazil). The main harvest season is February to May for the subspecies *stipitata* in Belém, Brazil (Morton, 1987). Two and sometimes up to four production seasons exist in Colombia's Northern Amazon owing to the short period of growth between fruit set and harvesting (around 84 days in San José de Guaviare, Colombia) (Galvis and Hernández, 1993a). The production is year-round in the southern Amazon (Hernández and Fernández-Trujillo, 2004).

As a tropical fruit, its potential economic value is very high. However, currently any economic value is limited to the countries of origin because the fruit is rarely exported. In Colombia, it is considered to belong to the second group of tropical fruits with export potential. The fruit is not usually edible as fresh, but is used after processing. The frozen pulp in different formats is offered for export to North America and Europe particularly from Costa Rica and Colombia, since Brazil consumes most of its own production.

6.1.3 Culinary uses, nutritional value and health benefits

Arazá is marketed fresh, but is usually consumed as a strong or weak juice or in fruit or juice cocktails. It is also used in nectars, jellies ('ates' or 'bocadillos' in Spanish), jams and preserves. Arazá flavoring is commonly used to flavor sweets, ice creams, sorbets, yogurts (including organic yogurt), yogurt shakes with up to 35% arazá pulp, and other beverages (milkdrink, acidmilkdrink, fitdrink, powerdrink, wheydrink, refreshments), syrup, or to produce pulp-based foods such as 'aragurt'. A jelly can be made from the pulp and seed, but excessive cooking partially destroys its attractive flavor.

Fruit composition reports in the literature are based on a dry or a fresh weight basis, depends on the subspecies considered (Table 6.1), and mainly consists of 8 to 10.75% proteins, 5 to 6.5% fiber, 69 to 72% other carbohydrates, 0.16 to 0.21 calcium, some phosphorus, potassium and magnesium and 10 to 12 $mg \cdot kg^{-1}$ of

Table 6.1 Composition of fully mature arazá fruit in percentage of fresh weight

Component	Subspecies		
	Sp. stipitata	Sp. sororia	E. stipitata (dry matter basis)
Humidity	90	91.5	–
Protein	1	1.0	11
Carbohydrates	7	5.5	48
Fats	0.3	1.1	ND
Ash	1.1	ND	4
Fibers	0.6	0.9	37
Ascorbic acid (mg)	7.7	30.3	300

Sources: Gentil and Clement (1997); Hernández *et al.* (2009); Rogez *et al.*, (2004.)
Note: ND = not determined.

zinc (ICRAF, 2009). Total dietary fiber is around 39% dry matter (Rogez *et al.*, 2004). The starch content is significant, even in ripe fruit (0.63%; Filgueiras *et al.*, 2002). In 100 g of fruit there is approximately 7.75 mg of vitamin A, 9.84 mg of vitamin B1 and 7.68 mg of vitamin C (doubling the orange juice levels) (Rogez *et al.*, 2004). The surprisingly high protein content presumably results from the inclusion of the seeds (ICRAF, 2009).

The predominant organic acid in arazá fruit is malic acid (250 $\mu mol \cdot g^{-1}$; Fig. 6.1a), while succinic and citric acids are low (below 50 $\mu mol \cdot g^{-1}$ at S3 stage) (Hernández *et al.*, 2007b). The concentration of soluble sugars (glucose, fructose and sucrose) is low (Table 6.1; Fig. 6.1b). Total phenolics in mature fruit reach 64 $mg.100^{-1}$ g fresh pulp of gallic acid (Vargas *et al.*, 2005).

Total pectic substance content in yellow fruit (0.4%) is not very high, and one-fifth of the total pectic material is water-soluble, while the high-methoxyl fraction is quite small but still predominant in the alcohol insoluble solids fraction. The native activity of the pectic enzymes (pectinmethylesterase and polygalacturonase) is relatively low (Filgueiras *et al.*, 2002).

Essential amino acids content is close to the needs of preschool children and is an ideal proportion for adults, in the case of valine, leucine, isoleucine, threonine, methionine, lysine, histidine and arginine. Of the amino acids, glutamic acid and glutamine followed by asparagine/aspartic acid show the highest concentration (Rogez *et al.*, 2004).

The bioactive compounds in arazá could have potential human health benefits owing to the potential antioxidant and free radical scavenging properties (Duke, 2009). Although local folk medicine recommends arazá for bowel and bladder treatments and for alleviating colds, no research has been done to contrast these treatments on a rational scientific basis.

The most abundant aroma compounds in arazá fruit are sesquiterpenes with 38% germacrene D followed by 10.4% α-pinene and 15.2% β-pinene, and others

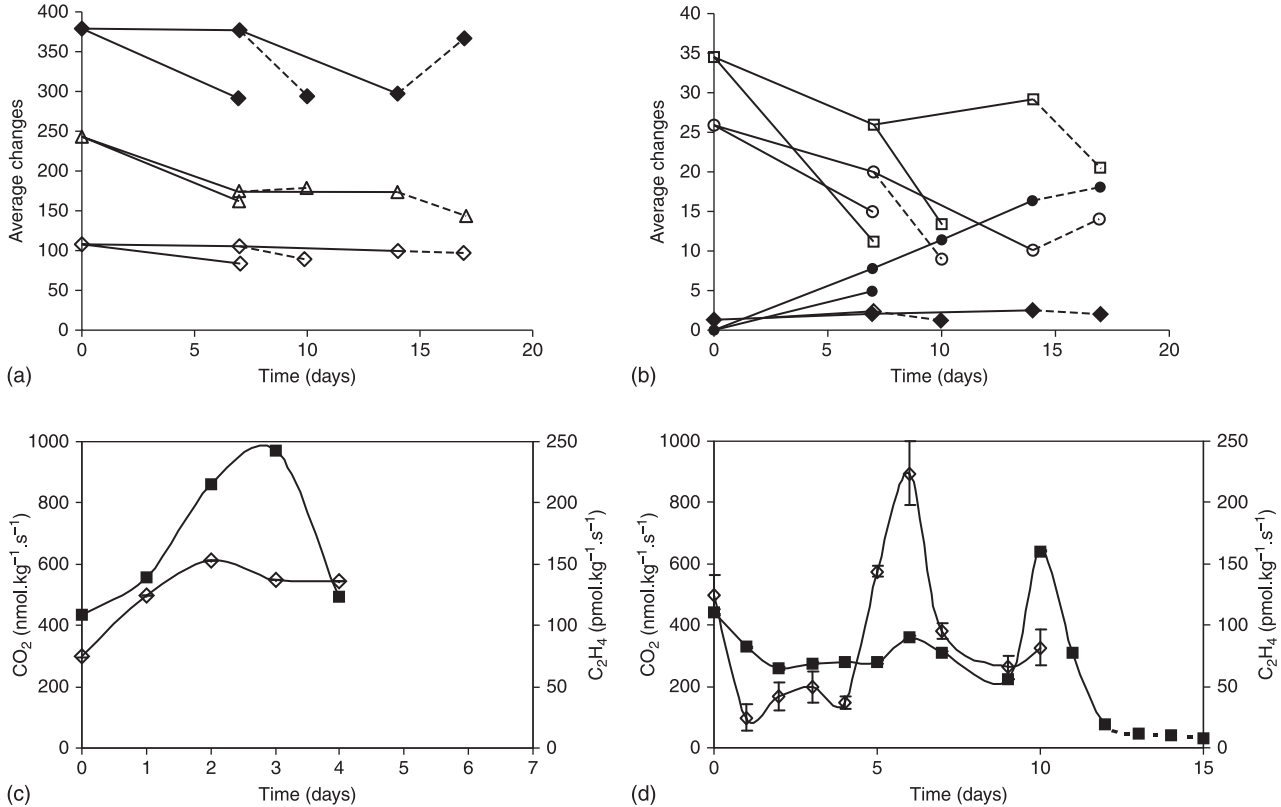

Fig. 6.1 Changes in arazá fruit during ripening and postharvest storage at 20°C and 12°C: (a) Titratable acidity (♦); Malic acid (Δ) Hue angle or h* in sexagesimal degrees, (◊); (b) Weight loss (percentage on a fresh weight basis at harvest), (●); Firmness; (N, □); Ascorbic acid (μmol/g fresh weight), ○); Fructose content (μmol/g fresh weight ▲). Levels at harvest were flesh firmness of 34.6 N, 26 μmol/g ascorbic acid and 1.2 μmol/g fructose; (c) Respiration rate (RR) in nmol·kg^{-1}·seg^{-1} of CO_2 of mature green arazá fruit during ripening at 20°C (♦) or 12°C (■) and 85% relative humidity; (d) Ethylene production (EP) expressed in μL·kg^{-1}·h^{-1} of C_2H_4 and the same storage conditions than RR.

at concentrations below 2.5% of the total headspace area counts. Traces or low relative total headspace percentages have been reported for another thirty aromatic compounds, while several remain unidentified. Esters are present at relatively low concentrations (Franco and Shibamoto, 2000).

6.2 Fruit development and postharvest physiology

6.2.1 Fruit growth, development and maturation

Fruit development follows a simple sigmoid curve with three phases of fruit growth: an initial phase of cellular division, followed by an exponential growth phase of cellular elongation, and finally the ripening phase (Hernández *et al.*, 2007b). Sigmoidal models of fruit growth have been developed for fruit weight (on a fresh and dry matter basis) and equatorial and longitudinal diameter (Hernández *et al.*, 2007b).

6.2.2 Respiration, ethylene production and ripening

Arazá fruit shows a climacteric pattern during its fast ripening, accompanied by peak of ethylene production (Galvis and Hernández, 1993b; Hernández *et al.*, 2007b and 2009). Before the initiation of the climacteric, respiration rates are around 50 mg $\cdot kg^{-1} \cdot h^{-1}$ of CO_2, while the upsurge of respiration during the climacteric period reaches a peak of around 200 $mg \cdot kg^{-1} \cdot h^{-1}$ of CO_2 (Fig. 6.1c). Ethylene production peak matches the climacteric CO_2 peak during arazá ripening; the levels in mature fruit reaching 20 $\mu L \cdot kg^{-1} \cdot h^{-1}$ of C_2H_4 (Fig. 6.1d).

Ripening changes include a pronounced change in skin color from green to yellow, softening, and the development of a pleasant aroma; an increase in polygalacturonase activity, soluble pectin and high-methoxyl alcohol insoluble pectin; a decrease in organic acid concentration (including ascorbic acid) and low-methoxyl alcohol insoluble pectin, accompanied by a decrease in titratable acidity and total and free and bound phenolics (Figs. 1A and 1B; Filgueiras *et al.*, 2002; Vargas *et al.*, 2005). For example, ascorbic acid may decrease by 25% during one to two weeks of storage at optimum temperatures (12°C) and particularly after transfer to ambient marketing conditions. Fruit skin is hairless and attains maximum antioxidant activity when fully mature (Filgueiras *et al.*, 2002; Vargas *et al.*, 2005).

Differences between subspecies are not well studied, but the subspecies *sororia* presents a pleasant acid taste and higher total soluble solids (6.2°Brix and 231 mM of H^+ of titratable acidity) when it is mature compared with the subspecies *stipitata* (3.8°Brix and 296 mM of H^+ of titratable acidity).

6.3 Maturity and quality components and indices

Arazá longitudinal and equatorial size is around 70 mm, and average fruit weight is 150 to 200 g (Donadio and Moro, 2002; Hernández *et al.*, 2009; Tai-Chun and

Álvarez, 1995). In the wild, fruit berry weight can vary from 30 to 800 g (Gentil and Clement, 1997). In Colombia, skin accounts for around 8% of the total weight, seeds 23% and pulp 69%, with an average of thirteen seeds per fruit (Hernández *et al.*, 2007b). In Jaboticabal SP (Brazil), an area where arazá has been tried for ornamental purposes, Donadio and Moro (2002) reported a total weight of 153 g with around 33% skin, 18% seeds and 49% pulp. This result indicates that small and less juicy fruit may be an indicator of less adapted trees and poorer fruit quality.

Skin color can be evaluated to classify the fruit maturity using a visual scale of 1 to 6 degrees (Plate IX: see colour section between pages 244 and 245) that matches lightness, chroma and hue skin color indices (L*, C*, h*), as defined by Hernández *et al.* (2009) and shown in Fig. 6.1a and Plate IX (see colour section).

Class 1 is mature green, with the entire surface being dark green, L* = 52 to 54 units, C* = 32 to 37 units, h* = 106 to 108° (but fruit still capable of ripening; Plate Xa: see colour section). Class 2 is a breaker with 85% green and 15% pale yellow, and L* = 54 to 57 units, C* = 38 to 41 units, h* = 101 to 105°. The rest of the classes show more than 50% yellow skin. Class 3, is a half-yellow (turning) fruit with 50% yellow and L* = 58 to 60 units, C* = 42 to 44 units, h* = 95 to 99°. Class 4 corresponds to yellow, with 75% yellow color with L* = 61 to 64 units, C* = 45 to 48 units, h* = 89 to 94°. Class 5 is fully mature, with 100% yellow color (the optimum color for fresh consumption, Plate Xb: see colour section) with L* = 65 to 67 units, C* = 49 to 54 units, and h* = 83 to 88°. Finally, Class 6 is overripe fruit, with dark to yellow skin with L* = 68 to 71 units, C* = 55 to 59 units, h* = 80 to 84°.

Harvest indices used in Colombia include a skin color hue value (h*) of around 110 ± 2° (corresponding to the dull green stage), a flesh firmness of around 30 N (Newton) and titratable acidity (TA) value above 300 mmol L^{-1} of H^{+}. A level of 1 in maturity index (obtained by dividing total soluble solids between titratable acidity expressed in percentage of malic acid) has also been suggested as harvest index (Hernández *et al.*, 2009). Depending on the stage of maturity at harvest, the pulp has a low soluble solids content (3.4 to 6.2°Brix), and pH is around 2.6 to 3.4 units, while titratable acidity is close to 3% malic acid (Fig. 6.1a).

Dry matter increases during fruit growth, reaching levels of around 17% w/w in mature fruit (Hernández *et al.*, 2009). Over-mature fruit (Plate Xc: see colour section) is prone to suffer fermentation, although its high pulp acidity limits microorganisms proliferation.

6.4 Preharvest factors affecting fruit quality

Fruit composition of arazá fruit given in the literature varies, particularly as regards the ascorbic acid content, probably due to differences in methodology used (extraction and analysis) and also to the stage of fruit maturity, subspecies, origin and natural genotypic and genotypic x environment variations. Arazá also shows differences in its nutrient content depending on the individual tree tested, particularly in thiamine, riboflavin, calcium, sodium, potassium and magnesium,

and, to a lesser extent, total protein content, fat, fiber, iron, phosphorus and ascorbic acid. Soil quality and mineral availability are important factors in the nutrient value of arazá (Barrantes *et al.*, 2002), and therefore influencing fruit size and composition.

Climactic conditions are critical for arazá trees and for the production of good quality fruit. External aspects of the fruit and its susceptibility to preharvest disorders and diseases are particularly affected. The main meteorological factor affecting arazá production is precipitation. Relative humidity and temperature have secondary impacts on the flowering and fruiting. If these factors are constant and annual rainfall ranges between 200 and 300 mm·month^{-1}, the shrub produces heavy and colored fruits (Aguiar, 1983). Otherwise the fruit is prone to attack by fruit flies and anthracnose during growth.

Donadio and Moro (2004) mention the poor adaptation of arazá trees in Brazil outside Amazonic areas and describe severe fungal infection. The susceptibility of fruit to mechanical damage is also evident during preharvest (bruises and fruit deformation; Plate Xd: see colour section between pages 244 and 245). Fruits without adequate shade are susceptible to sunscald. Fruit production increases when plants reach their mature stage (age six to eight years) but also in the months with more rainfall or when plants are shaded by trees such as *Cordia alliodora* (van Kanten and Beer, 2005) or *Hevea brasiliensis*. However, the shade intensity must not be too great: arazá fruit has greater fruit sizes under lower shade intensity, and the production of fruit increases (van Kanten and Beer, 2005). In Colombia, Barrera *et al*. (2009a and 2009b) recommends 82% of interception of radiation brightness for achieving the best production. Therefore, agroforestry seems to be a great option due to the shade requirements of this shrub. Such trees also supply nutrients to small arazá trees, protecting them against severe climactic changes (temperatures, rain and winds), and surrounding the fruit with a high relative humidity (above 80%) and adequate temperatures for ripening (Barrera *et al.*, 2009a).

6.5 Postharvest handling factors affecting quality

6.5.1 Temperature management

At harvest, temperatures in the areas of production usually range from 18 to 33°C. To keep arazá fruit cool after harvest, it should be kept as much as possible in the shade and transported overnight from the areas of production to its final destination, since the availability of precooling technologies in the production areas is scant.

6.5.2 Physical damage

Mechanical damage at harvest or during postharvest is the most critical problem for maintaining arazá fruit quality. The high susceptibly to arazá to such damage (with 50 to 80% total postharvest losses) is associated with fast softening, the absence of support tissue (collenchyma or sclerenchyma) and perhaps low fruit dry matter content (Hernández *et al.*, 2007b; Rogez *et al.*, 2004). Damage is caused by bruising (Plate Xe: see colour section) and impact during harvest and

postharvest, compression due to excessive fruit load in the plastic boxes (no more than three levels are advisable), and vibration during transportation. Internally in the fruit, mechanical damage is manifested as light to dark brown spots below the fruit skin with some degree of skin translucency, which may appear after few hours to one day after harvesting (Plate Xc and Xe: see colour section between pages 244 and 245).

6.5.3 Water loss

The second critical problem of arazá is weight loss, particularly in fruit stored above 18°C at low relative humidity, reaching up to 20% w/w at the highest ripening temperatures in less than one week (Fig. 6.1b).

6.5.4 Atmosphere

Ethylene treatments have not been developed for arazá fruit, but accelerated degreening seems to be feasible due to the fast ripening changes of arazá fruit. Carbon dioxide tolerance has not been systematically studied but levels below 6 to 10% seem advisable, with oxygen ranging from 10 to 20.9%, but not for more than 10 to 15 days at temperatures around 10°C (Gallego *et al.*, 2002; 2003).

6.6 Physiological disorders

The main physiological disorders of arazá fruit are chilling injury (scald, pitting, uneven ripeness, re-hardening and excessive acidity), uneven ripeness due to calcium chloride dips, shriveling and senescence off-flavors in over-mature fruit (Plate Xc, and Xe to Xj: see colour section).

6.6.1 Chilling injury

Arazá is very sensitive to chilling injury (CI) at temperatures below 12°C with different degrees of skin scald, followed by pitting (Plate Xf: see colour section), depending on storage duration, as seen from experiments conducted in a temperature range of 6 to 11°C. CI symptoms are more severe in less mature than in mature fruit, particularly uneven ripening (Plate Xg: see colour section). CI symptoms are exacerbated when transferring the fruit to additional shelf-life periods at temperatures above 12°C. Abnormal or uneven ripening in arazá is frequently associated with abnormally high fruit acidity and re-hardening (Hernández *et al.*, 2009). CI symptoms are frequently colonized in a few days by anthracnose rot caused by *Colletrotrichum gloeosporiodes* (Penz.) Penz. & Sacc. (teleomorph: *Glomerella cingulata*).

6.6.2 Other physiological disorders

Arazá fruit is susceptible to concentrated calcium chloride dips (0.36 M or above) with symptoms of uneven ripening in patches and skin injuries that are not alleviated by low-temperature dips (Hernández *et al.*, 2003b; Plate Xh: see colour section).

Arazá is also susceptible to shriveling (Plate Xe and Xi: see colour section between pages 244 and 245) owing to its high susceptibility to dehydration. Senescence symptoms in over-mature fruit include lack of acidity, flesh firmness below 10 N, and off-flavors concomitant with a dramatic increase in fruit decay.

6.7 Pathological disorders

The main postharvest disease in arazá is the above-mentioned anthracnose in wounds or in chilling-injured areas (scalded areas; Plate Xj: see colour section). *Gloesporium album* and *Monilia* sp. have been isolated from decayed fruit (Ferreira and Gentil, 1999; Hernández *et al.*, 2009). The fungi have also been identified in the seeds (Torres *et al.*, 2008). A fungicide treatment with Sportak 45% active ingredient (a.i.) plus prochloraz at 0.24 mL a.i. L^{-1}, blotting and drying in air flow at 12°C has occasionally been used to control anthracnose (Gallego *et al.*, 2003). However, postharvest fungicides are rarely used due to the trend towards organic certification in arazá production. Refrigeration (10°C) plus modified atmosphere packaging usually prevents anthracnose development with or without pre-conditioning the fruit (Gallego *et al.*, 2002). Control of anthracnose with hot water dips alone has been found unsatisfactory (Hernández *et al.*, 2002).

Cylindrocladium scoparium rot is characterized initially by small light brown lesions, which evolve to severe damaged areas that can reach about 0.3 cm of pulp depth (Nuñes *et al.*, 1995). During postharvest handling fruits are usually washed with hypochlorite (200 $mg \cdot L^{-1}$) but rots are only partially controlled and no treatment to control rot has been established.

The pathogenicity of *Curvularia* sp. (Wakk.) Boedijn may be important. This thick-walled pigmented fungus is considered necrotrophic and its development could be a problem because it requires longer postharvest treatments than thin-walled species to reduce germination (Buck *et al.*, 2002). For example, 21% of fruit stored for two weeks at 12°C, followed by a shelf-life period of three days at 20°C, suffered from this rot. Symptoms of *Curvularia* spp. include fruit softness and pink spot areas in the pulp with fermentative degradation and lack of juice (Hernández and Fernández-Trujillo, 2004; Hernández *et al.*, 2009). Fruits stored at lower temperatures showed half the incidence of this rot (Hernández *et al.*, 2009). Its causes have not been completely verified.

The incidence of rust (*Puccinia psidii* or *Uromyces* sp.) has been recorded in Manaus and Costa Rica (Moraes *et al.*, 1994; Tai Chun and Álvarez, 1995). Fruit selection and elimination of decayed fruits are the main preventive measurements against this disease and others.

Yeasts are a minor problem but can affect fruit bruises and/or chemical-scalded areas caused by treatments with calcium chloride dips of 0.36 or 0.72 M (4 or 8% w/v) (Hernández *et al.*, 2003b; 2007b).

In the testa of arazá seeds another sixteen fungi genera have been identified, two of them with sterile mycelium. This might have a negative impact on latent fruit infections. Five of the previous genera (*Colletotrichum* sp, *Fusarium* sp,

Curvularia sp, *Pestalotia* sp and *Cladosporium* sp) are opportunistic and another five are opportunistic pathogens (*Aspergillus* sp, *Penicillium* sp, *Rhizopus* sp, *Myrothecium* sp and *Helmintosporium* sp). *Geotrichum* sp., *Thielaviopsis* sp. and *Rhizoctonia* sp., well-known phytopathogens that affect the fruit of several species (Torres *et al.*, 2008), have been identified in the seeds but not in arazá fruit. Neither biological control of fungal rot nor combined treatments with hot water pretreatments have been applied to arazá fruit.

6.8 Insect pests and their control

The main arazá pests are fruit flies, such as *Anastrepha obliqua* and *A. striata* (diptera: tephritidae) (Saldanha and Silva, 1999), and the coleoptera *Conotrachelus eugeniae* and *Atractomerus immigrans* on rinds. *Neosilba zadolicha* (diptera: lonchaeidae) larvae are seldom present in fruit blemishes caused by these insects (Couturier *et al.*, 1996). The Mediterranean fruit fly (*Ceratitis capitata* Wied) has been identified in Costa Rican orchards (Moraes *et al.*, 1994; Tai Chun and Álvarez, 1995). In the field, plastic McPhail traps baited with attractants are used to capture these flies. Infested fruit must be collected and buried at least 50 cm deep in the ground (Villachica *et al.*, 1996).

The black bee (*Trigona branneri* Cockerell), a bee without a sting, feeds on the skin, pulp and sometimes the seed of the fruit, causes severe fruit damage if the bee population is large (Villachica *et al.*, 1996). There are no quarantine procedures against tropical flies for this fruit, but recommendations to avoid spread of pests from one plantation to another, and integrated protocol management during the pre- and postharvest phase are necessary (Couturier *et al.*, 1994; 1996). Cold quarantine treatments cannot be indiscriminately used because of CI. Pre- or postharvest biological control is not well established and has not even been widely studied yet for arazá.

6.9 Postharvest handling practices

6.9.1 Harvest operations

Fruit are carefully harvested during the morning, packed in polyethylene boxes and transported to a packinghouse (Carrillo *et al.*, 2009).

6.9.2 Packinghouse practices

Fruit are usually selected manually in the field on polished on flat tables covered by washable materials in order to remove small or rotten fruit and others with sunburn or mechanical or insect damages. Fruit can be graded according to the degree of maturity based on skin color (Plate IX: see colour section between pages 244 and 245). Only grades 2 to 3 are usually marketable, while more advanced stages of maturity are sent to local markets and/or immediate processing. Mature green fruit

are the best for long-distance markets (Plate Xa: see colour section between pages 244 and 245). Fruit are packed in reusable polyethylene boxes or boxes made of soft wood. An alternative is to pack the fruit in pouches (a net made of flexible low density polyethylene foam or 'mallalon') to reduce mechanical damage before packing in cardboard or plastic boxes (Carrillo *et al.*, 2009). However, traditional cardboard packaging is not recyclable, so that new recyclable cardboard packaging has been designed in Colombia to allow fruit ventilation and the packing of 8.5 kg fruit dividing the cardboard box into three compartments (Carrillo *et al.*, 2009). The packed fruit is kept in the shade and transported overnight (six to eight hours). Additional postharvest handling treatments involve washing fruit in tap water for 3 min to remove dust and other residuals, sanitizing with 80 to 100 $mg \cdot L^{-1}$ sodium hypochlorite for 5 min, and finally rinsing in tap water to remove residues of the treatment before allowing to dry in air. Such fruit are less susceptible to rot during ripening in the recommended storage conditions (12 to 13°C and 95% relative humidity; Peña *et al.*, 2007).

Arazá fruit is not subjected to waxing. Experimental edible coatings of yuca or cassava (*Manihot esculenta* Crantz) starch have been tested. This coating is prepared by dissolving yuca starch (2% w/v) for 15 min at 78°C until jellification. Glycerol (2%) is added as the plasticizer and the gel is stirred for 10 min. Fruit are dipped in this mixture for 1 min at 15°C and then let to dry for 3 h. Starch coatings do not contain emulsifiers or lipids because of possible deterioration of the film properties. The coating delays ripening changes, such as the climacteric peak and color changes from green to yellow; also, respiration rates and ethylene production are reduced, but coating does not affect other internal quality traits (Jiménez *et al.*, 2008).

6.9.3 Control of ripening and senescence

The short shelf life of arazá fruit (three to four days at 25°C or above) is due to a high respiration rate (RR), high levels of ethylene production (EP), accompanied by severe dehydration, shriveling, softening and susceptibility to mechanical damage, anthracnose decay, and also due to CI at temperatures below 11 to 12°C.

Hot-water dips (5 min at 50°C; HWD) can accelerate arazá ripening during subsequent storage at 12°C: At this treatment predominant acids are consumed, which is an advantage during the marketing of this acidic fruit.

A solution of calcium chloride in HWD increases calcium absorption by the fruit and contributes to the delay of some ripening changes. Calcium chloride dips alone (i.e. 0.36 M at 4°C), delay ripening changes during subsequent ripening at 12°C because of the better retention of sugars (mainly sucrose and fructose) and organic acids (malate and succinate). However, anthracnose, and to a lesser extent, other signs of decay can be exacerbated by this treatment. Low-temperature calcium chloride dips far below 0.36 M could be a promising treatment for retaining overall internal fruit quality and modulating calcium absorption by the fruit (Hernández *et al.*, 2003b).

1-methylcyclopropene (1-MCP) has been used at laboratory and semi-commercial scale in arazá (Carrillo *et al.*, 2011; Hernández *et al.*, 2007b). 1-MCP

is even effective for treating the fruit at tropical temperatures (27°C) for 1 h. Recommendations for maintaining postharvest quality are harvesting at the mature-green stage, treatment with 1 μL L^{-1} of 1-MCP for 1 h, and storage at 12°C for up to two weeks. This treatment prolongs arazá postharvest life by about one week by delaying or reducing the respiration and ethylene production rates, skin color changes, the loss of organic acids, and softening. Also, 1-MCP can have an important effect by reducing rots and weight losses. At 7°C, 1-MCP also reduces mature-green fruit weight loss and shriveling. Long 1-MCP treatment periods of 6 or 12 h at 20°C caused partial and uneven ripeness. Treating fruit in their post-climacteric stage of maturity had little effect on ripening compared with the mature-green stage. 1-MCP increases the respiration rate and/or the ethylene production in certain combinations of advanced harvest maturities and/or unfavorable storage temperatures.

Ethylene treatments seem to be unnecessary because of the fast ripening of mature-green arazá fruit after harvest.

6.9.4 Recommended storage and shipping conditions

The best storage temperature is 12°C for less than two weeks with 90 to 95% relative humidity because this avoids CI and reduces shriveling and rot development. Relative humidity levels below 85% would result in unacceptable weight losses and shriveling. A warming treatment of 18 h at 20°C with 90% relative humidity after six days at 10°C reduces skin scald and associated decay, and extends shelf life by up to two weeks (Hernández *et al.*, 2003a).

Respiration rates are very high during the postharvest phase at temperatures particularly above 12 to 13°C and carbon dioxide removal will prevent CO_2 accumulation within the storerooms. Ethylene scrubbing is also advisable if the fruit is kept in contact with other fruits susceptible to ethylene. Information about controlled atmosphere storage in arazá is lacking, but modified atmosphere (MA) packaging or individual seal packaging has been used. For example passive modified atmosphere was generated within a selective low-density polyethylene (LDPE 38 μm, film permeability 4,000 cm^3 m^{-2} d^{-1} to O_2, 2,700 cm^3 $m^{-2}d^{-1}$ to CO_2, and 0.4 to 0.6 cm^3 m^{-2} d^{-1} to water vapour) (Gallego *et al.*, 2002; 2003). Carbon dioxide levels above 5% within the packages should be avoided.

MA packaging of individual fruit has been tested. For example, the storage of arazá fruit under active MA conditions with the injection of 2% CO_2 and 21% O_2 preserves fruit quality for 2 weeks at 10°C. This treatment delays changes in color parameters (L*, C* and h*), and results in reduced incidence of anthracnose, scald and weight loss compared with control fruits and fruit packaged in macroperforated or the LDPE films reported before (Gallego *et al.*, 2003; Hernández *et al.*, 2007a). Compatibility for transportation is similar to that found in other climacteric and aromatic tropical fruit sensitive to CI. The fruit must be transported with other aromatic tropical fruit sensitive to ethylene and chilling injury (i.e. at temperatures of 12 to 13°C and preferably with good air renewal).

6.10 Processing

6.10.1 Fresh-cut processing

Arazá fruit has low potential for fresh-cut processing due to the presence of seeds and the very high acidity of the pulp. However, small chunks can be used in confectionery.

6.10.2 Other processing practices

Arazá unit processing operations to obtain pulp have been reported by Hernández and Barrera (2000; 2004). Fruits are rinsed with tap water (by sprinkling or immersion) to remove residues and the remains of tree branches and leaves. Fruits are then disinfected by immersion in a solution of 400 $mg \cdot L^{-1}$ thiabendazole for 5 min under continuous fruit movement. After that a second rinsing removes fungicide residues with pressurized tap water sprinklers. Then the fruit is allowed to dry before separating into maturity classes (Plate IX: see colour section between pages 244 and 245), removing fruit without the adequate quality attributes. Fully mature fruit (soluble solids/titratable acidity ratios of 1 to 3; Plate Xb: see colour section) are the best for pulp processing following the protocols reported by Hernández and Barrera (2000; 2004).

Processing practices such as freezing, canning, drying or osmotic dehydration have been used to preserve arazá pulp and juices. Aseptic packaging could be used to improve pulp quality. Blanching arazá pulp for 7 min, fast freezing and slow thawing help to maintain textural properties, including liquid retention and ascorbic acid content, while changes in phenolic compounds, β-carotene and antioxidant activity are minimized (Millán *et al.*, 2007).

Traditional products include frozen pulp, traditional canning of the whole fruit, nectars, jams, fermented beverages in milk serum, wines, spiced or non-spiced sausages, jellies, candies and different kind of biscuits, sweets and desserts (Hernández *et al.*, 2006; Carrillo *et al.*, 2009; Rodríguez and Bastidas, 2009). Candies of different compositions are one of the best-known fruit pulp uses, and certain brands are very successful in the national market. The fruits have also been used to produce liquors (Andrade and Ribeiro, 1997) and perfumes.

Arazá is lyophilized after adding 10% v/w of the dissacharide trehalose solutions (25°Brix) to fresh pulp, which results in reduced browning associated with the Maillard reaction and good flavor quality.

The last innovation in commercial-scale pasteurized pulp is the use of flexible packaging. These packages are stored under refrigeration for up to 50 days with minimum additives (0.15 $mg \cdot kg^{-1}$ sodium benzoate and potassium sorbate, respectively) (Carrillo *et al.*, 2009).

Deacidification of clarified arazá juice by electrodialysis can be used to produce malic acid but reduces flavor without affecting overall sensory properties (Vera *et al.*, 2007).

6.11 Conclusions

Challenges to maintain arazá's fresh fruit quality in the future will be based on reducing the high total losses without compromising flavor and nutritional quality.

The transport system is usually a limiting factor in the Amazon basin. New transportation systems should be developed and implemented, taking into account factors such as vibration and difficulties in adequate temperature management. This, in turn, is directly linked to energy supply guarantees at a reasonable economic and environmental cost.

Adapting general harvest and postharvest recommendations to different growing areas is required, because such aspects as the effect of fruit subspecies behavior or fruit variability in postharvest conditions have not been addressed. It is necessary to establish a table of quality grades for the fruit, taking into account the variability that exists between subspecies.

The first goal should be to develop alternative and sustainable fruit packages and a postharvest handling system to reduce mechanical damage during harvesting, handling and transportation. The second goal must be the development of quarantine procedures, particularly for mature-green fruit. A good start may be trials with metabolic stress disinfestation procedures. This procedure is based on physical manipulation, generating cycles of expansion and compression forces, which are combined with low vapor concentrations of natural disinfecting chemicals to disinfect and disinfest simultaneously and rapidly fresh agricultural products (Lagunas-Solar *et al.*, 2006).

The third goal must be the development of sustainable coatings to keep weight loss below reasonable levels in tropical temperatures without fermentation. Finding alternatives to sodium hypochlorite is also desirable.

The fourth goal should be to establish postharvest protocols combining the removal of rotten fruit, the careful selection of defect-free fruit according to the stage of maturity, precooling, temperature control and treatments with ripening inhibitors and other coadjutants in order to offer local consumers good produce and reinforce local markets. The development of new cultivars with a reduced number of seeds or parthenocarpic fruit may open up new possibilities for fresh-cut processing (particularly as cubes or slices). The development of molecular markers based on simple sequence repeat (SSR) loci in arazá (Zapata-Ortiz *et al.*, 2009) will boost gene expression studies in the future. Studies of postharvest behavior parallel to breeding as well as germplasm and biodiversity maintenance are required, because different ecotypes in the arazá subspecies have been identified.

New postharvest treatments must be developed, and others, such as heat treatments in combination, should be reevaluated. For example, gradual cooling combined with MA packaging using a suitable polymeric film and adequate storage conditions could avoid physiological disorders in arazá fruit.

The variability of some nutrients in arazá points out to interesting field that will benefit from proper crop management and nutritional quality-oriented arazá breeding for postharvest purposes. Cultivars with a lower susceptibility to postharvest disorders and diseases and higher resistance to postharvest handling without sacrificing flavor are required. Agroforesty associations can be developed to provide shade in order to improve fruit quality and size.

Socioeconomic and environmental issues must be carefully addressed, too. The marketing of the fruit is strongly based on sustainable management of the

crop, and care for the Amazon Basin and its population. It is used to promote business for local or international companies exporting fresh or processed tropical Amazonian fruit. However, arazá is now grown in areas outside the Amazon Basin, in Colombia for example.

In summary, arazá is a very perishable fruit, very sensitive to mechanical damage, CI and shriveling. The fruit has serious constraints for marketing at local or international level without the maintenance of the cold chain alone or combined with other postharvest treatments, such as MA packaging, ethylene inhibitors and good handling practices and packaging. In the absence of such measures and a market for fresh fruit, more than 70% of the production must be processed in producing areas and new products and by-products should be scaled to industrial level, taking into account possible loss of ascorbic acid and labile nutrients. Different food processing technologies could be used to improve pulp quality and added value to the derived products.

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Plate VIII Aonla fruits.

Plate IX Colour chart of the different classes of the six maturity classes of arazá fruit. 1. Mature-green; 2. Breaker; 3. Half-yellow (turning); 4. Yellow; 5. Fully mature; 6. Over-ripe.

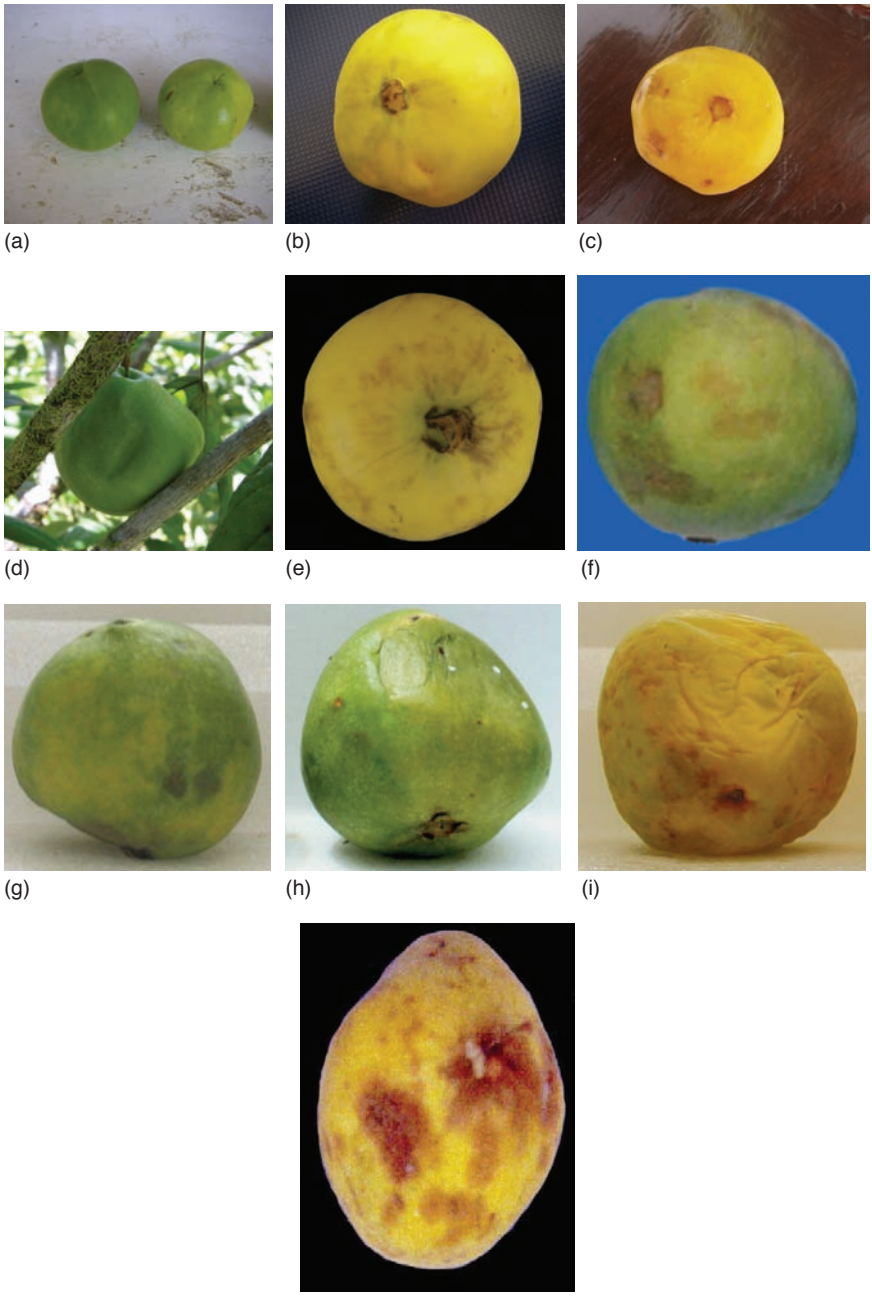

Plate X Major physiological and pathological disorders in arazá fruit (a) Sound, mature-green fruit; (b) Sound, fully mature fruit; (c) Over-mature fruit (water-soaked aspect); (d) Mechanical damage in the tree; (e) Shrivelling plus typical brown patches of mature fruit (bruising); (f) Pitting and skin scald; (g) Uneven ripeness (due to chilling injury); (h) Uneven ripeness due to calcium chloride treatments; (i) Severe shrivelling with skin scald (chilling injury symptom and certain degree of uneven ripening; (j) Anthracnose rot on skin scald.

7

Assyrian plum (*Cordia myxa* L.)

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Abstract: *Cordia myxa* (which bears the Assyrian plum) is a common tree in certain Asian and African areas. The tree, leaves and fruit of *Cordia myxa* have important applications in different societies and the fruit is known for its medicinal uses. Very little research on *Cordia myxa* has been published, but the focus of most articles to date has been nutritional and toxicological analysis. This chapter reviews the many useful characteristics of this underutilized and understudied fruit, including its health-promoting properties. There is the need to explore possible uses for bioactive or functional components extracted from the fruit, which may find application in food processing or in new products. More studies are needed to advance understanding of the fruit's postharvest quality attributes and characteristics and to develop useful postharvest technologies to help maintain quality and extend shelf life. This may not only encourage farmers to grow more *Cordia myxa* trees, but also would promote culinary uses and research into other applications. Increased production of this crop would help to enhance the nutritional status of many people, especially in Asia and Africa where the tree is cultivated, and at the same time introduce the fruit to new markets around the world.

Key words: *Cordia myxa*, postharvest, medicinal uses, quality attributes, soluble acids, titratable acidity, firmness.

7.1 Introduction

7.1.1 Origin, botany, morphology and structure

Cordia myxa L. is probably native to an area stretching from tropical Africa through to the Middle East. It is part of a genus of about 320 tropical species that belongs to *Boraginaceae* (Hound's-Tongue) family. Its common name is the Assyrian plum and the fruit has the following plant classification (Weaver and Anderson, 2007):

Kingdom:	*Plantae*
Subkingdom:	*Tracheobionta* (vascular plants)

Superdivision:	*Spermatophyta* (seed plants)
Division:	*Magnoliophyta* (flowering plants)
Class:	*Magnoliopsida* (dicotyledons)
Subclass:	*Asteridea*
Order:	*Lamiales*
Family:	*Boraginaceae* (borage family)
Genus:	*Cordia* L. (cordial)
Species:	*Cordia myxa* L. (Assyrian plum)

There are approximately 300 different species of trees and shrubs of the *Cordia* genus in the *Boraginaceae* family. The cordias are characterized by their extravagant, fragrant flowers, hairy leaves, and edible fruits. The name *Cordia* is derivative of the surname of sixteenth-century German botanist Valerius Cordus and the species name *myxa* comes from the Greek word for mucus. Common names of the fruit of *Cordia myxa* include Assyrian plum and sebesten. The tree is also known as the bird's nest tree.

Figures 7.1 to 7.4 and Plates XXI and XXII (see colour section between pages 244 and 245) show the different parts of the *Cordia myxa* tree. The tree, branches, leaves and fruits of *Cordia myxa* can be described thus (Oudhia, 2007): *Cordia myxa* is a

Fig. 7.1 *Cordia myxa* tree.

Fig. 7.2 *Cordia myxa* leaves.

dioecious shrub or small tree that can be as high as 12 m, with either a tortuous or straight bole and grey, cracked bark (Fig. 7.1). The branchlets are hairy, though they later become glabrous with very prominent leaf scars. The leaves are characterized by alternate, simple, stipules with a petiole length of 0.45 to 0.5 cm. The shape of the leaf is variable, with a blade that can be broadly ovate or orbicular, a base that can be round, cordate or cuneate, an apex that can be either rounded or acuminate and margins that vary from entire to toothed (Fig. 7.2). The flowers of the *Cordia myxa* are unisex; they have a white or creamy coloring and a pedicel length of 1 to 2 mm (Fig. 7.3). The fruit, an either globular or ovoid drupe of 2 to 3.5 cm in length, is apiculate and enclosed at the base by the accrescent calyx (Plate XI: see colour section between pages 244 and 245). As shown in Fig. 7.4, the pulp of the fruit is transparent, mucilaginous and sweet in taste. In addition, the fruit is pale brown or pink in color, becoming darker as it ripens. Small chains of flowers appear in March/April (University of Arizona, 2009). A selection of 30 groups of *Cordia myxa* collected from 95 sites with different

Fig. 7.3 *Cordia myxa* flowers.

Fig. 7.4 Cross-section of *Cordia myxa* fruit.

agro-climatic conditions showed significant variations in plant growth, leaf size, fruit size, yield and fruit quality; genotypes with large size leaves are more likely to produce larger size fruits (Samadia, 2005).

7.1.2 Worldwide importance

Cordia myxa is important in a number of cultures, in which it has several uses and applications. The Bobo people in Burkina Faso, for instance, consume the fruit and seeds, use the leaves for medicinal purposes, and consider the wood too sacred to be burnt (Weaver and Anderson, 2007). To give another example, the low productivity of khadins (a type of farming system for producing food grain, which is important in many areas around the world, especially in the western region of the

Indian arid zone) can be overcome by planting trees such as *Cordia myxa* (Prasad *et al.*, 2004). Furthermore, although in some regions the *Cordia myxa* does not require formal cultivation, it helps to improve the dietary status of local people, especially in certain regions of Asia and Africa (Aberoumand, 2009a).

7.1.3 Culinary uses, composition, nutritional value and health effects

Cordia myxa cultivation is not widespread. It is grown on a limited scale, especially in domestic gardens, In the state of Kuwait and other gulf countries, where it is known as Bambar, it is a popular summer fruit that can be eaten fresh when it is ripe or picked partially ripe for processing or pickling. Similar practices are also followed elsewhere. It is valued for its attractive aroma, delectable full round shape, pink color and fruity sweet flavor. Its popularity has been decreasing recently, though, probably as a result of its high perishablility, and hence short shelf life and limited marketability.

Most of the published papers about the Cordia species have focused on its composition and its nutritional, medicinal and toxicological properties. Compositional analysis shows that on a dry weight basis, *Cordia myxa* contains about 6.21% water, 12.75% glucose, 9.38% fructose, 29.09% sucrose, and 5.86% starch (which is relatively low for a fruit), 248 mg 100 gm^{-1} phytic acid and 1.39 TIU g^{-1} trypsin inhibitor (Aberoumand, 2009b). It also contains 25.7g. $100g^{-1}$ total dietary fiber (relatively high compared to other fruits), as well as 4.5% pectin (Aberoumand and Deokule, 2010). The fruit also contains 6.7% ash, 1.62 mg g^{-1} sodium, 7.83 mg g^{-1} potassium, 0.46 mg g^{-1} calcium, 0.51 mg g^{-1} iron and 0.35 mg g^{-1} zinc (Aberoumand and Deokule, 2009). Fageria *et al.* (2003) studied the effect of blanching and sulfitation on the composition and quality of *Cordia myxa* fruits at different maturation stages. They found that harvesting the fruit at 45 days and blanching for 3 minutes with 0.3% potassium metabisulphite (KMS) produced fruits with better sensory quality, higher drying ratios, and higher levels of total soluble solids, ascorbic acid, protein and carbohydrates.

Several researchers have investigated the antimicrobial (de Carvalho *et al.*, 2004; de Souza *et al.*, 2004; Ioset *et al.*, 2000), anti-inflammatory (Sertie *et al.*, 2005; Al-Awadi *et al.*, 2001; Akhtar and Ahmad, 1995), structural and functional properties of components of its fruit (da Silva *et al.*, 2004; Benhura and Chidewe, 2002; Gabbrielli *et al.*, 1993), and some medicinal properties (Canales *et al.*, 2003; Lans *et al.*, 2000) of different parts of the plant.

Extracts of *Cordia* leaves exhibit significant analgesic, anti-inflammatory and anti-arthritic activities (Ficarra *et al.*, 1995). Such activities are thought to be attributed to various flavonoids and phenolic compounds found in the leaves. Four flavonoid glycosides, robinin, rutin, datiscoside and hesperidin, were determined in the *Cordia* extracts, together with one flavonoid aglycone, dihydrorobinetin, and two phenolic derivatives: chlorogenic and caffeic acid.

When acute colitis was induced in the colon of rats, myeloperoxidase activity was high and levels of glutathione peroxidase, superoxide dismutase and trace

elements were low. Treatments composed of *Cordia myxa* fruits reversed these colitis-induced changes in the colon, liver and plasma of colitic rats. It is thought that this anti-inflammatory effect is caused by the antioxidants present in the fruit (Al-Awadi, 2001). A study suggested that the fruit's strong antioxidant activity enhances the activity of *Cordia myxa* against carbontetrachloride or acetamide-induced fibrosis in rats (Afzal *et al.*, 2007). Another investigation showed that the protective role of the fruit against fibrosis induced in rats by carbontetrachloride and thioacetamide could be due to the phenolic content of 11.1 mg g^{-1} gallic acid equivalent and to the antiradical activity, which is measured to be 10.0 (ARA percent) ascorbic acid equivalent (Afzal et al., 2009). The closely-related species *Cordia dichotoma* is also popular in certain cultures for medicinal uses. This is due to the anti-inflammatory compounds alpha-amyrin and 5-dirhamnoside in the seeds and allantoin, *β*-sitosterol and 3′, 5-dihydroxy-4′-methoxy flavanone-7-O-*α*-L-rhamnopyransoide in the bark (Orwa *et al.*, 2009).

7.2 Fruit development postharvest physiology

7.2.1 Fruit growth, development and maturation

Plate XII (see colour section between pages 244 and 245) shows how size, shape and color of *Cordia myxa* fruits change as the fruit matures; Al-Ati, 2010). As it matures, the fruit changes color from green (G) (not ripe), yellowish-green (YG), greenish-yellow (GY), yellow (Y) (fully ripe) and freckled yellow (FY). During the maturation stage the flavor of the fruit also goes through significant changes: while it starts off very astringent (inedible), it acquires a mild sweetness at the yellow stage which is most favored by consumers. The unripe *Cordia myxa* fruit is conical in shape, while fully ripe fruit are round and two to three times larger in size (Plate XII: see colour section). The skin of the fruit is very smooth and, once it reaches full maturity, becomes very delicate and hence very susceptible to even mild mechanical damage. When the fruit is immature, the flesh surrounding the seed is hard, but becomes gel-like as maturity advances acquiring its sweet, fruity flavor as it does so. The diameter of a fully mature fruit ranges from 26.4 to 33.1 mm.

7.3 Maturity and quality indices

Quality tests of *Cordia myxa* reveal that, on average, the fully ripened fruit have: 21.2% moisture, 22.6% soluble solids concentration, pH 6.6, titratable acidity (percentage malic acid) 1.2 (Al-Ati, 2010). The complexity of the taste and flavor is mainly controlled by pH and TA, which determine the sourness and acidity of the fruit, and the SSC determines sweetness (Mitcham *et al.*, 1996). The values of these parameters are therefore important attributes for *Cordia myxa* because they are most likely to be involved in the development of the unique flavor of the fruit. To compare *Cordia myxa* with other fruits, the TA of pineapple was reported to be 1.0% and its SSC is about 12%; while pomegranate has a TA of 1.4%, and its

SSC is 17% (Kader, 2002). Also, a test examining the textural properties of the fruit show that the fully ripe *Cordia myxa* has an average firmness of 1.56 Kg. This is reduced drastically when stored at 8°C for ten days to an average firmness of 0.704 Kg (Al-Ati, 2010).

7.4 Postharvest handling factors affecting quality

There have been very few postharvest studies of *Cordia myxa*. As mentioned above, the fruit is known for its sensitivity to rough handling and is therefore prone to mechanical damage. Cushioned packaging materials may help protect the fruit and its skin from such damage. Water loss seems to diminish the fruit's storage life significantly. According to AOAC (2002), the rates of water loss were investigated in a study by Al-Ati (2010). When the fruit was stored at room temperature for one day, the result was an average water loss of 1.6 g at the yellowish stage of ripeness, 2.5 g at the greenish-yellow stage, and 2.7 g at the yellow stage. However, at day 14 water loss became 4.9 g at greenish-yellow, 7.0 g greenish-yellow and 8.2 g at yellow stage of ripeness. Since a 5 to 8% decline in the water content of peaches and nectarines can result in shriveling that is visible to consumers (Mitcham and Mitchell, 2002), *Cordia myxa* should perhaps be harvested at the yellowish-green stage to help to maintain fruit weight and minimize shriveling.

7.5 Conclusions

Cordia myxa is very popular in certain Asian and African cultures due to its medicinal properties. Researchers have now begun to identify the fruit's nutritional value and demonstrate the health benefits of its components. However, cultivation is still very limited worldwide, and it is of no apparent economic value to any specific country. The cultivation of *Cordia myxa* in the countries in which it can be grown and the promotion of its consumption in different forms (fresh, pickled, etc.) can help societies in these countries to meet their nutritional needs. It has the potential to be a successful commercial product, either as a whole fruit or as an ingredient in a variety of processed food products, but this potential has yet to be exploited.

Current postharvest practices are insufficient to preserve, protect and extend the shelf life of the fruit, and do not allow it to be marketed long distances from its place of cultivation. Further studies on the fruit's postharvest biology and the effects of handling practices are required. These could promote global recognition of the fruit and encourage plant physiologists and technologists to study the fruit in more detail. Improved postharvest practices could also enable it to be exported internationally. Some basic properties of the fruit, such as its respiration rate, have not been measured, and therefore the effect of modified atmosphere packaging and controlled atmosphere storage are not known. Diseases of *Cordia myxa* trees

and causes of fruit quality deterioration and senescence patterns of fruits have also not been studied. Identifying and studying these would be beneficial.

Lastly, a product development approach could also help to produce different food, nutraceutical and pharmaceutical products based on *Cordia myxa*. Such an approach could increase the demand for this nutritious fruit worldwide.

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Plate XI *Cordia myxa* fruits.

Plate XII *Cordia myxa* changes in shape, size and colour as it ripens.

Plate XXI Diversity in the shape of breadfruit (*A. altilis*) cultivars growing at the Breadfruit Institute, National Tropical Botanical Garden. 1. Puurea, 2. Kea, 3. Lipet, 4. Pulupulu, 5. Tuutouauena, 6. Puou. Details for each variety available at http://ntbg.org/breadfruit/database/search. Photograph © Jim Wiseman, courtesy of the Breadfruit Institute, National Tropical Botanical Garden.

Plate XXII External and internal appearance of breadfruit stored for one week at 13°C either unwrapped (control) or wrapped in SealedFresh 15 μm film or in Clysar (DuPont) EHC 15 μm or EHC 60 μm or LLP 60 μm. Source: Worrell (1994).

8

Avocado (*Persea americana* Mill.)

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Abstract: Avocados are a subtropical climacteric fruit that is generally oblong in shape and green skinned, although 'Hass', the dominant commercial cultivar, ripens to purple-black. They are one of the few fruits that contain significant amounts of oils (fatty acids). The high concentrations of monounsaturated fatty acids and other phytochemicals make avocado a very healthy and nutritious fruit. Avocados do not ripen unless removed from the tree, meaning fruit can be mature but 'tree stored' for as long as 12 months. Increased commercial maturity is associated with increased fruit size, oil and dry matter content, and decreased ripening times. Avocados have a relatively short storage life, limited primarily by the expression of internal chilling injury (CI) symptoms, but rots are a limitation for fruit grown in many countries. Optimum storage temperature is generally around 6°C, and temperatures below 3 to 4°C (depending on cultivar and time in the season) lead to external CI (skin blackening). Controlled atmosphere storage and 1-MCP (SmartFresh^{SM}) are effective commercial tools for improving storage life. Since avocado cannot be consumed unripe, an increasingly important commercial tool is the use of ethylene to hasten and synchronize ripening. New processing options, such as cold-pressed oil extraction and high-pressure processing, are receiving increasing attention.

Key words: *Persea americana*, avocado, postharvest, chilling injury, pests, diseases, oil, processing.

8.1 Introduction

8.1.1 Origin, botany, morphology and structure

Avocado is a dicotyledonous plant from the Ranales order and the Lauraceae family. It was classified as *Persea gratissima* by Gaertner, and *Persea americana* by Miller. *P. americana* developed subspecies because of geographical isolation, which finally originated into different botanical types. The avocado tree (*Persea americana* Mill.) belongs to the family Lauraceae and is one of the few commercially significant members of the genus *Persea*. The fruit is called *Ahuacatl* by the Aztecs

in Mexico and from there derived the term 'avocado', *aguacate* (in Spanish), *avocat* (in French) and *abacate* (in Portuguese). The Aztecs considered avocados an aphrodisiac and called it *huacatl*, meaning testicles, reflecting the fruit shape. The fruit is also called *palta* in Chile, Ecuador and Peru, and has been referred to by a number of other terms such as alligator pear, vegetable butter, butter pear and midshipman's butter (Yahia, 2011).

The avocado originated in Central America and southern Mexico. Based on archaeological evidence found in Tehuacán, Puebla (Mexico), it is believed to have appeared approximately 12,000 years ago (Yahia, 2011). It has been determined that the centre of origin of this fruit is the central part of Mexico, passing through Guatemala to Central America. In this region, the natural gene stock can be found, which can be useful for the biotechnological improvement of the species. As evidence for this theory, primitive avocado trees have been found in the 'Oriental Sierra Madre' along from the State of Nuevo León (Mexico) to Costa Rica. From this region, avocado dispersed to the south-eastern part of the USA, the West Indies, and then to a large part of South America (Colombia, Venezuela, Brazil, Ecuador, Peru, Bolivia, Chile; Rodríguez Suppo, 1992; Yahia, 2011).

The avocado is botanically classified into three races, with differences in fruit maturity and oil content between the different races (Biale and Young, 1971). West Indian (WI), *Persea americana* Mill. var. *americana* (*P. gratissima* Gaertn.), are tropical with large variably shaped fruit and lower oil content; Mexican (MX), *P. americana* Mill. var. *drymifolia* Blake (*P. drymifolia* Schlecht. & Cham.), are semi-tropical with smaller elongated thin-skinned fruit and higher oil content; and Guatemalan (G), *P. nubigena* var. *guatemalensis* L. Wms., are subtropical with mostly round thick-skinned fruit and intermediate oil content (Bergh and Lahav, 1996).

The Mexican race, which originated in the mountains of Mexico and Central America, is characterized by relatively small fruit, ranging from 75 to 300 g, with a thin, smooth skin. Mexican race fruit are mostly green skinned (the natural seedling 'criollo' is black skin), and the pulp is green in colour with very high oil content (up to 30% by fresh weight). Mexican cultivars are well adapted to the cool climates of the tropics and subtropics and are the most cold-tolerant of the three races. Mature trees of the Mexican race are capable of withstanding temperatures as low as −4°C without damage (Joubert and Bredell, 1982).

The West Indian race is native to the lowlands of Central America and northern South America, and these are best adapted to lowland tropical conditions of high temperature and humidity. They are characterized by intermediate fruit size, with smooth, leathery and sometimes glossy skin. Generally, West Indian avocado trees are the most cold (frost)-sensitive and are damaged by temperatures below –1.2°C (Joubert and Bredell, 1982). While racial ancestry was identified as the most important factor influencing susceptibility to cold, other factors such as tree size, age and vigour, crop load and cultural practices were also shown to influence cold damage (Malo *et al.*, 1977; Yahia, 2011).

Fruit of the Guatemalan race are native to the highlands of Central America. The Guatemalan cultivars are intermediate between the other two cultivars with respect to climatic adaptation. Guatemalan fruit are large, averaging 500 to 600 g,

and characterized by thick brittle peel, high oil content and nutty flavoured pulp (Storey, 1988; Yahia, 2011).

Systematic studies have classified more than 500 varieties; however, many are not commercially produced, because of productivity problems (production time, amount of fruit), quality (protein and fat content), and handling problems (such as resistance to damage during transportation). Many of the commercial cultivars are hybrids of the three races. There is great variability in fruit traits not only between races but also between cultivars within a race. One of the most distinct differences between cultivars is the peel colour when ripe. The peel of some cultivars changes from green to black or purple with advanced maturity or ripening. 'Hass', a Guatemalan-Mexican (G-MX) hybrid, is a black-skinned (when ripe), ovate cultivar whose fruit weighs 140 to 300 g (Yahia, 2011) (Fig. 8.1). 'Hass' is the most important commercial cultivar worldwide, and the predominant cultivar in the important production countries (Mexico, Chile and the USA) and is also important in other smaller producer countries (e.g. Spain, Australia and New Zealand). Some other commercial cultivars include 'Bacon', 'Fuerte', 'Gwen', 'Ryan', 'Lamb Hass', 'Pinkerton', 'Reed', 'Sharwil', 'Edranol' and 'Zutano'. The main Florida cultivars (West Indian and Guatemalan races and hybrids) are 'Simmonds', 'Nadir', 'Booth 8', 'Choquette' and 'Lula'. With the exception of 'Reed', which is believed to be entirely of the G race, the other cultivars are considered primarily G-MX hybrids. 'Sharwil' is a MX-G cross and represents more than 57% of the commercial acreage in Hawaii. Its green-skinned fruit weigh 220 to 560 g, matures in winter and spring, and has small seeds and greenish-yellow flesh with a rich, nutty flavour (Yahia, 2011).

Fig. 8.1 Change of colour after ripening in 'Hass' avocado.

The avocado fruit can be round, pear shaped, or oblong, and the skin of the fruit may vary in texture and colour. The skin may be pliable to woody, smooth to rough, and green-yellow, reddish-purple, purple, or black in colour. The flesh of the fruit is greenish-yellow to bright yellow when ripe and buttery in consistency, but inferior varieties may be fibrous. The avocado fruit has one large seed, which makes up to 10 to 25% of the fruit weight. The fruit of different avocado cultivars vary in moisture and oil content, from less than 5% to more than 30% oil (Yahia, 2011).

8.1.2 Worldwide importance and economic value

About 349 000 ha (2007 data) are dedicated to the production of avocado in about 60 countries, producing more than 2.6 million tonnes annually (Table 8.1), with average yield of about 7.40 tonnes per ha. Mexico is the leading producer, accounting for about 34% of the total production, with other important producing countries including Chile (7.6%), Indonesia (6.1%), USA (5.7%), Colombia (4.8%), the Dominican Republic (5.1%), Brazil (4.7%), and Peru (3.7%; FAO statistics).

The largest importers of avocado are USA (47%), France (15%), the Netherlands (8%), UK (6%) and Japan (4%) (Yahia, 2011).

8.1.3 Culinary uses, nutritional value and health benefits

Avocado consumption and culinary uses

Avocado consumption (Table 8.2) is concentrated in the major producing areas. US per capita consumption of fresh avocados increased from 0.18 kg in 1970 to

Table 8.1 Production of avocado in different countries, 2007

Ranking	Volume (tons)	Country
1	734 456	Mexico
2	160 657	Chile
3	129 576	Indonesia
4	101 247	Colombia
5	108 509	Dominican Republic
6	120 878	United States of America
7	99 026	Brazil
8	78 220	Peru
9	77 115	Spain
10	73 523	Guatemala
11	60 175	Kenya
12	59 121	China
13	55 210	Israel
14	53 533	Venezuela
15	41 901	South Africa
	2 121 667	World total

Source: FAOSTAT, 2008.

Table 8.2 Consumption of avocado in the European Union, 1999

Country	Kg per person year^{-1}	Country	Kg per person year^{-1}
Austria	0.160	Ireland	0.194
Bel-Lux	0.899	Italy	0.033
Denmark	0.580	Netherlands	1.128
Finland	0.150	Portugal	0.035
France	1.420	Spain	0.596
Germany	0.157	Sweden	0.610
Greece	0.228	United Kingdom	0.315

0.68 to 1.0 kg in the late 1980s, and in 2000 ~1.4 kg. This is equivalent to consumption of nectarines and comparable to that of pineapples (0.77 kg), but considerably less than bananas (11 kg), apples (8.7 kg) and oranges (6.6 kg).

Avocado is consumed as a fresh fruit, besides its use in the oil, cosmetic, soap, and shampoo industries. Unlike many fruits that typically have a sweet or acidic taste, avocados have a smooth, buttery consistency and a rich flavour. A popular use is as a salad fruit, but avocados are also processed into guacamole and can be used in sandwich spreads. Oil extracted from avocados can be used for cooking and preparation of salads, sauces and marinades. Cold-pressed avocado oil (using extraction technologies similar to those for olive oil) for culinary use is a relatively new processed product (Woolf *et al.*, 2009), compared with olive oil. Avocado oil (typically refined after extraction) is used for skin care products such as sunscreen lotions, cleansing creams, and moisturizers, or for hair conditioners and makeup bases. Several more uses have been added around the world. For example, in Mexico and Brazil, it is added to ice creams and sorbets; in Japan it is eaten in sushi rolls; in Cuba the pulp is mixed with capers, green olives, lemon juice and olive oil to make a sauce that is served with steamed fish; and in Nicaragua it is stuffed with cheese, fried and baked. In Taiwan, it is eaten with milk and sugar; in Korea it is mixed with milk and used as a facial cream and body lotion; in Indonesia it is mixed with coffee, rum and milk to make a refreshing beverage; in the Caribbean it is mixed with salt, garlic, and coconut and served as an entrée; and in the Philippines the avocado purée is mixed with sugar and milk to make a beverage that is served as a dessert (Yahia, 2003).

Nutritional value and health benefits

Consumers have a mixed perception of avocados, some considering them healthy (Lerman *et al.*, 1994), while others who are aiming to lose weight believe avocados are fattening because of their high fat content (25 to 30% w/w FW). However, Pieterse *et al.* (2005) found in a study with 55 subjects who were on an energy-restricted diet, that the consumption of 200 g day^{-1} of avocado instead of 30 g of mixed dietary fat did not reduce weight loss compared with a control group. They also found no effect on serum lipid concentrations.

Mono-unsaturation of the lipids: The lipid content of avocados is made up of approximately 15 to 20% saturated fats, 60 to 80% monounsaturates and ≅10% polyunsaturates. A diet high in monounsaturated fatty acids (MUFAs) is recommended on healthy grounds. This diet has shown favourable effects on lipoprotein measurements, endothelieum vasodilation, insulin resistance, metabolic syndrome, antioxidant capacity, and myocardial and cardiovascular mortality (Serra-Majem *et al.*, 2006). The healthy Mediterranean diet recommends abundant plant foods and olive oil as the principal source of dietary lipids. Avocados and avocado oil have a very similar lipid profile to olives and olive oil, and hence can be included as a healthy addition to the Mediterranean diet.

Avocados also contain significant amounts of other beneficial healthy compounds including tocopherols (vitamin E), plant pigments, sterols, fibre, and folate (Yahia, 2011) (Tables 8.3 to 8.5).

Table 8.3 Avocado fruit composition

Component	Quantity
Water (%)	74.4
Lipids (%)	20.6
Proteins (%)	1.8
Fibre (%)	1.4
Ash (%)	1.2
Sugars (%)	
Glucose	0.30
Fructose	0.10
Sucrose	0.10
Organic acids (%)	
Malic acid	0.32
Citric acid	0.05
Oxalic acid	0.03
Vitamins (mg 100 g^{-1})	
Ascorbic acid	11.0
Thiamine	0.07
Riboflavin	0.12
Nicotinic acid	1.9
Vitamin B6	0.62
Folic acid	0.04
Biotin	0.006
Carotenoids (mg 100 g^{-1})	
α-carotene	0.29
β-carotene	0.03
Criptoxanthin	0.16
Minerals (mg 100 g^{-1})	
Potassium	480
Phosphorus	27.0
Calcium	14.0
Magnesium	23.0
Sodium	2.0
Iron	0.7
Zinc	0.5

Table 8.4 Nutritional content (g 100 g^{-1}) of some avocado cultivars grown in Mexico

Variety	Moisture	Ash	Fat	Protein	Carbohydrates	Total fibre
Pellejo	1.10	1.37	1.37	1.37	3.70	3.73
Grande	0.50	1.37	1.37	1.37	4.82	2.25
Verde	1.10	1.81	1.81	1.81	5.89	0.40
Hass	1.30	1.60	1.60	1.60	5.60	–

Table 8.5 Vitamin content (mg 100 g^{-1}) in three avocado cultivars

Vitamins	'Fuerte'	'Hass'	'Anaheim'
Thiamine	0.12	0.09	0.08
Riboflavin	0.22	0.23	0.21
Niacin	1.45	2.16	1.56
Pantoteic acid	0.90	1.14	1.11
Pyridoxine*	0.61	0.62	0.39
Folic acid	0.03	0.04	0.018
Biotin	0.005	0.006	0.0034

Note: *Including pyridoxal and pyridoxamine.

Vitamin E: Avocados have high concentrations of the antioxidant α-tocopherol (vitamin E), with as much as 2.87 mg 100 g^{-1} flesh reported for 'Hass' avocados (Lu *et al.*, 2005) (Table 8.5). Requejo-Jackman *et al.* (2005) reported concentrations ranging from 5.5 to 9.0 mg 100 g^{-1} oil, in oil extracted by cold-pressed extraction for a range of different cultivars grown in New Zealand.

Pigments: Avocados contain high concentrations of carotenoids and chlorophylls (Table 8.4). Carotenoids have been studied for their antioxidant capacities and ability to protect against diseases. These active components have been associated with a reduced risk of cancer and other chronic diseases. Avocados contain high amounts of lutein, which is known to reduce age-related macular degeneration (Richer *et al.*, 2004). Lu *et al.* (2005) reported 2.93 μg g^{-1} FW in the pulp of 'Hass' avocados. Ashton *et al.* (2006) determined the carotenoid concentrations in the skin and flesh sections (dark green, pale green, yellow) of the avocado and found differences across these tissues, and that these decreased with ripening after harvest. Alpha- and β-carotene have pro-vitamin A activity; their presence in the fruit enhances greatly its health-giving benefits. There is also a strong correlation between ingestion of foods with high chlorophyll concentrations and a decreased risk of certain types of cancer (Minguez-Mosquera *et al.*, 2002). Chlorophyll concentrations are highest in the skin of avocado ($\cong$186 μg g^{-1} FW), then decrease moving inwards from the dark green flesh to the yellow flesh, 38 to 2.2 μg g^{-1} FW, respectively (Ashton *et al.*, 2006).

Plant Sterols: Avocados also contain high amounts of plant sterols, the main sterol being β-sitosterol (Piironen *et al.*, 2003). Plant sterols are known to decrease

cholesterol absorption if 1.5 to 2 g of sterols is consumed per day. Avocado oil from a variety of cultivars was found to contain 2.25 to 4.3 mg g^{-1} FW, with the highest concentration in 'Hass' (Requejo-Jackman *et al.*, 2005). Avocados also contain a high concentration of folate (0.04 mg 100 g^{-1}), which is recommended for women of child-bearing age to reduce the risk of neural birth defects (South African Avocado Growers' Association, www.avocado.co.za). The amount of dietary fibre in avocados is also high, at 6.72 g 100 g^{-1} (Li *et al.*, 2002).

8.2 Fruit development and postharvest physiology

8.2.1 Fruit growth, development and maturation

The pericarp, which is the fruit tissue proper excluding the seed, comprises the rind (exocarp), the fleshy edible portion (mesocarp), and a thin layer next to the seed coat (endocarp) (Biale and Young, 1971). The large seed of the avocado consists of two fleshy cotyledons, a plumule, a hypocotyl, a radicle and two seed coats adhering to each other. The endosperm disappears in the course of development. The cotyledons consist of parenchyma tissue interspersed with idioblasts (oil-containing cells) and contain starch as the main storage material (Biale and Young, 1971). The avocado fruit is unusual, in that cell division in the mesocarp is not restricted to the initial period of growth but also continues during fruit development and even occurs in the mature fruit attached to the tree (Van Den Dool and Wolstenholme, 1983; Lewis, 1978). In some cases, cell enlargement stops when the fruit reaches about 50% of its size at full maturity, while cell division accounts for the continued growth (Cummings and Schroeder, 1942).

8.2.2 Hormonal control of fruit development

Two important endogenous factors affecting the physiology of fruit growth are hormones and nutrients (Bower and Cutting, 1988; Cutting *et al.*, 1986b; 1986c). At all stages of fruit development, it was observed that the mesocarp contained lower amounts of the auxin, indole acetic acid (IAA), than the seed and testa (Cutting *et al.*, 1985). Auxin increases the skin strength of the fruit and regulates endosperm development. There is strong evidence that ethylene is involved in the abscission of young avocado fruitlets, since Davenport and Manners (1982) observed that an increase in ethylene did not occur in fruit that failed to abscise. The prevention of the ethylene peak and associated fruitlet abscission could, therefore, be under the control of other plant growth substances such as cytokinins, which showed a strong peak during this period. Blumenfeld and Gazit (1970) found high amounts of cytokinins in both the cotyledons and testa of avocado, which decreased with development. The high amounts of cytokinin activity in the young seed served to increase the sink strength of the fruit for nutrients and other metabolites. The high cytokinin amounts detected in young fruitlets may actively assist in increasing the sink strength of the fruit, and therefore promote fruit growth (Bower and Cutting, 1988). Stress-induced increases in abscisic acid

(ABA) cause an irreversible loss in fruit growth, and the physiological mechanism associated with ABA-induced retardation of 'Hass' avocado fruit growth appears to be inextricably linked to a decline in cytokinin content and includes: reduction in mesocarp and seed coat plasmodesmatal branching, gating of mesocarp and seed coat plasmodesmatal by deposition of electron dense material in the neck region, abolition of the electrochemical gradient between mesocarp and seed coat parenchyma, and arrest of cell-to-cell chemical communication (Moore-Gordon *et al.*, 1998).

Adato and Gazit (1976) were unable to elicit initiation of fruit ripening, except with a very high dose of IAA. IAA decreases to low concentrations in all parts of the fruit with the onset of maturity (Wolstenholme *et al.*, 1985). A direct role of auxins in the initiation and development of the ripening response is not clear. Gazit and Blumenfeld (1970a) showed low concentrations of cytokinin activity in the mesocarp by the time the fruit was mature. Cutting *et al.* (1986a; 1986b; 1986c) were unable to confirm the role of cytokinins in avocado fruit ripening, although there were indications that the interaction with ABA may occur, as suggested by Lethman and Palni (1983). Lieberman *et al.* (1977) found that exogenous addition of gibberellins had little effect on avocado ripening. They showed an increase in ethylene and ripening following application of ABA before the climacteric peak, but depressed evolution if applied after the peak, concluding that ABA accelerates ageing. Gazit and Blumenfeld (1972) reported little change in ABA concentration during fruit development, but once ripening started, a considerable increase occurred. They have also reported that the increase in ABA closely followed the ethylene curve, with peaks at the same time. Bower *et al.* (1986) found that the free ABA content in ripening avocados increased with fruit softening, with the peak at approximately the same degree of softness at which the maximum ethylene peak occurred, and declined thereafter. Factors other than water stress can also affect both ABA concentrations and ripening rate.

8.2.3 Respiration, ethylene production and ripening

Avocado differs from most other fruits in that ripening does not normally take place on the tree, but only after picking (Schroeder, 1953). This means that they can be held on the tree even for many months after they are physiologically mature (that is to say, will ripen normally after removal from the tree). After harvest, their 'resistance' to ripening is lost within one to two days (Gazit and Blumenfeld, 1970a) and fruit will ripen, although the time to ripen will reduce with increasing time on the tree (often loosely referred to as 'maturity' by industry). Time to ripen decreases with time in storage, and (Gazit and Blumenfeld, 1970b) treatment ('pre-ripening', ethylene conditioning or conditioning), as carried out for bananas, is becoming an important tool for providing consumers with 'ripe tonight' fruit. Fruit ethylene production begins after harvest and increases greatly with ripening to >100 μl C_2H_4 kg^{-1} h^{-1} at 20°C.

Avocados are best ripened at 15 to 20°C (Hopkirk *et al.*, 1994). The ripening rate at <15°C is relatively slow, and ripening at >25°C may result in increased

decay, uneven ripening of the flesh and off-flavours. Fruit generally ripen better (more evenly and with less rots) if they are stored for one or two weeks, then ripened at 20°C. However, if fruit are to be ripened at 25°C, then final quality is better if the fruit are not refrigerated but held at a temperature closer to the final ripening temperature. Following ripening, fruit should be pre-cooled to less than 5°C and held for ~ a week at most. Ripe (soft) avocados require care in handling to minimize physical damage.

Respiration and ethylene production

The avocado is a climacteric fruit, with a marked rise in respiration rate and ethylene production at the onset of ripening, followed by a decline (Zauberman and Schiffman-Nadel, 1972). The respiration rate of avocado fruit is relatively high compared with that of many other fruits; about 20 to 50 mg CO_2 kg^{-1} h^{-1} at 5°C, 50 to 160 at 10°C, and 80 to 300 mg CO_2 kg^{-1} h^{-1} at 20°C (Kader and Arpaia, 2001). Rates of ethylene production are generally low for unripe avocados, <0.1 μL kg^{-1} h^{-1} at 20°C, but increase rapidly after harvest up to >100 μL kg^{-1} h^{-1} at 20°C when fully ripe. Thus, the implications for ethylene on avocados depend on the physiological state of the fruit. For unripe, newly harvested fruit recently placed into storage, ethylene concentrations will be undetectable and exposure to ethylene will result in an increased ripening rate, and reduced storage and shelf life. However, ripe fruit will produce significant ethylene in storage and thus should be kept separate from unripe avocado or other ethylene-sensitive products. Because avocados are sensitive to ethylene, they should not be stored near ripe fruit or other fresh produce that produce more than trace ethylene (Chaplin *et al.*, 1983).

Ethylene exposure during storage accelerates ripening/softening and can increase incidence and severity of internal chilling injury (CI) and decay. Exogenous applications of ethylene after harvest cause an earlier climacteric with consequent ripening (Eaks, 1978). Although other factors initiate the respiratory rise, alter sensitivity to ethylene, or control its increase, the autocatalytic production of ethylene is of vital importance to normal avocado ripening. Any factors affecting this process could be expected to alter the fruit-ripening pattern.

1-methylcyclopropene (1-MCP)

1-MCP works by binding to the ethylene receptors, thus preventing ethylene binding and subsequent action. The main response in avocado is delayed ripening. This means that treatment with high concentrations (e.g. 10 μL L^{-1}) can result in fruit remaining unripe for weeks at room temperature without softening. The first published work (Feng *et al.*, 2000) examined the ripening response of a range of cultivars ('Ettinger', 'Hass', 'Reed' and 'Fuerte') after 1-MCP treatment and showed that even 30 to 70 nL L^{-1} could delay ripening at 20°C for over 10 days, including concomitant reduction in cell wall softening enzymes (PG and cellulase) and climacteric ethylene production. This effect was observed even though fruit were treated with 300 μL L^{-1} ethylene immediately after 1-MCP treatment, clearly demonstrating the ability of 1-MCP to bind with near-complete efficacy against subsequent ethylene exposure.

1-MCP and wax significantly delayed the ripening of 'Tower II' avocados stored at 20°C (Jeong *et al.*, 2003). Fruit treated with both 1-MCP and wax had better retention of green skin colour and fruit firmness, and delayed climacteric ethylene evolution and respiration rates than fruit under other treatments. Waxing alone reduced weight loss and delayed softening, but did not delay climacteric ethylene evolution and respiration rates. Whereas firmness of control fruit decreased from >100 to 20 N over a 7-day period at 20°C, fruit treated with both 1-MCP and wax required more than 11 days at 20°C to soften to 20 N. The firmness of waxed 'Booth 7' avocados declined from >170 to 15 N during 19 days' storage at 13°C, whereas fruit treated with both 1-MCP and wax required nearly five weeks to reach firmness values of 25 N.

Adkins *et al.* (2005) investigated the potential of 1-MCP to manipulate ripening of non-stored 'Hass' avocado fruit by treatment before or after ethylene and at different times during ripening, and found that ripening of fruit exposed to 100 μL L^{-1} ethylene for 24 h at 20°C could be delayed by up to 3.3 days by applying 1-MCP. However, once the fruit started to soften, there was little effect of 1-MCP, compared with non 1-MCP-treated fruit. There is little potential to control ripening using ethylene after treatment with 500 nL L^{-1} 1-MCP, but higher concentrations may be more effective.

1-MCP binding to the receptors is irreversible, but over time, inhibition of ethylene effects can be overcome by production of new receptors (Sisler *et al.*, 1996). In avocado, however, 'restarting' of the ripening process seems to be much harder to achieve than in other fruits. A possible reason for the apparent relative 'irreversibility' of 1-MCP in avocado was suggested by Dauny *et al.* (2003), who found that 1-MCP was absorbed faster and in greater amounts by 'Hass' avocados and avocado oil than by 'Cox's Orange Pippin' apple fruit and water, respectively (Dauny *et al.*, 2003). Thus, release of 1-MCP from the oil fraction and 're-binding' to ethylene receptors may be the possible mechanism that influences ripening and 1-MCP efficacy in avocado.

It has been found that for 1-MCP-treated avocado stored for four weeks, ethylene treatment has little effect on reducing average shelf life, even with high concentrations (1,000 μL L^{-1}; Woolf and White, unpublished). Recent work in South Africa has suggested that CO_2 treatment (20% for 24 h at 20°C) after storage may be a possible method of reversing the ripening inhibition (Roets *et al.*, 2009).

The key commercial benefit of 1-MCP is its ability to reduce the internal chilling injury (flesh greying or diffuse flesh discolouration) that occurs during storage, a ripening and/or ethylene-related disorder (Pesis *et al.*, 2002; Woolf *et al.*, 2005). This is discussed further below.

8.2.4 Cell wall metabolism and softening

During avocado fruit ripening, it was found that the middle lamella of cell walls begins to disappear, with pectin removal from the matrix of the cell walls. Later, a loss of organization and density in the walls occurs and during the

post-climacteric, the walls almost completely disappear (Platt-Aloia *et al.*, 1980; Platt-Aloia and Thomson, 1981). Scott *et al.* (1963) reported cellulose as the major constituent of avocado cell walls. Huber (1983) considers the avocado to be the fruit most representative of those in which cellulases are of primary importance. Pesis *et al.* (1978) found a rapid increase in this enzyme accompanying softening, which was closely correlated with the respiratory climacteric and ethylene. Application of ethylene in the air surrounding fruit for 48 h after harvest also caused an increase in cellulase activity, which led Pesis *et al.* (1978) to conclude that ethylene plays a role in controlling cellulase activity. Tucker and Laties (1984) showed that ethylene treatment increases transcription of cellulase-encoding genes. The early stages of softening in the avocado appear to be due to cellulase, controlled at least in part by ethylene, with polygalacturonase (PG) responsible for final softening (Bower and Cutting, 1988). However, although Feng *et al.* (2000) found similar trends in cellulase activity, they suggested that the initial phase of avocado fruit softening appears to occur without significant PG activity. Jeong *et al.* (2002) observed a reduction in pectin methyl-esterase (PME) activity with ripening, and this was correlated with the delay associated with 1-MCP treatment.

8.3 Maturity, quality at harvest and phytonutrients

8.3.1 Maturity and quality at harvest

Avocado is characterized by great natural variability. This is dramatically influenced by the very long period for which fruit can remain on the tree, as long as 18 months or more after flowering in some environments. Determining the point at which to commence commercial harvesting is of course important, and in avocado this can be a problematic area because of the relative lack of maturity indices compared with those in other crops. Harvesting fruit too early leads to poor ripening, often associated with shrivelling, rubbery texture, 'stringy' vascular tissue, watery/green flavour and increased rots (Lee *et al.*, 1983; Pak *et al.*, 2003; Pak and Dawes, 2001). Fruit that have reached physiological maturity (i.e. will ripen after harvest) may not be commercially acceptable because of poor taste (low dry matter/oil content), lack of flavour, uneven ripening (within a fruit), and highly variable ripening between fruit of the same lot ('checkerboarding'). Over-mature fruit may have off-flavours, tend to have more rots, and generally have shorter storage potential.

The main harvest maturity index used in most countries is dry matter (or its inverse – water content, as is used in South Africa), which is highly correlated with oil content (Lee *et al.*, 1983). Other measures of early maturity may include changes in skin colour (emerald green colour), loss of skin glossiness, or a brown seed coat.

Minimum dry matter content required ranges from 17 to 25%, depending on cultivar and country. In California, the minimum dry matter percentages at harvest for the major cultivars are: 'Bacon' (17.7%), 'Fuerte' (19.0%), 'Gwen' (24.2%),

'Hass' (20.8%), 'Pinkerton' (21.6%), 'Reed' (18.7%) and 'Zutano' (18.7%). In California, fruit are also released onto the market at predetermined dates based on dry matter and size for each cultivar. For example, the size/release dates for 'Hass' are: size 40 and greater, November 28; size 48, December 12; size 60, January 2; and size 70 or smaller, January 16. Based on the experiences obtained in Mexico for export fruit, it can be established that avocados should have an average of 22% of dry matter, and the lowest value of a sample should not be under 20%. The California regulation defined the minimum maturity of avocado fruit as containing 21% dry matter content. In 1983, dry matter content became an index of maturity for the California avocado industry, and this has been followed by the Mexican avocado growers (Kurlaender, 1996). Although most countries use a minimum dry matter of around 21% (probably following California standards for market access reasons), a higher minimum dry matter concentration of 24 to 25% (as used in New Zealand) generally results in a higher quality product. Florida (West Indian) avocados have lower oil content (3 to 15% oil) and are generally harvested at a specified calendar date (days after full bloom) and weight or size (Ahmed and Barmore, 1980).

Recent interest in possible revision of commercial standards has led to some sensory and consumer studies. Arpaia (2003) examined responses from a smaller number of panellists repeatedly over a season using a hedonic scale, with 'Hass'. The dry matter concentration at which the panellists 'liked slightly' was ~23%. In an Australian study (with over 100 consumers), consumer preference (likelihood of purchase) increased with increasing dry matter concentrations (and continued to increase even above 30% dry matter; Gamble *et al.*, 2010). Significantly, a concentration of more than 26% was needed to achieve a rating of 'Probably will buy' (70 to 89% chance of purchase).

Dry matter (DM) measurement is simple in principle: remove a sample of flesh from the fruit, weigh it, then dry to a constant weight, and re-weigh. However, the large spatial variation in dry matter in avocado fruit (Schroeder, 1985; Woolf *et al.*, 2003) means that the way in which the tissue is sampled can have a significant effect on the resulting dry matter value and its repeatability. Countries have developed their own protocols for DM assessment: e.g. South Africa: Swarts (1978); California: Lee and Coggins (1982); Australia: Brown and Trout (1986); and New Zealand: Woolf *et al.* (2003); Pak *et al.* (2003). The range of flesh sampling strategies include sampling from opposing eighths cut longitudinally (Arpaia *et al.*, 2001); opposing quarters cut longitudinally (Brown and Trout, 1986); one longitudinal quarter (Pak *et al.*, 2003); or equatorial samples from the Hofshi coring system (Arpaia *et al.*, 2001). A recent development, the Hofshi coring machine removes equatorial flesh samples ('cores' or 'plugs') of 15.8 mm diameter, and is increasingly being used around the world because it gives statistically similar results to the more traditional 'opposing eighths' method, yet it is faster, safer, less cumbersome, and less prone to sampling-induced variation from DM gradients in the fruit (Arpaia *et al.*, 2001; Woolf *et al.*, 2003).

Various methods are used to dry the flesh tissue – ovens, dehydrators, or microwaves, the key being to achieve a constant dry weight, without burning the

sample, e.g. using a temperature of 60 to 65°C (Woolf *et al.*, 2003), although some use higher temperatures (100°C; Brown and Trout, 1986).

Non-destructive measurement of dry matter would have a range of potential benefits. NIR (Near Infra Red) spectroscopy is the technology that is the closest to successful commercialization. In the packinghouse, NIR could be used to grade fruit into dry matter categories, which might be sold to different markets depending on taste, or more likely, shipped to different markets. Clark *et al.* (2003) showed that transmittance NIR could be used to predict dry matter of avocados; they have developed a model that predicted dry matter with at least 90% accuracy. Alternatively, hand-held NIR 'guns' could be used in the orchard to measure large numbers of fruit non-destructively and rapidly (for monitoring of dry matter trends and/or clearance to harvest (Brown and Sarig, 1994)).

For some countries, late-season production is a potential market. However, for late-season fruit, dry matter and oil are not reliable indicators of maturity (Hofman *et al.*, 2000), and indeed these reach a plateau for a number of months. Burdon *et al.* (2007) examined changes in late-season fruit (>32% dry matter) measuring dry matter, soluble solids content (SSC), starch, and individual sugars (perseitol, mannoheptulose, sucrose, fructose and glucose). However, few consistent trends were found over the two seasons.

8.3.2 Taste

As previously noted, avocado is an atypical fruit in that it has a smooth, buttery consistency and a rich flavour. The sensory quality of an avocado should be judged when the fruit is eaten ripe. Flavour, aftertaste, odour, texture and flesh colour are all key quality attributes that have an impact on the overall acceptability. These attributes are dependent on many factors such as cultivar, maturity/oil content, flesh firmness at the point of consumption, and fruit size.

The most important factor influencing acceptability is the oil content, which correlates strongly with fruit maturity, as measured by dry matter. Several studies have investigated the relationship between maturity and overall taste acceptability; however, many researchers have commented on the variability within and between fruit picked at the same time (Lewis, 1978). Harding (1954) assessed fruit ('Hass') for flavour and taste; these attributes were not assessed individually but grouped together in four distinct categories. Common flavour descriptors were green, nutty and grassy bitter; texture descriptors: rubbery, soft and buttery. An 'unpleasant aftertaste' was also detected. The bitter flavour is a characteristic of immature avocado flesh, in many cases leaving a distinctive aftertaste on the palate. In some varieties ('Hass', 'Fuerte' and 'Sharwil') this flavour is undetectable in mature, ripened flesh. Brown (1972) found an association between the presence of ten C_{17} olefinic and acetylenic oxygenated aliphatic compounds with the 'unpleasant bitter-type flavour'. Lewis *et al.* (1979) examined 'Hass' fruit for colour, texture, flavour and general acceptability, although no descriptors were used. Flavour was found to be the most important attribute affecting acceptability, with acceptability ratings increasing as fruit matured. Later, Lee *et al.* (1983) examined avocados, of

which 'Hass' was one, for two flavour descriptors (nutty and green) and texture (watery to creamy) and found that taste scores increased as fruit matured.

In the literature, the effect of fruit maturity on taste acceptability has been examined, yet taste acceptability has not been explicitly described using sensory descriptors. The sensory team at Plant & Food Research (formerly HortResearch, New Zealand) used a trained sensory panel to develop the following sensory descriptors of 'Hass' avocados with the reference standards (Table 8.6; Walker,

Table 8.6 Sensory descriptive terms and reference standards developed for 'Hass' avocados, New Zealand

Sensory attribute	Definition	Reference standard (intensity on 150-mm line scale)
Odour		
Green odour	Green/Vegetative odour	Liquor from Watties® canned green beans Intensity = 135
Hay odour	Dried grassy odour	Dried marjoram Intensity = 135
Nutty odour	Nutty odour of crushed macadamia nuts present when the avocado pulp is pressed with the back of a spoon	Crushed macadamia nuts Intensity = 90
Flavour		
Woody pine flavour	Flavour characteristic of pine nuts/ oaky Chardonnay	Crushed pine nuts Intensity = 120
Canned pea flavour	Cooked green pea flavour characteristic of canned peas	'Hartleys' mushy peas (canned) Intensity = 135
Savoury taste	Savoury taste similar to that from shellfish or broth	MSG 2 g L^{-1} Intensity = 120
Bitter taste	Bitter taste similar to that occurring in vegetables such as overly mature broccoli	Caffeine 0.2 g L^{-1} Intensity = 75
Floral flavour	Characteristic of fresh flowers	(Absent/present)
Banana flavour	Characteristic of fresh bananas	(Absent/present)
Citrus flavour	Characteristic of fresh citrus fruit	(Absent/present)
Texture		
Firmness	The force required to compress the sample between the back teeth	'Mainland' Edam 1.5 cm^3 Intensity = 150 'Philadelphia' Cream Cheese 1.5 cm^3. Intensity = 60
Oil release	Amount of oil released from the sample when pushed against the roof of the mouth with the tongue	'John West' Tuna chunks in oil. Intensity = 135

(Continued)

Table 8.6 continued

Sensory attribute	Definition	Reference standard (intensity on 150-mm line scale)
Water release	Amount of water released from the sample when pushed against the roof of the mouth with the tongue	Surimi 1.5 cm^3 Intensity = 75
Rate of breakdown	Rate at which the sample breaks down when chewed with the back teeth	'Philadelphia' Cream Cheese 1.5 cm^3 Intensity = 35 Spreadable 'Philadelphia' Cream Cheese 1.5 cm^3 Intensity = 130
Fibrousness	Presence of fibres detected during chewing with the back teeth	'Hartleys' canned rhubarb Intensity = 120
Particles	Flesh breaks down into particulate mass when chewed	(Absent/present)

Source: Walker, White, Harker, and Woolf, unpublished data.

White, Harker, and Woolf, unpublished data). The following attributes: 'hay/dried grass', 'green' and 'nutty' odours, 'woody/pine', 'savoury' and 'canned pea' flavours, 'bitter' taste and the texture terms 'oil release', 'water release' and 'fibrousness' were assessed on line scales having anchors at 0 = absent and 150 = extreme. The attributes 'firmness' and 'rate of breakdown' were assessed on line scales having anchors at 0 = soft and 150 = firm, and at 0 = slow and 150 = melts quickly, respectively. Four minor attributes were assessed by indication of presence or absence: 'floral', 'banana' and 'citrus' flavours and the texture term 'particle breakdown'.

8.4 Preharvest factors affecting postharvest fruit quality

8.4.1 Mineral nutrition

Thorp *et al.* (1997) surveyed mineral content in 'Hass' and found a range for average fruit mineral concentrations of: Ca, 25 to 47 mg 100 g^{-1} dry weight (DW); Mg, 91 to 113 mg 100 g^{-1} DW; and K, 1126 to 1608 mg 100 g^{-1} DW. Others have also noted the wide variation in levels such as calcium, magnesium, potassium, boron and zinc concentrations between trees (Marques *et al.*, 2006).

Calcium appears to be the most significant mineral in terms of fruit quality with impacts on rots and ripening. Higher Ca concentrations led to reduced rots (Hofman *et al.*, 2002) and reduced storage disorders such as vascular browning and mesocarp discolouration (Thorp *et al.*, 1997; Hofman *et al.*, 2002; Marques *et al.*, 2006). Hofman *et al.* (2002) also noted an interaction between calcium and magnesium (Mg) concentrations and the (Ca + Mg)/potassium ratio with negative correlations observed between these minerals and rots, storage disorders and days to ripen (Hofman *et al.*, 2002). Everett *et al.* (2007; 2008) found that application of calcium lead to reduced postharvest rots.

Negative correlations were observed between fruit potassium and phosphorus and time to ripen (Hofman *et al.*, 2002). Potassium and magnesium (and calcium) were found to impact on body rot severity, percentage dry matter and fruit weight (Marques *et al.*, 2006).

There are recent reports of the possible beneficial effects of silicon on rots, either as a pre-harvest application, or as a postharvest dip (Bertling *et al.*, 2009).

8.4.2 Rootstock

The large differences between adjacent trees and the seedling origin of rootstocks led Hofman *et al.* (2002) to propose that rootstocks might be a significant contributing factor to fruit quality. Work was therefore carried out using clonal 'Velvick' (CV) or clonal 'Duke 7' (CD) rootstocks for 'Hass' that examined fruit quality and mineral concentrations for non-stored or stored fruit (Marques *et al.*, 2003). CV had lower severity of body rots for both non-stored and stored fruit than CD (20 vs 38%). CV also led to lower diffuse discolouration and vascular browning than CD. Interestingly, CV fruit had ~15 to 20% more flesh calcium and boron, and lower nitrogen concentrations. They concluded that rootstock can influence fruit quality, and that mineral concentrations have a role. However, in New Zealand, no significant effect of cultivar ('Fuerte', 'Zutano', 'Vista', 'Reed', or 'Hayes', 'Hopkins') was observed over a 2-year period (Dixon *et al.*, 2007).

8.4.3 Sun exposure

It has been reported that exposure of the avocado fruit to direct sunlight can result in temperatures in excess of 15°C above the ambient air temperature (Woolf *et al.*, 1999), as has also been observed in other crops such as apple (Ferguson *et al.*, 1998). Indeed, we have observed temperatures of over 30°C even in mid-winter with air temperatures of 12°C where incident radiation is at its lowest, and skin temperatures as high as 52°C in mid-summer (Woolf, unpublished data). Fruit exposed to such temperatures have a wide range of differences in postharvest responses including reduced chilling injury (0°C storage) on exposed sides of the fruit, higher tolerance to 50°C hot water treatment, slower ripening of the whole fruit (including higher fruit firmness on the exposed side of the fruit (Woolf *et al.*, 1999)). Thus, it appears that preharvest temperature experienced by avocado fruit affects their postharvest behaviour in manners similar to postharvest heat treatments (Woolf *et al.*, 1999). This work was verified in a completely different growing environment (Israel) with five cultivars (Woolf *et al.*, 2000). High pre-harvest temperatures due to exposure to the sun dramatically affected a range of postharvest responses in 'Ettinger', 'Fuerte', 'Hass', 'Horshim' and 'Pinkerton'. Along with verifying the results obtained in New Zealand, the shaded fruit were found to exhibit more extensive and faster development of inoculated *Colletotrichum gloeosporioides* than the sun-exposed fruit. Both works showed

accumulation of RNA, which encodes for heat shock proteins (hsps) and their proteins (as determined by western and radio-labelled protein synthesis analyses), which showed patterns of accumulation concomitant with thermotolerance. Thus, sun exposure and its resulting temperatures are likely be responsible for the variability observed in many postharvest responses and should be considered in sampling of fruit for both experimental trials, and commercially.

8.5 Postharvest handling factors affecting fruit quality

Coursey (1971) reported that postharvest losses of avocado were estimated to be 43%, and smooth-skinned varieties were more prone to physical injuries during handling and transport than the rough skinned varieties. Some of the most important causes of postharvest losses in avocado include mechanical damage, physiological disorders (especially chilling injury: CI), decay, and insects. Avocado is a subtropical fruit sensitive to CI (Pesis *et al.*, 1994). The main symptoms are black stains in the epidermis and a grey or brown discolouration in the mesocarp. Morris (1982) reported another symptom as alteration of internal metabolism, which leads to an increase in anaerobic respiration and, as a consequence of abnormal metabolites, results in the development of a foul taste and odour. Anthracnose (commonly caused by *Colletotrichum gloeosporioides*) is the most important disease in avocado that reduces fruit quality after harvest. Friction damage, which is characterized by an oxidation of the tissue that later inclines downward and becomes necrotic, is one of the most frequent problems during fruit harvest and handling. A cut to the skin breaks the protective layer of the fruit completely, accelerates water loss, and exposes the tissue directly to the environment. Damage is typically more serious where there are inadequate packaging processes.

8.5.1 Temperature management

Temperatures above 30°C generally cause adverse effects on avocado quality and ripening (Erickson and Takaake, 1964; Zauberman *et al.*, 1977). From 10 to 25°C, the avocado fruit commonly softens faster as holding temperature increases. From 5 to 8°C (typical storage temperatures for most cultivars), softening is usually controlled, but ripening will occur in a shorter and less variable manner when fruit are transferred to higher temperatures. For most cultivars, external chilling injury (discrete skin discolouration) (Plate XIII: see colour section between pages 244 and 245) occurs at between 0 and 4°C, depending on cultivar, maturity and ripeness. When fruit are ripe, or near-ripe (soft), they can be stored at lower temperatures without external chilling injury (Young and Kosiyachinda, 1976). Freezing of fruit occurs at ~1.5°C (White *et al.*, 2009), but of course exposure time is an additional factor.

Temperature is no doubt the single most important factor in fruit storage and quality of avocados, as it is the case for other fruits. All biological processes are controlled by temperature, including ripening, and fruit quality from both

physiological and pathological perspectives. The rate of ripening depends on temperature of storage (Eaks, 1978). The response of avocado to storage temperatures varies according to fruit type (race), variety, growing conditions, time in the season (stage of maturity) and stage of ripeness. Of course, there are also many postharvest treatments that can influence the fruit's physiological response to temperature, such as 1-MCP (primarily influencing ripening) and temperature treatments (e.g. heat treatments or low temperature conditioning, which influence physiological responses to low temperature). In terms of genetic influence on storage responses, Guatemalan and Mexican cultivars are generally stored at 4 to 8°C, while West Indian cultivars are more sensitive to low temperatures and are stored at temperatures similar to those for most tropical fruits (~13°C; Hatton *et al.*, 1965; Zauberman *et al.*, 1973). The most significant commercial cultivars (e.g. 'Hass' and 'Fuerte') are generally stored at ~5 to 7°C.

In terms of storage duration, avocados are generally in the short to medium category compared with other fruits, with a successful storage time of two to four weeks for most cultivars. For the main commercially traded cultivars, three to four weeks of storage should be achievable, but longer times are more challenging because of either expression of physiological and/or pathological disorders. For 'Hass', it remains a challenge to achieve good fruit quality reliably after six weeks. However, there are reports of successful storage times of 12 weeks for 'Hass' and eight weeks for 'Fuerte' using a combination of prochloraz, fungicide, waxing, SmartFresh^{SM} treatment followed by controlled atmosphere (CA) storage (Lemmer *et al.*, 2006).

8.5.2 Physical damage

While avocado are generally robust fruit, physical damage to the skin during harvest, cleaning and packing can have significant negative fruit quality effects, both cosmetically and from a pathology perspective (Fig. 8.2). Although some avocados are 'smooth-skinned', many exhibit raised bumps on the skin, most (but not all) of which contain a lenticel at the top. These are particularly prone to physical damage. Everett *et al.* (2008a) showed that physical damage to the lenticels (due to fruit-to-fruit damage) was influenced significantly by the turgidity of the cells in the lenticels. Thus, harvesting immediately after rainfall is likely to increase damage, and probably rots in storage. This may explain the results of Elmsley *et al.* (2007), who observed that, although time of harvest in the day generally had relatively little effect on fruit quality, there was a slight reduction in body rots in fruit harvested in the afternoon compared with early morning.

While there may or may not be significant pathological implications to damage to the lenticels, any damage to the skin is generally not desirable, and should be avoided where possible. Even if rots are not an issue, clearly there are at least commercial implications in terms of appearance of the fruit, both at importer and/or wholesaler points in the supply chain, and of course for the consumer. This issue is even more important for green-skinned fruit, since the colouring of darker skin (such as 'Hass') disguises minor skin defects.

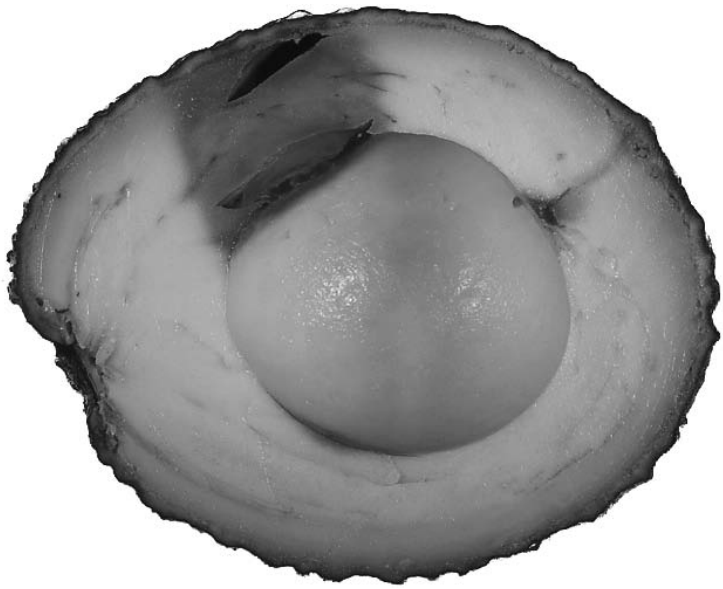

Fig. 8.2 Bruising injury. Image courtesy of Plant and Food Research, New Zealand.

8.5.3 Water loss

As for most crops, weight loss is a significant commercial factor since, at the very least, it can be seen as 'very expensive water'. Recommendations of a relatively high relative humidity during storage (85 to 95%) and common use of wax coatings are aimed at reducing weight loss. Weight loss between harvest and storage has been found to be a significant issue in terms of storage (Yearsley *et al.*, 2002; Dixon *et al.*, 2005), and thus it was recommended that time taken to pack the fruit should be minimized.

Generally weight loss is an issue that should be considered as something to minimize. However, there are points of balance that need to be considered. Firstly, most treatments that significantly reduce weight loss (e.g. modified atmosphere (MA) bags of various sorts) often lead to excessive rots. Also, some weight loss is important in promoting the ripening of avocado; indeed weight loss has been considered as a possible ripening trigger (Dixon *et al.*, 2003). For example, we found that storing fruit in a 100% RH environment (which led to negligible weight loss) resulted in very significant delays in ripening, and thus subsequent expression of rots (White, Burdon and Woolf, unpublished data).

8.5.4 Atmosphere

Optimum modified atmospheres (MA) and controlled atmospheres (CA) (2 to 5% O_2 and 3 to 10% CO_2) delay softening and skin colour changes and reduce

respiration, ethylene production rates, and CI of avocado fruit (Yahia, 1998). CA delays the softening process, and thus maintains the resistance of the fruit to fungal development (Spalding and Reeder, 1975). There is also a range of other CO_2/O_2 manipulations that have physiological effects, and extensions to regular CA storage such as 'dynamic CA' that are now receiving attention.

Controlled atmosphere (CA) storage

Low O_2 injury may appear as irregular brown to dark brown patches on the skin and may additionally cause diffuse browning of flesh beneath affected skin (Yahia, 1997a; Carrillo-López and Yahia, 1991; El-Mir *et al.*, 2001; Loulakakis *et al.*, 2006; Yahia and Rivera, 1994), and can be expressed as browning at the stem-end of the fruit (Yearsley and Lallu, 2001), a 'chocolate dipped' appearance. Carbon dioxide atmospheres above 10% can be detrimental, leading to discoloration of the skin and development of off-flavours, particularly when the O_2 concentration is less than 1%.

Very early research by Overholser (1928) reported that the storage life of 'Fuerte' avocados was prolonged for 1 month when fruit were held in an atmosphere of 4 to 5% O_2 and 4 to 5% CO_2 at 7.5°C, compared with air storage. Brooks *et al.* (1936) reported that fruit could be held in atmospheres containing 20 to 50% CO_2 at 5 to 7.5°C for two days without causing any injury. Atmospheres with CO_2 concentrations below 3% prolonged the storage life of Florida avocados at all temperatures, and reduced the development of brown discolouration of the skin (Stahl and Cain, 1940). Extensive work was later done also with 'Fuerte' avocado, and concluded that the time for the fruit to reach the climacteric was extended in proportion to the decrease in O_2 concentration from 21 to 2.5% (Biale, 1942; 1946). In later years, Young *et al.* (1962) demonstrated that the delay of the climacteric could also be achieved by 10% CO_2 in air, and the combination of low O_2 and high CO_2 further suppressed the intensity of fruit respiration. Hatton and Reeder (1965; 1969; 1972) and Spalding and Reeder (1972; 1974) found that a CA of 2% O_2 and 10% CO_2 at 7.5°C doubled the storage life of the cultivars 'Lula', 'Fuch' and 'Booth 8'.

Mature-green 'Hass' avocado can be kept at 5 to 7°C in 2% O_2 and 3 to 5% CO_2 for nine weeks, then will ripen in air at 20°C to good quality. Elevated (>10%) CO_2 concentrations may increase skin and flesh discolouration and off-flavour development, especially when O_2 is <1%. 'Reed' and 'Hass' avocados were reported to be stored for up to three, and two months respectively, in CA (Sive and Resnizky, 1989). Jordan and Smith (1993) reported that 'Hass' avocados remained firm and unripe for seven to nine weeks in CA of 2 to 10% O_2 and 4 to 10% CO_2 at 7°C. Below 4% CO_2, storage life was five to six weeks. Truter and Eksteen (1987a; 1987b) reported that a mixture of 2% O_2 and 10% CO_2 extended the shelf life, reduced the grey pulp and virtually eliminated pulp spot of 'Fuerte', 'Edranol', and 'Hass', but an increase in anthracnose was observed. 'Booth 8' and 'Lula' avocados were reported to be held successfully for up to eight weeks in a CA of 2% O_2 with 10% CO_2 at 4 to 7°C and 98 to 100% RH, and removal of ethylene further improved the keeping quality of the 'Lula' fruits (Spalding and

Reeder, 1972). Fruit of 'Booth 8' had slight CI at 4.5°C. 'Fuerte' and 'Anaheim' fruit were stored in Brazil for up to 38 days in 6% O_2 and 10% CO_2 at 7°C, but only for 12 days in air (Bleinroth *et al.*, 1977). Storage of 'Waldin' and 'Fuchs' avocados in 2% O_2 and 10% CO_2 for up to four weeks at 7°C was also reported to prevent development of anthracnose and CI (Spalding and Reeder, 1974; 1975). 'Hass' avocado was reported to be stored for up to 60 days in atmospheres of 2% O_2 and 5% CO_2 (Faubion *et al.*, 1992; Jordan and Barker, 1992; McLauchlan *et al.*, 1992). Four commercial CA rooms were constructed in Florida in the season of 1972/1973 for storage of 'Lula' avocados in bulk bins (Spalding and Reeder, 1974). The rooms were run at 2% O_2 and 10% CO_2 at 7.2°C and 95% RH, and fruit were reported to be marketed in excellent conditions after five weeks of storage, except for some fruit with rind discolouration (CI), where temperature dropped below 4.4°C. In South Africa, Bower *et al.* (1989) suggested that even though fruit stored in CA (2% O_2 and 10% CO_2) were superior than those from other storage systems, the economic and logistical realities were not significant.

The percentage of acceptable fruit after storage was increased by absorption of ethylene during CA storage (Hatton and Spalding, 1974). Thus, exclusion and/or removal of ethylene from CA storage is generally recommended.

There is an indication that CA treatments can reduce external CI. Moderately high concentrations of CO_2 (up to 10%) were shown to ameliorate CI in 'Taylor' avocados (Vakis *et al.*, 1970). Spalding and Reeder (1972) found less internal and external CI in CA than in air storage of 'Booth 8' and 'Lula' avocados.

Dynamic CA

While CA storage (or static CA storage – SCA) works by use of a predetermined and constant O_2 and CO_2 concentrations for the entire storage period, dynamic CA (or DCA) monitors the fruit's response to the applied atmosphere and seeks to minimize the O_2 concentration (Burdon *et al.*, 2008). The most successful way to achieve DCA storage is the use of a sensor that provides rapid feedback to the fruit response. Chlorophyll fluorescence (also found to be a sensitive indicator of fruit response to heat; Woolf and Laing, 1996) is the most practicable sensor (e.g. the fluorescence interactive response monitor (FIRM) from Isolcell, Italy (formerly available as the HarvestWatch™ sensor); Burdon and Lallu, 2009).

Use of DCA also means the safe achievement of low O_2 concentration, which maximizes the low O_2 response but avoids reduction in fruit quality due to high CO_2 (Burdon *et al.*, 2008). The safe achievable oxygen concentration was found to be 0.2 to 0.8%, and recommendations are to achieve DCA rapidly (minimal delay from harvest), use an O_2 back off at 0.2% (rather than higher 0.8%), and repeatedly measure O_2 tolerance concentration (more than once during the storage period). Another benefit of DCA is that the shelf life is not unduly extended (as found with regular CA storage, or 1-MCP treatment), and fruit ripen more uniformly (Burdon and Lallu, 2009). This leads to a significant reduction in rot problems because of the common 'rule of thumb' for avocados, which is that

almost any treatment that results in longer shelf life leads to increased rot incidence. However, the 'intermediate' shelf life found by Burdon *et al.* (2008) might be a response to the low ethylene concentrations (0.040 μL L^{-1}). Further experimental and pilot commercial trials are underway in New Zealand with this technology.

CO_2 shock treatments

Truter and Eksteen (1987b) found that a 25% CO_2 shock treatment applied one day after harvest reduced physiological disorders without any increase in anthracnose. Allwood and Wolstenholme (1995) were able to delay ripening of 'Fuerte' fruit using a 25% CO_2 shock treatment applied in pulses three times every 24 h. Marcellin and Chavez (1983) reported that intermittent exposure to 20% CO_2 of 'Hass' avocados stored in air delayed senescence at 12°C, reduced CI at 4°C, and controlled decay at both temperatures. However, such treatments in New Zealand were not found to be effective (Hopkirk and White, unpublished data).

In addition, Prusky *et al.* (1991; 1993) reported that 30% CO_2 (with 15% O_2) for 24 h increased the concentrations of the antifungal compound 1-acetoxy-2-hydroxy-4-oxo-heneicosa-12,15-diene in the skin and flesh of unripe avocado fruits, and delayed decay development. This diene has been suggested as the basis for decay resistance in unripe avocados (Prusky *et al.*, 1982; 1988; 1991). High concentrations of CO_2 (20%) can be tolerated by thick-skinned avocados such as 'Hass' and 'Lula', but causes browning of the skin in thin-skinned varieties such as 'Ettinger' (Collin, 1984). Intermittent high CO_2 treatment (three treatments during 21 days) reduced CI symptoms (Marcellin and Chaves, 1983). 'Fuerte' avocados had less pulp spot and blackening of cut vascular bundles after storage in 2% O_2 and 10% O_2 at 5.5°C for 28 days, or after a 'shock' treatment of 25% at 5.5°C for three days and an additional 28 days at normal atmosphere at 5.5°C (Bower *et al.*, 1990). Spalding (1977) concluded that the CO_2 must be kept below 15% to prevent fruit injury.

O_2 shock treatments

Pre-storage of 'Fuerte' avocados in 3% O_2 (balance N_2) atmosphere for 24 h at 17°C significantly reduced CI symptoms after storage at 2°C for three weeks (Pesis *et al.*, 1993; 1994). Fruit pre-stored in 97% N_2 had lower respiration and ethylene production, lower ion leakage, higher reducing power (expressed as SH groups, mainly cysteine and glutathione) and longer shelf life than the untreated fruit.

'Hass' avocados maintained in CA (0.1 to 0.44% O_2, 50 to 75% CO_2, balance N_2) for up to five days at 20°C had higher CO_2 production than fruit stored in air, probably reflecting anaerobiosis (Carrillo-Lopez and Yahia, 1990; 1991; Yahia, 1993a, 1993b; Yahia and Carrillo-Lopez, 1993; Rivera and Yahia, 1994; Rivera *et al.*, 1993). Fruit stored in this CA and then ripened in air had mesocarp and exocarp injury after two days. On the basis of these results, Yahia (1993b) and Yahia and Carrillo-Lopez (1993) concluded that 'Hass' avocado fruit is very sensitive to insecticidal atmospheres, tolerating only one day at 20°C. These findings were confirmed by

Yahia and Kader (1991) and Ke *et al.* (1995). 'Hass' avocados kept in 0.25% O_2 alone or in combination with 80% CO_2 for three days at 20°C had higher concentrations of acetaldehyde and ethanol (Ke *et al.*, 1995).

Modified atmosphere (MA) storage

Oudit and Scott (1973) reported a considerable extension in the storage life of 'Hass' avocados sealed in polyethylene bags. 'Hass' avocados sealed in polyethylene bags (15–660 μm) ranging in permeability from 111 to 605 cc O_2 m^{-2} h^{-1} atm^{-1}, and from 0.167 to 0.246 g H_2O m^{-2} h^{-1} atm^{-1} and stored at 5°C for up to four weeks lost less weight and firmness than unsealed fruits (Gonzalez *et al.*, 1990; 1997; Yahia and Gonzalez, 1998). Meir *et al.* (1997) demonstrated the potential for achieving a long storage life (nine weeks) of 'Hass' avocados using 30-μm polyethylene bags around 3.2-kg trays. Storage at 5°C was superior to 7°C, and the resulting atmosphere was ~4% O_2 and 5% CO_2.

Dixon *et al.* (2004) examined the efficacy of Freshaway™ bags during storage for four weeks at 5°C. Use of non-perforated bags resulted in a significant extension to shelf life over controls (eight vs five days), but also resulted in significant increase in rots (stem end and body rots) and a large reduction in proportion of sound (acceptable) fruit. These results are typical of fruit with a high propensity for rots.

Overall, although there have been many attempts to develop an effective MA bag for avocado, no significant commercial use has resulted. It is likely that it will only be successful for fruit grown in environments where there is low rot pressure (e.g. Chile, Peru, and California).

Table 8.7 describes some possible effects of low O_2 and/or high CO_2 atmospheres on avocado fruit.

Ethylene

As noted previously, avocado responds to ethylene exposure and produces significant amounts of ethylene. As discussed in Section 8.6.1, ethylene plays a key role in internal chilling disorders (diffuse flesh discolouration/flesh greying; Pesis *et al.*, 2002), hence the beneficial application of 1-MCP to avocado (see next subsection). In addition, as already noted, avoiding ethylene exposure and/or build up during storage is recommended, both for air and CA storage. Conversely, ethylene exposure is an important tool used to synchronize ripening for 'ripe tonight' retail sales (see Section 8.3.3).

1-MCP for long-storage

As noted previously, the key commercial benefit of 1-MCP in avocado is its use to extend storage of avocados by reducing chilling disorders associated with long-term storage, which are ethylene/ripening related (Pesis *et al.*, 2002). Woolf *et al.* (2004) describe the range of disorders associated with long-term storage of 'Hass' that could be reduced by 1-MCP treatment: diffuse flesh discolouration ('flesh greying', or 'internal chilling injury'), vascular browning, vascular leaching (browning of flesh around the vascular bundles), stringy vascular tissue (thickening

Table 8.7 Some reported effects on avocado fruit at different conditions of modified and controlled atmospheres

Variety	$\%O_2$	$\%CO_2$	Temperature °C	Remarks
Hass	2–10	4–10	7	Storage time of 7–9 weeks
Lula, Booth 8, Fuchs	2	10	7.5	Increase shelf life two-fold
Fuerte, Edranol, Hass	2	10	–	Reduces internal disorders
Non-specific	–	25	–	Reduces disorders and increases anthracnose
Fuerte	–	25	–	Delays maturation
Fuerte	2	10	5.5	Less dark spots in the pulp
Fuerte	–	25	5.5	Less dark spots in the pulp
Fuerte	3	0	24 h at 17°C	After this treatment, fruit can be stored at 2°C for 3 weeks
Booth 8, Lula	2	10	4–7	Storage time of 8 weeks
Fuerte, Anaheim	6	10	7	Storage time of 38 days
Waldin, Fuchs	2	10	7	Storage of 4 weeks, prevents anthracnose and CI
Hass	2	5	–	Storage time of up to 60 days

and separation of the vascular strands), and outer flesh blackening (blackening of the outmost layer of the mesocarp).

Pesis *et al.* (2002) applied 1-MCP at 5°C at 100 to 300 nL L^{-1} for 24 or 48 h and showed that after storage for four weeks, mesocarp discoloration and polyphenol oxidase (PPO) activity could be reduced, whereas PPO activity was increased in ethylene-treated fruit. Repeated treatments during storage were more effective than a single treatment.

Woolf *et al.* (2004) examined a wide range of 1-MCP treatment factors in relation to 'Hass' where fruit were stored for four and seven weeks at 6°C. This included treatment temperature, 1-MCP concentration (50 to 1,000 nL L^{-1}) and duration (6, 12 and 24 h) as well as time in the season (maturity) and grower effects. 1-MCP was a powerful tool for reducing ripening (softening and skin colouration) and physiological disorders associated with long-term storage such as diffuse flesh discolouration, outer flesh blackening, stringy vascular tissue, vascular leaching. Treatment at a storage temperature of 6°C was as effective as at higher temperatures, and treatment times of 18 to 24 h are recommended. Possible negative aspects of 1-MCP treatment of avocado are that higher concentrations may result in excessive delays to softening and ripening (particularly during shelf life), which are likely in turn to increase disease incidence, as observed by Adkins *et al.* (2005).

Other cultivars show similar response to 1-MCP. For 'Ettinger' and 'Pinkerton', 1-MCP treated fruit stored at 5°C for 3.5 weeks maintained greener skin colour, lower chlorophyllase activity and less chlorophyll breakdown, reduced CI symptoms

(expressed as mesocarp discolouration) and reduced PPO and peroxidase (POD) activities (Hershkovitz *et al.*, 2005).

Hypobaric storage
Low-pressure atmosphere (LP), especially below 100 mm Hg, markedly prolonged the storage life of 'Hass' avocados (Apelbaum *et al.*, 1977). Optimum conditions for LP storage of Florida avocados were suggested to be 20 mm Hg at 4.5°C (Spalding and Reeder, 1976; Spalding, 1977). Fruit held in these conditions for up to three weeks were firmer, and had less decay and CI than fruit held in 76 or 760 mm Hg. However, gases such as CO_2 and CO cannot be added when an LP system is used. Carbon dioxide is considered to be essential for control of decay and to ameliorate CI in avocados.

8.6 Physiological disorders

The wide range of physiological and pathological disorders of avocados can cause confusion, and make clear communication between researchers and industry personnel challenging. In order to standardize the nomenclature, White *et al.* (2009) developed a manual (*The International Avocado Quality Manual*) with colour photographs, descriptions and ratings of the disorders. This manual, along with a smaller version designed for use by industry and retailers (*The International Avocado Quality Pocketbook*), has also been translated into Spanish.

A wide range of physiological disorders affect avocado fruit and most of these occur following long storage periods (two to four weeks, depending on cultivar; Zentmyer, 1984). Key internal chilling disorders are flesh greying (diffuse flesh discolouration), vascular browning and pulp spot (Eaks, 1976) (Plate XIV: see colour section between pages 244 and 245), which generally occur after long storage, or at higher than optimum storage temperatures. External chilling injury (skin blackening) (Plate XIII: see colour section), on the other hand, is induced by low temperatures (generally less than 2°C). When fruit are stored for excessively long periods, the flesh may fail to ripen evenly, and become increasingly susceptible to pathogens and a range of other disorders.

8.6.1 Internal chilling injury

Internal CI (Plate XIV: see colour section) is manifested as a greyish-brown discolouration of the flesh, particularly at the base of the fruit around the seed. This can be associated with vascular browning, which starts at the base of the fruit (rather than at the stem end, which is often associated with stem-end rots). The timing of expression of internal CI and its severity depend on temperature management, initial ripeness, cultivar, production area, and fruit maturity. Avocados exposed to 3 to 5°C for more than two weeks may exhibit internal flesh browning (grey pulp, pulp spot, vascular browning), failure to ripen, and increased susceptibility to pathogen attack. The timing of CI development and its severity depend on cultivar,

production area and maturity-ripeness stage. Disorders described include brown discolouration of the vascular system, hardening of vascular strands, uneven ripening, and development of off-flavours in avocado fruit (Hatton *et al.*, 1965; Florissen *et al.*, 1996; Chaplin *et al.*, 1982; Couey, 1982). Kosiyachinda and Young (1976) found that lower temperatures were tolerated during the post-climacteric phase. In 'Hass' avocado fruit, internal CI tends to occur after about four or more weeks of storage at about 6°C, depending on maturity and growing conditions. The calcium content in the fruit might be a possible reason for differences in internal CI (Chaplin and Scott, 1980). Internal CI is the key limiting factor to long-term storage of avocados, generally associated with softening of fruit during storage, and is increased by the presence of ethylene (Chaplin *et al.*, 1982).

'Pulp spot', a low temperature disorder, is observed almost solely in 'Fuerte' fruit as small dark spots in the flesh, and blackening of a region surrounding cut vascular bundles. Swarts (1984) reported the incidence to be higher early in the season. Both pulp spot and mesocarp discolouration involve browning reactions, implicating particularly the enzyme PPO (Kahn, 1975) and phenolics (Kahn, 1977).

Application of exogenous ethylene, irrespective of the method of application, caused intensification of mesocarp discolouration in the fruit of several avocado cultivars during cold storage (Pesis *et al.*, 2002). 'Ettinger' fruit treated with ethrel (2-chloroethyl phosphonic acid) (a chemical that releases ethylene) before packing and storage developed severe CI symptoms, expressed as mesocarp discolouration after three weeks at 5°C. 'Fuerte' fruit treated with ethylene gas (100 μl l^{-1}) for 24 h at 20°C before storage at 5°C exhibited mesocarp discolouration, which increased dramatically during shelf life at 20°C. 'Fuerte' fruit treated in cold storage with a continuous low ethylene dose (4 μL L^{-1}) developed severe browning in the fruit pulp after three weeks at 5°C. 'Hass' fruit treated with 50 μL L^{-1} ethylene, for 12, 24 or 48 h at 5°C showed a gradual increase in mesocarp discolouration after three weeks in cold storage plus shelf life; the 48-h ethylene-treated fruit exhibited the most severe pulp browning. Use of absorbent sachets that removed ethylene from modified atmosphere (MA) packages reduced mesocarp discolouration and decay development in 'Hass' fruit after five weeks of storage at 5°C.

8.6.2 External chilling injury

Classic external CI occurs if fruit are stored at low temperatures (0 to 3°C), but, less commonly, after long periods (>six weeks) at standard storage temperatures. Skin pitting, scalding, and blackening are the main external CI symptoms on mature-green avocado kept at 0 to 2°C for more than seven days before transfer to ripening temperatures. External CI occurs as irregular patches of blackening on the skin and can be observed during storage, but generally increases slightly in intensity after removal from cold storage (White *et al.*, 2009). The damage is first seen in inner cell layers of the exocarp and then the outer layers of the skin (Woolf, 1997). In cultivars that naturally darken during ripening, such as 'Hass', the damage will be less apparent after ripening, but may be discriminated as brown, corky skin tissue in ripe fruit. External CI is generally induced by temperatures

lower than 3°C, but fruit become less sensitive with increasing maturity, and ripe fruit are less affected. Fruit exposed to low temperatures may be of poor internal quality when ripe, with a high incidence of rots and softening disorders (Woolf *et al.*, 1995), but will have lower incidence of internal CI (greying). 1-MCP does not reduce external chilling injury (Woolf *et al.*, 2004).

For 'Hass' fruit stored for long periods at standard storage temperatures (six to seven weeks at about 6°C), a form of external CI is expressed that is of a very similar appearance to that observed at low temperature, which can sometimes be seen in fruit that are quite soft (nearly ripe) at the point of removal from storage.

8.7 Pathological disorders

Postharvest rots (or 'ripe rots') (Fig. 8.3) are one of the key problems of avocado in most growing regions/countries with the exception of very dry environments such as Chile, Peru and California.

8.7.1 Epidemiology

In order to minimize postharvest diseases of avocados an integrated disease management programme needs to be implemented. Both pre-harvest and postharvest protocols and procedures are important for their control. A basic

Fig. 8.3 Severe stem end rots and associated severe vascular browning. Image courtesy of Plant and Food Research, New Zealand.

understanding of the infection processes and the periods of highest risk for infection to take place are required so as to achieve best control.

The most important postharvest decays of avocados are caused by the fungi *C. gloeosporides*, which causes anthracnose or black spot decay, and *Diplodia natalensis*. Also important are *Phomopsis* spp. and *Dothiorella* spp. which cause stem-end rot (Ahmed and Barmore, 1980).

Diseases of avocados are divided into two categories based on their location (Snowdon, 1990). Stem-end rots (Fig. 8.3) enter the fruit at the stem, or peduncle end of the fruit and move down the fruit resulting in discoloured flesh, often with associated browning of the vascular strands (Johnson and Kotze, 1994), which often extend well beyond the disease margin of the flesh. Body rots invade through the skin and generally manifest as circular brown to black spots that may be covered with spore masses in the later stages of infection. Decay penetrates through the flesh, resulting in discrete areas of discoloured flesh. In cultivars that darken when ripe (such as 'Hass'), rots may be less obvious externally (unless they are sporulating). The most prevalent fungi responsible for postharvest diseases of avocado fruit are *Colletotrichum acutatum, C. gloeosporioides, Botryosphaeria parva, B. dothidea* and *Phomopsis* (Hartill, 1991). Apart from *Phomopsis*, which is almost exclusively isolated from stem-end rots, these fungi can cause both stem-end rots and anthracnose (a disease usually characterized by necrotic lesions on the body of the fruit) on 'Hass' avocados. *Botryosphaeria* spp. is generally isolated in greater numbers from rots of avocados than are any of the other fungi. Everett and Pak (2001) found that *Colletotrichum acutatum* was more often associated with stem rots, and *Botryosphaeria parva* with body rots, but also that there were significant regional and seasonal differences.

Infection with *C. gloeosporides* occurs while the fruit is developing on the tree. Fruit spot disease caused by *C. gloeosporioides* is the most commonly occurring disease of avocado. Infection of avocado fruits by *Fusarium solani* and *F. sambucinum* causes accelerated softening of fruits. Other diseases of avocados are cercospora spot (*Cercospora purpurea*) and scab (*Sphaceloma perseae*), which attack leaves as well as fruits (Kadam and Salunkhe, 1995). Anthracnose, caused by *Glomerella cingulata,* of which the conidial state is *Colletotrichum gloeosporioides,* is found in the USA, Israel (Prusky *et al.*, 1983), Argentina (Oste and Ramallo, 1974), Australia (Peterson and Inch, 1980), New Zealand (Hartill, 1991), India, South Africa (Rowell, 1983) and Puerto Rico (Nolla, 1926). Infection studies have identified *Colletotrichum gloeosporioides* as a weak pathogen. Anthracnose appears as the fruit begins to soften as circular black spots covered with pinkish spore masses in later stages. Decay can penetrate through the flesh and induce browning and rancid flavour. Infection is enhanced by wounding, artificially and by the fruit-spotting bug (Fitzell, 1987). On the tree during the season, spores of this fungus have been shown to germinate, form an appressoria and a short infection peg that penetrates about 1.5 μm into the skin (Coates *et al.*, 1993). The fungus then remains quiescent until harvest, when antifungal dienes in the skin of avocado fruit break down because of degradation by lipoxygenase activity (Karni *et al.*, 1989; Prusky *et al.*, 1988). The fungus then resumes growth and invades the avocado fruit to

cause postharvest rots (Prusky *et al.* 1982; 1983; 1984; 1988; 1990; 1991; Adikaram *et al.*, 1992; Neeman *et al.*, 1970). Breakdown of the antifungal dienes was delayed by CO_2 (Prusky *et al.*, 1991), hypobaric pressure (Prusky *et al.*, 1984) and by treatment with antioxidants (Prusky *et al.*, 1995).

Cercospora spot of avocados, caused by *Pseudocercospora purpurea,* causes spots on fruit, which at first form small greenish-white dots that expand into slightly sunken irregular brown blotches. Mature lesions are rarely larger than 0.5 cm, but the cracks and lesions formed provide entry for other fungi, particularly anthracnose (Snowdon, 1990). This disease is found in Brazil (Albuquerque, 1962), South Africa (Darvas, 1982), Cameroon (Gaillard, 1971), Japan (Hino and Tokeshi, 1976), Mexico (Fucikovsky and Luna, 1987) and USA (Nagy and Shaw, 1980). Up to 69% of preharvest fruit loss on some orchards in South Africa has been attributed to infection with this fungus (Darvas and Kotze, 1987).

Dothiorella rot, caused by *Botryosphaeria ribis*, of which the conidial state is *Dothiorella gregaria* is found in Israel, South Africa (Labuschagne and Rowell, 1983), the USA (Stevens and Piper, 1941), and parts of South America (Zentmyer, 1961). In New Zealand this disease is caused by *Botryosphaeria parva* (Hartill *et al.*, 1986) or *Botryosphaeria dothidea* (Hartill, 1991) and in Australia by *Dothiorella aromatica* (Muirhead *et al.*, 1982). This disease can invade avocados through the body of the fruit or through the cut stem end (Snowdon, 1990). Symptoms usually only appear as fruit begin to soften after harvest, although this fungus has been isolated from lesions on hard unripe Californian avocados (Snowdon, 1990).

Stem-end rot is generally caused by *Botryodiplodia theobromae* in Australia (Peterson, 1978), South Africa (Darvas *et al.*, 1987), the Ivory Coast (Frossard, 1964) and the USA (Stevens and Piper, 1941). *Dothiorella* spp., *Phomopsis perseae* (Peterson, 1978) and *Thyronectria pseudotrichia* (Darvas *et al.*, 1987) have also been implicated in stem-end rots. *Dothiorella* spp. and *Phomopsis* spp. can cause latent infection in developing fruit (Peterson, 1978). However, *Botryodiplodia* is a wound parasite, and most infections with this fungus probably take place at harvest. In New Zealand, *Botryosphaeria dothidea, B. parva, Colletotrichum gloeosporioides, C. acutatum* and *Phompsis* spp. have all been associated with stem-end rot (Hartill, 1991). This appears as dark brown to black discolouration, which begins at the stem and advances toward the blossom end, finally covering the entire fruit. *Dothiorella gregaria* is another cause of stem-end rot in ripe avocados. Scab, caused by *Spaceloma perseae*, affects young developing fruit. Raised corky brown spots are produced on the skin, which mar the cosmetic appearance of the fruit. Wound pathogens can gain entry to the fruit through lesions caused by this fungus (Ramallo, 1969). Scab occurs in North, Central and South America, in the West Indies (Jenkins, 1934), and in South Africa and the Philippines (Snowdon, 1990).

Some other fungi that can cause postharvest diseases of avocado worldwide, but are rare in occurrence and are not perceived to be important include *Alternaria* sp. in Israel (Zauberman *et al.*, 1975); *Penicillium expansum* in the USA and the West Indies (Horne, 1934; Wardlaw, 1934); *Fusarium* spp. in Israel (Zauberman and Schiffmann-Nadel, 1979); South Africa (Darvas and Kotze, 1987); the USA (Horne, 1934) and the West Indies (Wardlaw, 1934); *Pestalotiopsis versicolor* in

South Africa (Darvas and Kotze, 1987); *Phytophthora citricola* which attacks fruit near the ground in Mexico (Fucikovsky and Luna, 1987) and the USA (Koike *et al.*, 1987); *Trichothecium roseum* in the USA (Horne, 1934); and *Rhizopus stolonifer* in South Africa, the USA and Israel (Darvas and Kotze, 1987; Zentmyer *et al.*, 1965). In New Zealand species of *Fusarium* have also been isolated from anthracnose (Hartill, 1991). In New Zealand *Colletotrichum acutatum* has been isolated from both stem-end rots and anthracnose of 'Hass' avocados (Hartill, 1991). *Colletotrichum acutatum* spores released from infected dead twigs and fruit in the canopy, or possibly on the orchard floor, seem to infect avocado fruit while hanging in the tree. Most infections are probably initiated from within the avocado tree, the influence of shelter-belt infections does not seem to be important, and timing of infection appears to be random throughout the year (Everett, 1994). *C. acutatum* may be a wound pathogen, as only a few fruit became infected when unwounded fruit were artificially inoculated throughout the season in the orchard. Damage caused by grading equipment was insufficient to aid infection.

Avocado blight, caused by *Sphaceloma perseae* (Myriangiales: Elsinoeaceae), found in Michoacán (Mexico), Florida, Puerto Rico, Brazil, Africa, Peru, Cuba, Haiti and California, attacks the fruit (in all stages), leaves, and young branches. The affected fruit present brown lesions of corky aspect with round or irregular shapes at first. When these lesions grow, they can cover a large part of the fruit or the whole fruit, and cause fissuring in leaves and branches. In the fruit, the damages are exclusive of the exocarp, while the rest of the fruit remains healthy. However, the lesions can be an entry point for other organisms (Gallegos, 1983). The *S. perseae* fungus requires a high relative humidity and high temperatures for its proper development. The most susceptible stage of the fruit is when it reaches a third or a half its normal size. Damage to the fruit caused by insects, rodents or mechanically, allows the entrance of the disease, which produces spores on the attacked tissue. Among all the cultivars grown in Mexico, 'Fuerte' is the most susceptible to this disease. 'Hass' can also be severely affected if the fungus is not prevented. 'Booth 1', 'Pollock', and 'Waldin' are considered slightly susceptible. The Mexican local hybrids (Criollos) are also likely to be affected by the fungus, although the incidence is lower because fruit from these trees ripens in the spring (Gallegos, 1983).

8.7.2 Preharvest control

Preharvest control methods for postharvest fungal decay include good orchard sanitation (removal of mummified fruit and dead wood; Everett *et al.*, 2007a) and effective preharvest application of a fungicide such as copper, which is widely used in some countries where humid growing conditions prevail. Although the effects may not be strong, there is some indication that more open canopy (better airflow) might reduce rots (Everett *et al.*, 2007a; 2008b).

Most researchers working in humid growing environments find significant inter-orchard differences, particularly in terms of rots. Often one finds that in a group of three to five orchards, one or two orchards will show significantly higher rot incidence (Adkins *et al.*, 2005; Burdon and Lallu, 2009). This suggests firstly that

there are good orchard practices that should be understood and more widely applied, and secondly that for markets that require a long storage time, low-rot orchards should be selected. Likewise, using fruit too early or late in the season is also going to increase the risk of a poor out-turn after prolonged storage (Dixon *et al.*, 2003).

Preharvest sprays with copper have been shown to significantly reduce postharvest diseases (Hartill *et al.*, 1990a). Everett and Pak (2001) correlated the number of copper fungicide applications/season and showed a significant relationship to body rots ($r^2 = 0.81$). Four sprays during the season were insufficient to reduce postharvest rots, and twelve sprays were required before significant differences were obtained.

Preharvest copper alternatives

Benlate application has been shown to reduce disease significantly when three sprays were applied during the season (Hartill *et al.*, 1990b). Everett *et al.* (2007b) examined a range of treatments for fruit stored for four weeks. Boscalid, Pristine® (boscalid/pyraclosrobin), and fluazinam were found to give better control than the unsprayed control, and were comparable to two copper sprays (Kocide® Opti and Camp™ DP (copper hydroxide formulations). Everett *et al.* (2008b) reported that phosphoric acid trunk injections reduced postharvest rots (both body and stem end rots).

Development of prediction models in the orchard for calculation of periods of infection risk is a valuable tool to enable growers to target spray applications more effectively and thus reduce costs, and also reduce the risk of resistance to chemicals (Everett *et al.*, 2003). Understanding of temperature effects on spore germination (as carried out by Everett and Pak, 2002) may provide useful information to incorporate into such models.

8.7.3 Postharvest control

Postharvest handling, especially temperature and ripening control should be optimized. Sanitation in the packinghouse is necessary. Harvesting should not be carried out in the rain or when fruit are wet, and careful handling to minimize skin damage helps to reduce rots (Mandemaker *et al.*, 2006).

The most important postharvest factor for reducing rots is maintaining optimum temperature during handling, storage, transport, and ripening. It is also critical not to store fruit for long periods. Postharvest temperature control is effective in reducing the incidence of diseases (Truter and Eksteen, 1987a, 1987b; Young and Kosiyachinda, 1975; Fitzell and Muirhead, 1983). However, optimum temperatures are specific for different cultivars and in different regions. For example, New Zealand 'Hass' avocados stored under appropriate South African recommendations ('Hass' from KwaZulu/Natal) were affected by more rots than the standard New Zealand postharvest temperature regime (Hopkirk *et al.*, 1994). Storage in 2% O_2 and 5% CO_2 extended the effective storage of 'Hass' avocados to four weeks, but rots were severe (Hopkirk *et al.*, 1994). High concentrations of CO_2 (10%) were reported to prevent development of anthracnose for three to four weeks in 'Fuchs' and 'Waldin' fruit stored at 7.2°C in Florida (Spalding and Reeder, 1975),

but such treatments don't appear to be effective in New Zealand (White and Hopkirk, unpublished data). As noted previously, ripening fruit at lower temperatures (15 to 20°C) can lead to significant reduction in rots compared with higher temperatures (Hopkirk *et al.*, 1994). Although ripening at 15°C has been found to be a robust and reliable regime, it is difficult to instigate commercially.

Postharvest fungicides (prochloraz, benlate/benomyl and thiabendazole) are used in some countries, but these are not registered for use in the USA (Darvas *et al.*, 1990). Use of prochloraz (Sportak®) is required for export to Australia from New Zealand and thus much research has been carried out into its efficacy. It can be applied either as a dip or spray, but New Zealand experience has lead to the recommendation of spray application rather than a dip, since build-up of spores in dipping tanks has been observed. Postharvest dipping with prochloraz can be unreliable. It appears that there may be a curing effect, or alternatively an infection period immediately after harvest that is not halted by a delayed application of prochloraz. Hartill *et al.* (1986) found no difference in rots if prochloraz was applied within 24 h of picking. Everett and Korsten (1996) have demonstrated the effectiveness of applying prochloraz either in wax or as an ultra-low volume spray. Fruit treated with prochloraz cannot be exported to Asia, the USA and some countries in Europe.

In the recent years a wide range of possible postharvest fungicide treatments have been examined in New Zealand. Although not registered, Thiabendazol (TBZ) and Pristine® (boscalid/pyraclosrobin) were applied and there were generally beneficial effects on body rots, and sometimes stem-end rots, but variation between orchards in efficacy (Everett *et al.*, 2007a). For late season fruit (generally higher rot pressure), Mandemaker *et al.* (2007a) found no effective treatments among the following; Carbendazim, azoxystrobin, folpet, fatty acids (potassium salts), and benomyl.

Work in New Zealand lead by Everett and in South Africa lead by Korsten has sought to develop biological control agents for postharvest rots. Examples include Seranade® Max (*Bacillus subtilis* QST 713), and *Serratia marcescens* HR42. As is often the case with biological control agents, lack of repeatable efficacy limits commercialization.

Wax by itself also seemed to reduce incidence of stem-end rots; however, waxing has been reported to increase the incidence of all postharvest diseases on 'Fuerte' avocados (Darvas *et al.*, 1990). Waxing probably increases the humidity next to the skin of the fruit, and also the production of ethylene, both can promote the growth of anthracnose fungi (Darvas *et al.*, 1990; Flaishman *et al.*, 1995). However, Darvas *et al.* (1990) have shown that wax extended the shelf life of 'Fuerte' avocados.

8.8 Insect pests and their control

Avocado trees growing in dry climates have relatively few insect pests. One that has become very significant lately is the avocado thrip (*Scirtothrips perseae,* Nakahara), which has recently moved into California. This resulted in significant losses of fruit due to feeding on the skin (Fig. 8.4), leading to fruit described as 'avocado spuds',

Fig. 8.4 Extreme damage to avocado due to feeding of avocado thrips (*Scirtothrips perseae,* Nakahara). Image courtesy of Plant and Food Research, New Zealand.

since fruit can be completely devoid of green skin, thus resembling a potato. Perhaps surprisingly this does not significantly affect ripe-fruit quality. Other thrips may be a problem in other countries such as red-banded thrips (*Selenothrips rubrocinctus)* in Australia, and greenhouse thrips (*Heliothrips haemorrhoidalis)* in New Zealand.

Leafroller caterpillars typically cause damage to the skin due to feeding of the larvae (caterpillars), often around the stem end of the fruit, or where leaves are touching fruit. Examples include: Ivy leafroller (*Cryptoptila immersana,* Walker) and avocado leafroller (*Homona spargotis,* Meyrick) in Australia; Amorbia (*Amorbia cuneana*), Orange tortrix (*Argyrotaenia citrana*) and Omnivorous looper (*Sabulodes aegrotata*) in California; and Greenheaded leafroller (*Planotortrix octo*) and Brownheaded leafroller (*Ctenopseustis obliquana*) in New Zealand.

Fruit spotting bug can cause damage to fruit where 'stings' to the fruit lead to hard lumps or 'stones' in the flesh (of ripe fruit). Species include *Amblypelta nitida* and banana spotting bug (*Amblypelta lutescens lutescens*).

A range of other insects may be pests, including mealybug, scale and various mites.

8.8.1 Preharvest control

In order to establish a good strategy for integrated pest control, thresholds of economical damage need to be determined. These can help to reduce the frequency

of preharvest sprays, lower the crop handling costs, increase production, and reduce the incidence of postharvest fumigation. In Mexico, only four pesticide products are recommended for chemical control: 1) parafinic petroleum oil; 2) Malathion CE 47; 3) Methylic parathion, and 4) Permetrine. In Chile, the presence of a large fauna of biological control agents has helped to contain potential avocado pests. However, there is no doubt that the use of pesticides in the orchards contributes to maintaining this situation. Different pests that sometimes need to be restrained can be handled with selective pesticides that do not interfere significantly with biological control agents (BCAs). In other cases, spraying specific sectors of the orchard will help to maintain the beneficial fauna. In the same way, the establishments of reservoirs for biological controllers, together with cultural practices such as the elimination of low branches, the removal of branches that constitute the origin of infections, and the maintenance of vegetation that feed beneficial fauna in the adult stage, are also biological control practices. Finally, the artificial introduction of biological controls through the development and release method can help where the beneficial fauna are not efficient enough or do not colonize the orchard in time (López-Laport, 1999).

8.8.2 Postharvest control

Methyl bromide

Avocados grown in fruit fly-infested areas require quarantine treatments to be marketed in many countries. Methyl bromide (MeBr) treatment is an APHIS-approved treatment for Mediterranean fruit fly, but can result in a significant reduction in fruit quality. Avocados are also commonly MeBr-fumigated at entry into countries for quarantine insects other than fruit fly. Avocado fruit treated with MeBr can exhibit some external damage, ripening two to four days earlier than non-fumigated controls. Pitting and other visual damage caused by fumigation is commonly masked in the case of cultivars with purple or black fruit when the fruit ripen and achieve a dark colour. The cultivars least damaged are those with purple or black skin. MeBr fumigation does not affect the flesh as much as the skin. Flesh colour and flavour are commonly acceptable in most cultivars, and the former is usually equal to that of controls in appearance. In certain cultivars, however, fumigated fruit commonly show more internal browning, with visibly affected vascular bundles throughout the flesh (Ito and Hamilton, 1980).

Irradiation

Extension of shelf life by gamma irradiation has been successful for some fruits, but appears to hold little prospect for avocado. Akaine and Goo (1971) found avocado fruit to show surface and internal damage at 5 Krad. At this dosage and lower, the climacteric respiration occurred earlier than that for controls, and so gave no storage advantage. Smith and Jansen (1983) found 2.5 Krad to be the maximum safe dosage, but without significant advantage from a postharvest perspective. Young (1965) studied the effect of gamma radiation on respiration,

ethylene production and ripening of 'Fuerte' avocados, and reported that irradiation in the pre-climacteric phase at 5 and 10 Krads caused an immediate doubling of respiration and a small ethylene production, 100 Krads caused a doubling of respiration and small ethylene production, but severe injury and fruit did not ripen. Irradiation after the climacteric has been initiated or in the post-climacteric phase had no effect on ethylene production or respiration, nor was there any effect on the appearance or quality of the fruit. Doses in excess of 20 Krad seemed to cause brown discolouration to the mesocarp; 10 Krads resulted in extension of storage life of 'Fuerte' by ~five days at 20°C, but fruit irradiated at 50 Krads did not ripen, the tissue remained hard and turned brown (Nogalingam, 1993).

Low-temperature or 'cold' disinfestation

Use of low temperatures (generally 11 to 16 days at <1.1°C) is an effective fruit fly treatment for some fruit and fruit fly species. However, such temperatures and storage times are likely to result in commercially unacceptable external chilling injury (discrete patches on the skin) in many cultivars, and in 'Hass' under most growing conditions. There is a range of possible ways to increase the tolerance of the fruit to the low temperature that is required for low temperature disinfestation treatments, but the two ways that have both physiological success and commercial applicability are low-temperature conditioning and heat treatments.

Low-temperature conditioning

Low-temperature conditioning (LTC) is the process of holding fruit at temperatures just above the temperature at which chilling occurs, thus inducing tolerance to subsequent low temperatures. Woolf *et al.* (2003) applied an extreme chilling treatment of three and four weeks at 0°C after a wide range of LTC treatments and found that the optimum treatments were in the range of 6 to 8°C for three to five days.

Hofman *et al.* (2003) examined these treatments in relation to development of a commercial cold disinfestation treatment for Queensland fruit fly (*Bactrocera tryoni,* Froggatt) in 'Hass' (16 days at <1°C). LTC at 4°C for four days or at 6 to 8°C for three to four days increased the percentage of fruit with acceptable external appearance (less than 5% of the fruit with discrete dark patches on the skin, and skin spotting combined) after disinfestation from 0 to 100%, because of the effective elimination of discrete patches on the skin. Disinfestation alone increased body rots and diffuse flesh discolouration severity in ripe fruit, while LTC before disinfestation reduced severity of these disorders to similar incidence as that in non-disinfested, non-stored fruit. The optimum LTC treatment (6°C for three days) followed by disinfestation resulted in no survivors from 50,748 third instar Queensland fruit flies (*Bactrocera tryoni* Froggatt). LTC efficacy was further verified commercially by conditioning fruit at 6°C for three days, followed by cold disinfestation and airfreight to New Zealand. External fruit appearance and internal ripe fruit quality after disinfestations were found to be high.

Thus, although LTC combined with cold disinfestation is effective for 'Hass' avocados, such a treatment combination may not be effective for all fruit fly

species and cultivars because of tolerance differences. Indeed, for five cultivars grown in sub-tropical conditions (New Caledonia), significant cultivar differences were noted, and in some cultivars, LTC treatments were ineffective at significantly reducing chilling injury in response to a cold disinfestation treatment (Kagy, White and Woolf, unpublished data).

Heat treatments

Two of the most common heat treatments are hot air and hot water. Avocados are relatively sensitive to high temperatures, and treatments that are likely to kill insects (both hot air and hot water) will result in unacceptable heat damage to the fruit (Yahia, 1997a; 1997b; 2001). Another use for heat treatments is to induce tolerance to low temperature (~0°C, which can control fruit fly; Sanxter *et al.* 1994). Hot air treatments have been shown to reduce external chilling injury (Sanxter *et al.*, 1994; Woolf *et al.*, 1995; Florissen *et al.*, 1996; Roman-Mares and Yahia, 2000a; 2000b; Yahia 1997a; 1997b; 2001), but are slower to apply, and generally require higher capital investment, and thus are more commercially challenging.

Hot water treatments can reduce chilling injury (Woolf, 1997), and a temperature of ~38°C is optimal. Hofman *et al.* (2002) examined the use of hot water treatment (HWT; 38 to 42°C for 20 to 60 min) to improve quality of 'Hass' avocado following cold disinfestation for fruit flies. HWT significantly reduced skin damage caused by cold disinfestation, with 40°C for 30 min, 41°C for 20 to 30 min and 42°C for 25 to 30 min resulting in the greatest reduction. HWT also reduced body rots in ripe fruit, with 40 and 41°C for 30 min being consistently the most effective. Treatment at 42°C increased body rots compared with the other HWTs in one season, and there was no benefit of HWT for durations longer than 30 min. The severity of vascular browning (VB) and mesocarp discolouration (MD) in ripe fruit was generally low, and increased following cold disinfestations. Treatment at 41°C for 25 to 30 min and 42°C for 25 min increased the percentage of externally acceptable fruit (less than 5% of the skin area with defects) from 0 to about 80% after removal from cold disinfestation. The same treatment also increased the percentage of ripe fruit with acceptable flesh quality (less than 5% of the flesh with rots or disorders) from 0 to 16 to 20%, mainly because of reduced body rots. These results indicate the commercial potential of HWTs of about 41°C for 25 to 30 min, or 42°C for 25 min, to improve avocado external and internal fruit quality following cold disinfestation.

The efficacy of LTC and HWT alone and in combination was examined (Hofman *et al.*, 2003) and LTC was found to be more effective than HWT, either alone or in combination with HWT. LTC before disinfestation reduced the severity of discrete patches, and improved flesh quality more than HWT.

The effects of a transient (warming) temperature spike on the efficacy of an APHIS-approved quarantine cold treatment, T107 (a), against the Mediterranean fruit fly (*Ceratitis capitata*), were tested on Hawaiian-grown 'Sharwil' avocados (Jang *et al.*, 2001). Avocados infested with late stage eggs were subjected to a warming temperature spike (~4.2°C for 1 h) at six to nine days into the treatment, and subsequently allowed to resume the treatment until conclusion (12 days at

<1.1°C, 14 days at <1.67°C or 16 days at <2.2°C). Insertion of a ~4.2°C temperature spike into the treatment at six to nine days had no effect on the efficacy of the quarantine cold treatment, when fruit were allowed to resume the treatment to completion. Infested fruit that did not receive a 'heat shock' treatment (recommended to improve fruit quality) and were subjected to cold treatment for six to 16 days at a fruit centre temperature of <1.1, <1.67 or <2.2°C had no fruit fly survivors in the fruit by the ninth day of cold treatment. Infested avocados subjected to a 'heat shock' treatment for 10 to 12 h at 38°C before cold treatment had no survivors in the fruit by the eighth day of cold treatment. Therefore, the T107 (a) cold treatment (as stated in the APHIS treatment manual) seems to be effective against Mediterranean fruit fly eggs in 'Sharwil' avocados, and such a use of a 'heat shock' to prevent CI during the cold treatment does not reduce mortality of fruit fly eggs.

8.9 Postharvest handling practices

8.9.1 Harvest operations

Fruit are commonly hand harvested when mature (Fig. 8.5), using an array of picking aids (Fig. 8.6), such as ladders, telescopic poles fitted with a cutting blade and catch bag, or hand clippers. Depending on the country, economics and topography, fruit may be harvested using hydroladders (or 'cherry pickers'), or in some cases more extensive harvesting aids (multiple people/machine) are used. Fruit are picked into large bins, usually mounted on trailers to facilitate their

Fig. 8.5 Harvesting avocados. Image courtesy of Adel Kader.

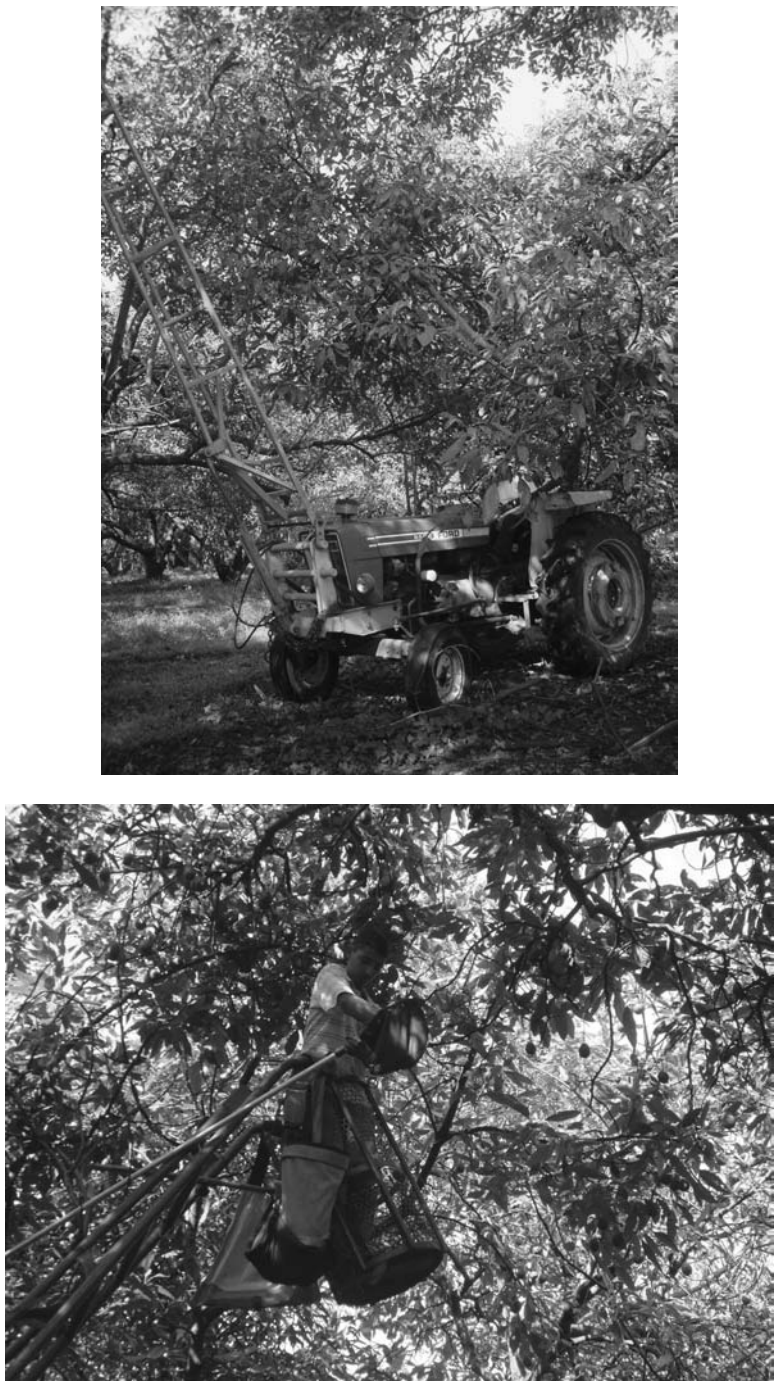

Fig. 8.6 Harvesting aids used in Mexico.

Fig. 8.6 Continued.

movement to the packing shed (Fig. 8.7). The fruit is removed from the tree by either clipping or snapping the stem at the base of the fruit ('snap picking'). For most cultivars, fruit needs to be clipped with a 'button' retained on the pedicel end. This reduces the chance of bruising and puncturing adjacent fruit once they are placed in containers (Ahmed and Barmore, 1980). Commercial organizations are often interested in moving to 'snap picking', since it means a significant increase in the rate of harvesting fruit, and reduces health and safety concerns (danger to personnel from cutting implements).

Snap picking has been shown to increase stem-end rots (Kurlaender, 1996), while other methods of picking have shown a reduction (Darvas *et al.*, 1990). The effectiveness of snap harvesting is dependent upon fruit maturity, growing conditions (rain) and cultivar (Arpaia and Hofshi, 1998). Overall, snap picking has little effect on ripening time (although some have shown faster ripening; Tingwa and Young, 1975), weight loss or physiological disorders. However, increased stem-end rotting is a key risk (Hartill and Sale, 1991), and it is not recommended that snap picking be adopted in high rainfall and/or high-rot pressure growing environments (Woolf *et al.*, 1998a, 1998b).

The time of the day at which fruit are harvested generally has relatively little effect on fruit quality, although a slight reduction in body rots in fruit harvested in the afternoon compared with early morning has been observed (Elmsley *et al.*, 2007). This may reflect skin turgidity and damage susceptibility, and is not likely to be a problem in dry growing conditions. General recommendations are to avoid harvesting in rain.

Fig. 8.7 Fruit packing in Mexico. Image courtesy of Kenneth Luis Treviño Cassilly.

During harvesting and handling, fruit should be handled gently, as discussed previously in terms of physiological damage (skin damage and bruising). In addition, drop heights of 0.1 to 0.3 m can lead to increased rots (although this can be mitigated by use of postharvest application of prochloraz; Mandemaker *et al.*, 2007b).

After harvesting, it is important to keep the fruit out of direct sunlight (for example bins and crates in the orchard) and thus fruit should be placed in the shade while awaiting transport. Exposure to excessive sunlight will lead to increased weight loss and possibly sunburn.

8.9.2 Packing house practices

Fruit are generally unloaded from the truck or tractor, received, and weighed. In Mexico, fruit arrives in boxes of different colours to identify its final destination (domestic market, export, organic fruit, etc.). Crates or picking bins are generally carefully tipped onto a packing line, where the fruit are cleaned with rotating brushes (usually with some wetting of the brushes). At this time, postharvest treatments such as fungicides, insecticides (e.g. pyrethrum) and/or waxes may be applied. Fruit are then dried (typically using fans over brushes, possibly with heating) and graded on a 'pre-grading table' by hand. Inspection grades are based mainly on a variety of characteristics: shape, colour, maturity, trimming of stems, defects (e.g. caused by insects, rodents, or mechanical mishandling), external contaminants (e.g. spray residues or bird guano) and decay (Nogalingam, 1993).

Fruit are then generally run onto a packing line, where sizing by weight is carried out using digital load-cells, and fruit are dropped into 'count sizes'. Fruit are placed into trays or crates by hand, or machine-filled then generally palletized (Fig. 8.7).

The packaging material varies according to the origin and the destination market, being cardboard, plastic, or wood (wood is not used in Europe). The most common containers used for avocado are single-wall corrugated fibreboard or plastic boxes. The first usually have a capacity of 4 kg with one layer of fruit. In California, avocados are packed in a single layer of 5.6 kg flats or trays, two layers of a total of 11.3-kg lugs and 11.3-kg volume-fill boxes. Returnable Plastic Containers (RPCs) are being used increasingly in parts of the USA and Europe. In some European supermarkets, 100% of the avocado is delivered in RPCs. There is also increased usage of pre-packed units such as polyethylene containers (clam shells) or mesh bags. For Florida avocados, the common packages used are: single layer, 6.1 kg flats; 2-layer, 12.5 kg lugs; 15.9-kg cartons and 4.5-kg natural packs.

Individual boxes are then palletized, where boxes are stowed and tied together. Pallets have to comply with the measurements established by the containers in which they will be carried. The number of boxes per pallet varies, but is commonly 264 boxes of 4 kg each and a lesser number of boxes when package weight is 6 kg, with a total of 5,280 boxes (4 kg) per 40-foot container. Pallets are then immediately pre-cooled, and then refrigerated until they are loaded into the transport containers.

For New Zealand 'Hass' fruit, Yearsley *et al.* (2002) recommended packing and storage within 24 h, and holding fruit at temperatures above the dew point (~12 to 16°C). In hot countries (e.g. South Africa), fruit are generally transported as rapidly as possible to the packinghouse, and 'field heat' removed in cool rooms before packing.

8.9.3 Control of ripening and senescence

Avocado fruit require very careful manipulation of ripening in order to achieve good fruit quality, particularly in a commercial setting. For example, while some fruit can be treated with 1-MCP to halt softening at near-harvest fruit firmness levels (e.g. sweet persimmon or some apples), avocado require further softening in order to be eaten ripe. The added problem is in many cases, treatments that extend shelf life (time to ripen), result in significant increases in rots. This leads to the desire, on one hand, to slow softening/ripening in storage (to avoid physiological disorders), while on the other hand to achieve a reasonably short and predictable shelf life on removal from storage.

Pre-storage treatments

Some pre-storage treatments have been reported to delay ripening and prolong storage life of avocado fruit. Waxing can be regarded as a cosmetic treatment, since it imparts glossiness, but it also has pronounced physiological effects, especially on the internal atmosphere and weight loss of the fruit (Durand *et al.*, 1984). A gain of one or two days of shelf life may be achieved, but in some cases at the expense of development of some fruit rots. Waxing was found to cause a considerable

reduction in moisture loss, in addition to modifying the internal atmosphere of the fruit tissue, decreasing the internal oxygen and increasing carbon dioxide concentrations (Durand *et al.*, 1984). There is a wide range of 'coating'-type products in the market that purport to increase the storage and/or shelf life of avocados and/or improve quality and out-turn. Significant commercial failures have occurred. We recommend careful testing/verification of product efficacy in each country, region/grower and cultivar. This should include full storage trials over a season, and fruit should be ripened to an edible stage of ripeness and external and internal quality assessed carefully. Small-scale test shipments (with appropriate controls and ripe-fruit assessments) would also be wise before extensive rollout.

Low-oxygen atmosphere pre-storage treatments (3% oxygen and 97% nitrogen) for 24 h reduced CI symptoms and softening in 'Fuerte' avocado fruit after three weeks of storage at 2°C (Pesis *et al.*, 1994). Carbon dioxide shock pre-treatment (25% in air, for three days) was reported as a promising treatment (Bower *et al.*, 1989). Prusky *et al.* (1995) suggested that a postharvest dip or spray of avocado fruit with the antioxidant butylated hydroxyanisol might reduce postharvest decay in avocado by modulating the natural fruit resistance.

Commercial 1-MCP treatment has grown in recent years, and AgroFresh applies 1-MCP as SmartFresh^{SM} under carefully controlled conditions. Typically, an AgroFresh representative visits the site where fruit are held in a suitable room, tests the room for leakage rate, then starts the treatment using a specialized gas-release device. The room is then sealed and no access is allowed until the end of treatment, at which time the representative opens the room and it is vented before release to the client. A fruit sample is generally taken to verify treatment efficacy. Treatment is generally carried out at storage temperature (~6°C) for 18 to 24 h and at 'half rate' (300 nL L^{-1}). SmartFresh^{SM} has been applied commercially since 2003 and is registered for use in avocados in 40 countries.

As noted previously, the main benefit of 1-MCP treatment is a reduction in internal chilling disorders such as flesh greying and vascular browning. Combining 1-MCP with other postharvest treatments can be used to achieve better fruit quality. For example, Jeong *et al.* (2003) found that 'Booth 7' treated with both 1-MCP and wax had better retention of green skin colour and fruit firmness. While waxed fruit reached a fruit firmness of 15 N after 19 days at 13°C, fruit treated with both 1-MCP and wax took ~5 weeks to reach firmness values of 25 N. As noted previously, very long storage times (>8 weeks) may be possible by use of combined treatments (1-MCP, wax and fungicides; Lemmer *et al.*, 2006). In addition, the problem of 'restarting' ripening following storage of 1-MCP treated fruit led Kruger and Lemmer (2007) to make recommendations for minimum dry matter concentrations, to ensure ripening quality was acceptable.

Cooling and storage

Pre-cooling soon after harvest is recommended to remove field heat. Removal of excess heat before or immediately after packing reduces the refrigeration required during shipment to maintain fruit at recommended temperatures, and also provides improved control of the ripening process. This is critical where long storage periods

or long transport shipments are required or where field temperatures are high (>25°C). Pre-cooling diminishes or slows the metabolic rate, ethylene synthesis and its action on the fruit, loss of texture, fruit ripening, and fungal infections. Ideally, there should not be more than 6 h from harvest to pre-cooling, and when this is not possible, the harvested fruit should not be allowed to reach an internal temperature higher than 26°C in the field and during transportation to the packinghouse.

Forced-air cooling is the method best suited for avocado pre-cooling. It is carried out until the fruit reaches 6 to 7°C for 'Fuerte' and 'Hass' avocados. The time required to achieve these temperatures varies according to the initial temperature of the fruit, the temperature and velocity of the air. Hydro-cooling of 'Hass' is also used commercially. It is important to ensure that fruit are not cooled below the minimum recommended temperature, which may result in external CI.

Storage temperature and management of the cool chain is the most important postharvest factor in determining avocado fruit quality. Optimum storage temperature depends on a wide range of factors, including fruit type (race), cultivar, growing conditions, fruit maturity and the duration of storage required (Table 8.8). Recommended optimum storage conditions vary according to the avocado variety (Table 8.8). All West Indian cultivars are chilling-sensitive and are best stored at 12.8 to 13°C for a maximum period of two weeks, and Guatemalan and Mexican cultivars are commonly maintained at 4°C and 8°C, respectively (Hatton *et al.*, 1965; Zauberman *et al.*, 1973). Chilling-tolerant cultivars such as 'Lula', 'Booth 8' and 'Taylor' are stored best at 4.4°C, while a few cultivars such as 'Fuerte', 'Hass' and 'Booth 7' are intermediate in sensitivity to CI (~7°C). Optimum storage temperatures for 'Hass' are 5 to 7°C for early-season fruit and 4 to 5.5°C for late-season fruit. After three to four weeks of storage, 'Hass' fruit quality is reduced, and storing fruit for >6 weeks remains a challenge. Storage temperature should be maintained with a maximum variation of 1°C or better if possible, and it is important to avoid temperature fluctuations during transport and storage. Optimum relative humidity is 85 to 95% RH, but a balance between weight loss and fruit quality is needed. The South African industry successfully developed a 'step-down' temperature protocol (Vorster *et al.*, 1987). Container-set temperatures are typically decreased 1 to 2°C each week during shipping. These protocols were developed for each cultivar, for differing times in the season and growing regions.

Table 8.8 Post-harvest life of some avocado cultivars at optimum temperature and relative humidity (RH)

Cultivar	Temperature (°C)	RH (%)	Postharvest life (weeks)
Hass	3–7	85–90	2–4
Fuerte	3–7	85–90	2–4
Fuchs	13	85–90	2
Pollock	13	85–90	2
Lula	4	90–95	4–8
Booth 1	4	90–95	4–8

CA and MA are commonly used for transporting avocado fruit by sea to distant markets in refrigerated shipping containers (Yahia, 1993a; 1998). The atmospheres used, and the technology for controlling the atmosphere, vary between shipping companies. Generally concentrations of 2 to 5% O_2 and 3 to 10% CO_2 are used.

8.9.4 Ethylene ripening

Market research has shown that avocados sales can be doubled or tripled if fruit are offered to the consumer in a ready-to-eat condition, generally marketed as 'ripe tonight'. This has led to a system of ethylene ripening ('pre-ripening', 'conditioning' or 'ethylene conditioning') before stocking, similar to that for bananas. This significantly reduces both the time it takes to ripen (to three to six days, depending on cultivar and maturity), and fruit-to-fruit variability in ripening (Gazit and Blumenfeld, 1972). This is achieved by treating avocados with 10 to 100 μL L^{-1} ethylene at 17 to 20°C for one to three days in a high airflow, or preferably forced-air room. Treatment times vary depending on the time in the season (maturity) and time of storage before treatment. New Zealand experience for 'Hass' has found that the most uniform ripening is achieved using 48 to 72 h for early season, 24 to 48 h for mid-season, and 12 to 24 h for late season. Where fruit are stored before ethylene treatment, the duration of treatment required to achieve maximum rate of ripening is reduced. For 'Hass' avocado, after three to four weeks of storage there may be relatively little benefit in ethylene treatment (particularly for later season fruit) and simply rewarming the fruit with careful temperature management may be sufficient. However, many commercial operators will use ethylene at all times, since it provides a more predictable result.

The high heat production of avocados during ripening means that careful attention should be paid to air-flow and temperature management during ethylene treatment and subsequent ripening. During ethylene treatment with low air-flows, palletized fruit may reach temperatures of more than 30°C, with negative effects on ripe fruit quality (Arpaia, personal communciation). For this reason, ethylene treatment of palletized fruit should be carried out under forced-air conditions.

Ripening rate depends on physiological maturity of the fruit, temperature and humidity, O_2 and CO_2 concentrations (Kurlaender, 1996). Although there are recommendations to maintain CO_2 concentrations below 1 to 2% during ethylene treatment, we have found no negative effects on ripening rate or fruit quality with concentrations as high as 10% (White and Woolf, unpublished data). However, concentrations above 2% have health and safety concerns, and thus it is worth considering use of a continuous ethylene dosing system with continual venting of the room.

8.9.5 Retail display issues

A key challenge for consumers is identifying ready-to-eat avocados, this being an even bigger problem for cultivars that do not blacken when ripe. In retail outlets,

the use of stickers that indicate what fruit have been ethylene-treated are sometimes used to assist consumers in selecting ripe fruit.

An innovative system that aims to improve fruit quality, while assisting consumers' decisions, is the ripeSense® concept (www.ripesense.com). Fruit are placed in a package and a sticker placed in the package which changes colour (from red to yellow) as the fruit ripen by detecting specific volatiles from the fruit. The fact that ripeness can be selected without squeezing fruit means that fewer fruit are bruised by consumer 'pressure testing'. Use of a clamshell provides additional protection from consumer and handling damage.

Avocados ripen very rapidly and quality can be quickly lost on the retail display. Although the dark skin of some cultivars (e.g. 'Hass') 'hides' external problems (including body rots), poor internal fruit quality is a common complaint of consumers. In the case of ripe or near-ripe fruit, this problem can be avoided by displaying limited quantities of fruit, and if possible holding soft fruit at low temperatures (1 to 5°C). As noted previously, fruit ripened at lower temperatures (15°C instead of 25°C) will result in less rot. Avocados should not be 'misted' during retail display.

8.10 Processing

The primary target of avocado growers is high-quality fruit for the fresh market, and it is very unlikely that avocado will be commercially grown solely as a processing crop. However, the availability of a processing industry for reject fruit is important for industry profitability. It is important to note that fruit used for most forms of processing still require a relatively high fruit quality (i.e. fruit rejected primarily because of external damage or small fruit sizes). Rotten or disordered fruit can only be used for oil extraction that should be subsequently refined, bleached and deodorized, as poor fruit will result in off-flavours, and high free fatty acid (FFA) and peroxide values (PV; Wong *et al.*, 2008).

Although harvesting of the fruit for fresh market generally starts when the dry matter reaches 21%, they are generally not yet suitable for processing. This is because of lack of the typical nutty flavour, the colour of the pulp being pale green and the viscosity of the product being too low (i.e. runny; Kurlaender, 1996). For oil extraction, yields would also be commercially unacceptably low at such early stages of maturity.

It is fair to say that avocado is a particularly difficult fruit to process. Browning is a common problem for most fruit, and the most simple and cost-effective means of inhibiting browning is the use of heat (McEvily *et al.*, 1992). However, even mild heat treatments induce bitter off-flavours in avocado (Bates, 1970), which makes its use for food products limited.

8.10.1 Ultra-high pressure processing

This is a relatively new processing technology, and producing items such as guacamole by ultra-high pressure processing (UHP or high pressure processing:

HPP) is one of the recent commercial success stories (Torres and Velazquez, 2005). Guacamole produced by UHP is shelf stable for up to 50 days at ≅4°C and its taste is very close to that of the fresh product, something that is particularly difficult to achieve using traditional techniques (freezing and/or the use of antioxidants). Ultra-high pressure processing is the use of extreme pressures (200 to 600 MPa, or 30 to 85 000 psi), which significantly reduces biological activity because of denaturation of proteins, and in particular enzymes (Torres and Velazquez, 2005). This leads to a large reduction in browning reactions (Weemaes *et al.*, 1999), and significantly, killing of bacteria that pose food safety risks. Treatment is carried out in a liquid phase (normally water), and for avocado the product is generally pre-packed in plastic packaging (e.g. guacamole in a plastic or foil pouch).

Capital investment is high (≅USD 1M/line), and the systems tend to be 'batch' in nature, with treatments carried out in tubes of up to 500 L. Treatment is rapid, with times of ~1 to 3 min/run. Processing of avocado using UHP has been a significant commercial success (Torres and Velazquez, 2005) and is a 'flagship' product for this technology, along with other high-value products such as shellfish products (e.g. oysters) and crustaceans (crab and lobster).

8.10.2 Freezing

The key problems are the development of off-flavours (bitterness; Bower and Dennison, 2003) after thawing, and of course browning. Bower and Dennison (2004) found that treating half of the fruit with lower concentrations of citric acid and pasteurization (80°C) before freezing helped to maintain structure, reduced off-tastes and browning. MA storage had no beneficial effect. Freezing at a controlled rate is important to avoid flesh cracking, preferably by use of a blast freezer. Storage for 6 months and at least 2 h after defrosting was acceptable.

8.10.3 Fresh-cut processing

To stop browning, citric acid can be used (Dorantes-Alvarez *et al.*, 1998), but Bower and Dennison (2003) found that the flavour of the citric acid overly dominated the flavour. Achieving an acceptable quality out-turn for fresh-cut avocado appears to be very difficult.

8.10.4 Processing for oil

The other key processing product of avocado is its oil. Because of its high concentration of vitamin E (α-tocopherol) and absorption by the skin, it has been used for cosmetic purposes for many years. Oil is generally extracted from flesh and the seed should be removed, since it contains little oil (<2%) and may contain toxins (Botha, 2004). Skin tissue is often included (because of both the challenges of separating pulp and skin, and that skin tissue may aid in oil extraction), and contains higher concentrations of pigments such as chlorophyll and carotenoids, such as lutein (Ashton *et al.*, 2006).

Traditionally, extraction has been carried out using relatively 'harsh' technologies (heat and/or solvents) and the resulting oil refined, typically RBD (refined, bleached and deodorized; Wong *et al.*, 2008). The resulting oil is pale yellow in colour (because of the removal of all the pigments), stable (because of the removal of free fatty acids) and of low flavour (because of the deodorizing step). This oil has been used for cosmetics, cooking and massage oils.

Commercialization of 'cold pressing' (in a manner very similar to oil extraction from olive fruit), has led to a new product line that has a rich emerald-green colour, and subtle flavour (Werman *et al.*, 1989). Compared with other oils, avocado is notable in its high concentrations of *β*-sitosterol, chlorophyll and carotenoids (particularly lutein), as well as its health-favourable fatty acid composition (high monounsaturates; Woolf *et al.*, 2009).

Oil is extracted using technologies similar to those for olive oil – a hammer mill, malaxing (stirring) and separation of oil from water and solid (pomace) phases using a horizontal decanter (centrifuge). Further 'polishing' of the oil using a vertical centrifuge is recommended (Wong *et al.*, 2008).

Supercritical extraction can be carried out using carbon dioxide at ~350 atmospheres (Botha, 2004). The oil that was recovered was yellow (not the full green colour achieved using hexane), indicating some damage to the oil during processing.

8.11 Conclusions

Avocado is a distinctive fruit in many ways and remains a fruit where confident and repeatable extension of storage life past five to six weeks remains elusive, particularly on a commercial scale. While 1-MCP can significantly reduce internal chilling injury, a way to 'restart' even ripening after storage is needed. Ripe rots are a significant challenge for all but the driest of growing areas, and developing non-chemical postharvest rot control would be a major breakthrough. Other measures of maturity (other than dry matter) would be beneficial for optimizing both the start, and potentially the end of commercial harvest times. Increases in commercial opportunity to process reject fruit (e.g. ultra high pressure and oil) will improve overall grower returns.

8.12 References

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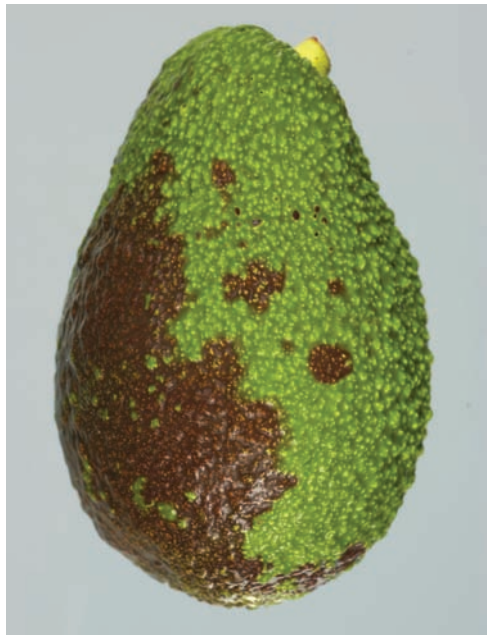

Plate XIII Severe external chilling injury. Image courtesy of Plant and Food Research, New Zealand.

Plate XIV Internal chilling symptoms. Image courtesy of Plant and Food Research, New Zealand.

9

Bael (*Aegle marmelos* (L.) Corr. Serr.)

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Abstract: Bael fruit (*Aegle marmelos* (L.) Corr. Serr.) is an underutilized fruit of the Indian subcontinent. The tree can thrive under adverse agro–climatic conditions but its commercial cultivation is very limited. Bael fruit is recognized for its wide range of medicinal and nutritive properties. The fruit is difficult to eat out of the hand because of its hard shell, mucilaginous texture and numerous seeds. The mature green fruit is used extensively in making preserves, while ripe bael fruit is used for processing. Various acceptable processed products have been standardized but not yet commercialized. The chapter on bael fruit covers various aspects of the postharvest handling of the fruit, including its excellent potential for commercial processing as fruit juice, nectar or confectionary products.

Key words: Bael fruit, *Aegle marmelos*, antioxidants, underutilized fruits.

9.1 Introduction

9.1.1 Origin, distribution and worldwide importance

Bael fruit has been known in India since ancient times, and the tree on which it grows is regarded as sacred. The leaves of the tree are traditionally used as sacred offerings to 'Lord Siva' in Hindu rituals. Prathipati *et al.* (1961) found mention of the bael fruit in Vedic times (c. 800 to 200BC) and also in early Buddhist and Jain literature (c. 800 to 325BC). In the 'Upavana Vinoda', a Sanskrit treatise on silviculture (Majumdar, 1935) and in the 'Brihat Samhita' (referred to by Aiyer, 1956), mention was made of bael fruit. It has been said that this tree indicates the presence of underground water.

Bael is an indigenous fruit of India. The plant belongs to the family *Rutaceae*. Bael fruit grows throughout the Indian Peninsula as well as in Sri Lanka, Nepal, Pakistan, Bangladesh, Burma, Thailand and most Southeast Asian countries.

Bael is a valuable tree species and its fruits are recognized for their medicinal and nutritive properties. It is traditionally used in curing several diseases and as

ingredients of nutritive foods. The livelihoods of some ethnic groups depend on bael fruit collection, processing and marketing (Roy and Singh, 1979; Shrestha and Parajuli, 2002).

In spite of its long history and therapeutic properties, bael fruit has not been domesticated via human selection. Its cultivation is currently limited and it grows mainly in the wild or in temple gardens. It is grown to some extent by connoisseurs for the fragrant flavour of the fruit. There is also some demand in the indigenous systems of medicine such as 'Ayurveda' and 'Unani'. There is no organized orchard production of this fruit tree in India, but presently efforts are underway by the Government of India under the National Horticulture Mission to promote diversification of agriculture for sustainability and new plantations of several fruits in India including bael (http://agricoop.nic.in/Strategy%20in%20Agriculture/UPHorticulture.ppt).

Because of its hard shell, mucilaginous texture and numerous seeds, the bael fruit is difficult to eat out of the hand and is not popular as a dessert like other tropical fruits. Since there is a growing demand from consumers all over the world for new, nutritious, attractive and delicately flavoured products with a leaning toward natural and health foods, the excellent aroma and therapeutic properties of the bael fruit offer a wealth of untapped potentiality.

9.1.2 Botany, morphology, structure and cultivars

Bael is a subtropical and deciduous tree, which is very hardy and can thrive well under diverse agro-climatic conditions. The genus *Aegle* consists of two or three species. The generic name is Greek and the species *marmelos* is of Portuguese origin. The tree reaches a height of 6 to 8 metres with trifoliate, aromatic leaves. The terminal leaflet is 5.7 cm long and 2.8 cm broad with a long petiole. The two lateral leaflets are 4.1 cm long and 2.2 cm wide, almost sessile, (Allen, 1969). Some leaf abnormalities of *A. marmelos* have been noticed (Rao, 1951). Abnormalities of lobation have also been reported by Dutta and Mitra (1960). The leaf characters, development pattern and shoot growth of eight selected genotypes of bael were studied by Misra *et al.* (1999).

The branches are unusual with strong, axillary spines. The bark is shallowly furrowed and corky. The bisexual flowers are nearly 2 cm wide and borne in lateral panicles of about 10 flowers, which are sweetly scented and greenish-white. The calyx is gamosepalous, 5 lobed and pubescent. There are 5 petals (rarely 4); corolla polypetalous, leathery (Fig. 9.1). Androecium is polyandrous, sometimes coherent in bundles while Gynoecium is light green, has capitate stigma and a terminal style. The ovary is oblong ovoid, slightly tapering with a wide axis. Cells are numerous, small and arranged in a circle, with numerous ovules in each cell. The fruit is usually globose with a pericarp nearly smooth, greyish-yellow, about 3 mm thick, hard and filled with soft, yellow and orange, very fragrant and pleasantly flavoured pulp (Fig. 9.2). The number of cells (seed cavities) in the fruit arranged in a circle is equal to the number of cells (seed cavities) in the ovary. Seeds are numerous, compressed and arranged in closely packed tiers in the cell

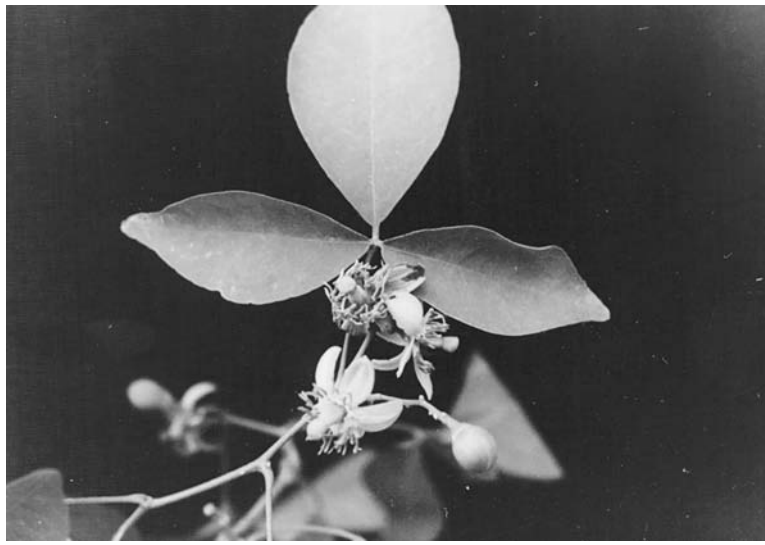

Fig. 9.1 Trifoliate leaves with flower bud and flower.

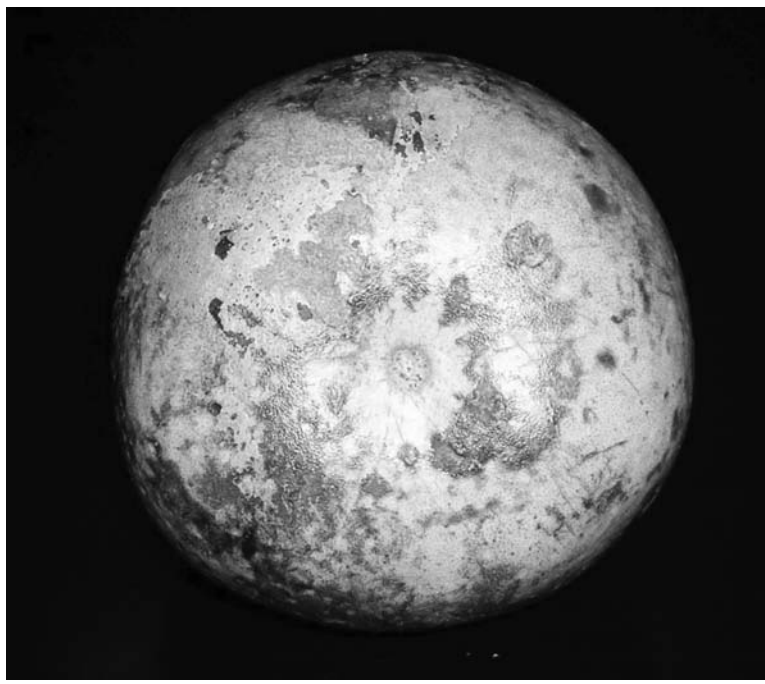

Fig. 9.2 Fully matured bael fruit.

surrounded by very tenacious, slimy, transparent mucilage, which becomes hard when dry (Plate XV: see colour section between pages 244 and 245). The testa is white with woolly hairs and the embryo has large cotyledons (Hume, 1957 and Reuther *et al.*, 1967).

Roy (1975) made monthly observations on the changes in morphological characteristics of bael fruits during development. The external colour of the fruit remains deep green until four months after fruit set, thereafter it gradually turns light green to yellowish-green, and on ripening it becomes yellow. The peel is soft initially but becomes hard, woody and finally brittle at the time of ripening. The internal colour of the fruit is light yellow in the early stages and the intensity increases to deep yellow with maturity and remains more or less the same until ripening. The shape of the fruit, which is oblong initially, turns spherical after four months and remains unaltered during the rest of the period of development and ripening. Small and soft seeds appear after two months, the hardness of which increases with kernel formation at the end of four months and thereafter they become very hard. Full kernel development with woolly growth on the seed surface is noticed in the seventh month of growth. The consistency of mucilage, which is thin initially, gradually thickens with growth and development. The texture of the pulp, which is initially quite hard, becomes soft with ripening.

Seedling bael trees take seven to eight years to commence bearing, while budded plants start bearing after four to five years. Reclaimed sodic soil with the application of gypsum can be successfully used for growing seedlings of bael (Pandey and Pathak, 1988). The number and size of the fruit increase with the advancement in age and size of the tree. The number of fruits per tree may increase from 200 to 400 between the ages of 10 to 15 years. It is not uncommon to find a crop of 800 to 1000 fruits on 40- to 50-year-old seedling trees (Jauhari and Singh, 1971).

Bael is usually propagated via seeds, but this seldom produces a plant true to type. The tree can also be vegetatively propagated via root suckers or budding. Singh (1954) reported 80% success with budding in June with bud wood from 1-month-old scions when the buds were put on 2-year-old stocks grown in beds. Singh *et al.* (1976) found that among several types of budding, patch budding in June and July was the best with 100% success. Moti and Chaturvedi (1976) also mentioned the superiority of patch budding over the shield method. Bael can be grafted onto a number of related plants, such as *Aegle fraeqlegabonensism, A. chevlierim, A. paniculata* and *Swinglea glutinosa* (Hayes, 1957) and *Olinda valencia* and *Valencia criolla* sweet oranges, (Rodriguez *et al.*, 1986). In vegetatively-propagated plants, fruiting begins after five years and full bearing can be attained in about 15 years. Seedlings take somewhat longer to commence fruiting.

An old and uneconomic bael tree can be rejuvenated by top-working. The top-worked trees start fruiting in five years (Singh, 1963; Mukherjee *et al.*, 1986). Following this technique, inferior and old, unproductive bael trees can be transformed into superior and remunerative trees.

Traditionally there were no standardized names of bael fruit cultivars, which were generally named after the locality where the trees were being grown. Reports on the cultivars available in India were mainly from the states of Uttar Pradesh,

Uttarakhand, Bihar and West Bengal. Singh (1961) described six varieties of bael fruit. 'Mirzapuri' was considered to be the best, followed by 'Darogaji'. 'Ojha', 'Rampuri', 'Azamati' and 'Khamaria'. Teaotia *et al.* (1963) also listed five varieties from Uttar Pradesh and found that 'Kaghji Gonda' was the best, producing large fruits with a thin rind and soft yellow pulp of excellent flavour. The keeping quality of this variety was also excellent. Jauhari *et al.* (1969) presented the morphological and physico-chemical data on seven varieties of bael fruit. Jauhari and Singh (1971) surveyed some varieties of bael fruit in the important fruit growing areas of India and found that among the varieties studied, 'Kaghji Etawah', 'Sewan Large', 'Mirzapuri' and 'Deoria Large' were excellent in taste and other qualities. Selection of some bael fruit cultivars was also carried out by Singh *et al.* (1973).

In an experiment conducted by Singh *et al.* (2000) on evaluating eight genotypes for different physical or chemical characteristics, 'Pant Shivani' and 'Pant Urvashi' were found superior to other genotypes. Supporting this recommendation Saroj *et al.* (2008) reported that NB 5, NB 9, 'Pant Urvashi' and 'Pant Shivani' could be recommended for cultivation in hot arid ecosystems. The Central Institute for Subtropical Horticulture (CISH) has 54 accessions of bael for further identification of promising cultivars. CISH-B-1 and CISH-B-2 cultivars of bael were selected from the seedling population (http://www.cishlko.org/achievements.php).

9.1.3 Economic importance and traditional uses

Bael fruit has been in use from time immemorial in traditional systems of medicine for relieving constipation, diarrhoea, dysentery, peptic ulcer and respiratory infections. Important medicinal properties of bael are anti-diabetic, antimicrobial, anti-inflammatory, antipyretic, analgesic, cardio-protective, anti-spermatogenic, anti-cancer and radio-protective.

The bael tree is very hardy and can grow under adverse agro-climatic conditions, unlike other delicate fruit trees. Most tropical and subtropical fruits have a limited storage life, but bael fruit has a potentially long post-harvest storage life because of its hard outer shell, which can withstand transport and marketing hazards. No commercial attempt has yet been made to utilize or preserve ripe bael fruits.

Techniques for extracting bael fruit pulp have been developed. Adding an equal amount of water gives about 125% yield of pulp, which has the consistency of mango pulp. This is very important economically, as no other fruit gives such a high yield of pulp for processing. Moreover, the total solids content of bael fruit is nearly double (40%) that of other common fruits. Although the mucilage of the fruit is usually thought to be an interfering substance, it provides a beneficial and uniform body to the pulp. Investigation has indicated that a number of acceptable products can be prepared from bael fruit pulp. Such preparations have been standardized, and storage requirements have been formulated to enable commercial exploitation of this fruit for the first time. Further, bael fruit flavour is entirely

unknown in the world market, and a good number of products that have been developed fully retain the natural flavour (Roy and Singh, 1979a).

Traditionally, tender green bael fruits are used to make 'Murabba' (a fruit preserve), which is generally taken for stomach ailments (Lal *et al.*, 1968). The green bael fruit slices are often sun dried and stored for future use (Singh and Roy, 1984). Ripe bael fruit is in demand for its therapeutic uses. Sometimes drinks are prepared at home by mixing tamarind or yoghurt with fresh bael fruit pulp.

9.1.4 Nutritional value and health benefits

The bael fruit is highly nutritious. According to Gopalan *et al.* (1971) the edible portion contains 61.5 g water, 1.8 g protein, 0.39 g fat, 1.19 mg riboflavin, 1.1 mg niacin, and 8 mg vitamin C per 100 g. No other fruit has such a high content of riboflavin. Marmelosin ($C_{13}H_{12}O_3$) is the most important, therapeutically active principle of bael fruit. It is isolated as a colourless crystalline compound (Dixit and Dutt, 1932). Kirtikar and Basu (1935) have extensively described the medicinal properties of bael fruit. It is said that the ripe fruit is a tonic, a restorative, an astringent, a laxative, and good for the heart and brain. The unripe fruit is regarded as astringent, digestive and stomachic and is prescribed to treat diarrhoea and dysentery.

Bael is nutritious and can form an important dietary supplement (Barthakur and Arnold, 1989). Compared to orange and grapefruit, bael fruit contains about three times the total soluble solids (TSS) and at least 1.5 times as many calories. The essential and non-essential amino acid contents of bael compare favourably with those in the citrus fruits. Aspartic acid constitutes over 32% of the 17 amino acids analysed. Of the 11 minerals studied, Fe was found to be 21 times as abundant in bael as in either of the reference fruits. Zinc, chlorine and sodium concentrations were also higher in bael.

Pal *et al.* (1993) describing the seed qualities of bael, reported that dehulled seeds contained 40.7% oil while whole seeds contained 29.3%. Both oil types were highly unsaturated. Based on GLC analyses, the main triglycerides were C50 (16.4%), C52 (48.9%) and C54 (28.6%); diglycerides were of minor importance (6.1%). Both dehulled and whole seeds showed the same fatty acid composition of 31.2% oleic, 22.7% palmitic, 22.6% linoleic, 19.6% linolenic and 3.7% stearic acids. Studies on the pharmacological effects suggested that *A. marmelos* has therapeutic value in treating inflammation associated with certain injuries, and tumours created by abnormal cell division. Pharmacological studies of bael support the use of these plants for human and animal disease therapy, and reinforce the importance of the ethno-botanical approach as a potential source of bioactive substances (Pattanayak and Prithwiraj, 2008).

9.1.5 Medicinal value

Bael is known for its multiple medicinal properties. It acts as an antioxidant, antimicrobial, anti-cancer, anti-diabetic, anti-diarrhoeal and in prevention of liver

damage. The therapeutic value of bael has long been recognized in different systems of traditional medicine. Gavimath *et al.* (2008) reported that this plant was promising in the development of phyto-medicine for treatment of bacterial diseases. Singh and Rao (2008) reported that the pulp and seeds of bael provided protection from carbon tetrachloride induced liver damage in rats. Khan and Jabbar (2002) reported gastrointestinal and diuretic activity of bael. Jagetia *et al.* (2003) demonstrated the radio-protective effect of a hydroalcoholic extract of bael. Bael is used in the treatment of hepatitis in folk medicine. Dhuley (2004) reported a possible anti-diarrhoeal effect of unripe fruit extract of bael. Panda and Kar (2006) reported anti-thyroid, anti-oxidative and anti-hyperglycemic activity of scopoletin from bael leaves.

In an evaluation for antimicrobial activity of crude aqueous extract of unripe fruits of bael, it was reported that Gram positive and Gram negative bacteria, except for *Klebsiella pneumoniae* and two fungi, were sensitive to the aqueous extract of unripe bael fruits (Krushna and Devi, 2005).

Bael is widely used in Indian Ayurvedic medicine for the treatment of diabetes mellitus. The aqueous seed extract of bael was seen to possess anti-diabetic and hypolipidemic effects in diabetic rats (Kesari *et al.*, 2006 and Narender *et al.*, 2007). Sharma *et al.* (2007) reported on anti-cancer and the radio-protective properties of bael.

Subramaniam *et al.* (2008) reported about the chemotherapeutic properties of bael. In a study regarding anti-proliferative effect, it was demonstrated that extracts from bael were able to inhibit *in vitro* proliferation of human tumour cell lines including breast cancer (Lampronti *et al.* 2003). Similar anti-cancer properties have been reported by Singh *et al.* (2008). Chauhan *et al.* (2008) reported that aqueous extract of bael leaves had an anti-spermatogenic/anti-fertility effect in male rats. Bael has been reported to have larvicidal and smoke-repellent effect against the dengue vector, *Aedes aegypti* (Vineetha and Murugan, 2009).

9.2 Preharvest physiology

9.2.1 Flowering, fruit set, fruit drop and fruit retention

Bael trees undergo only one flush of growth each year. Vegetative and reproductive shoots emerge simultaneously in the second half of May after leaf fall. The top terminal buds open first and bud burst in the entire tree is completed in seven to nine days. Four distinct types of shoots are noticed. Significantly higher numbers of fruits are formed on 1-year-old shoots than on (in descending order) 2, 3, 4-year-old shoots and old branches. The highest numbers of mature fruits are produced on the upper part of the tree followed by the middle and lower parts (Singh, 1986).

Fruit drop is a problem in bael fruit for which no remedy has yet been found. Application of different growth substances including, 2,4-D, GA 3, and 2,4,5-T in various concentrations could not prevent fruit drop (Pramanick and Bose, 1974). No documented information is available on fruit retention of bael fruit.

9.2.2 Fruit growth and development

The detailed changes during fruit growth and development including physiological, physical and chemical characteristics were studied by Roy (1975) and Roy and Singh (1980). Bael fruits for these studies were obtained from a single cultivar of a 20-year-old tree (the cultivar name was not known). The tree had uniform vigour and productivity, and was selected from the experimental orchard of the research centre at IARI, New Delhi. The studies indicated that fruit set in bael took place during early May in Northern India; however this may vary in different agro-climatic zones. Figures 9.3 to 9.8 are all based upon original data (Roy, 1975).

According to Roy (1975), development of bael follows a simple sigmoid curve. The growth rate of the fruit has three distinct phases; the initial slow phase for one month, until June, followed by a rapid increase until September in the case of diameter and by weight until December followed by a stationary phase until the fruits are harvested. The diameters (transverse and polar) and fruit weight of bael fruit after fruit set increase very rapidly initially then the rate of increase is slower and, thereafter, diameters remain constant until harvest. The fruit weight starts decreasing after remaining constant for a short period and during ripening a considerable reduction in fruit weight takes place. It is interesting to note that polar diameter (length) is considerably more than transverse diameter (width) in the beginning then suddenly it is reversed, which results in a change of fruit shape

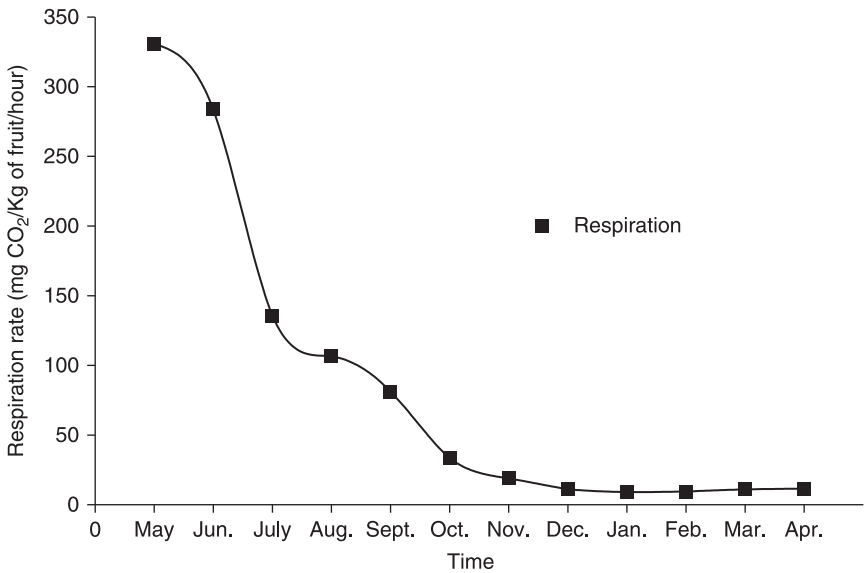

Fig. 9.3 Respiration rate changes during development and ripening. Note: line indicates time of ripening. Source: Roy (1975) (redrawn from original data).

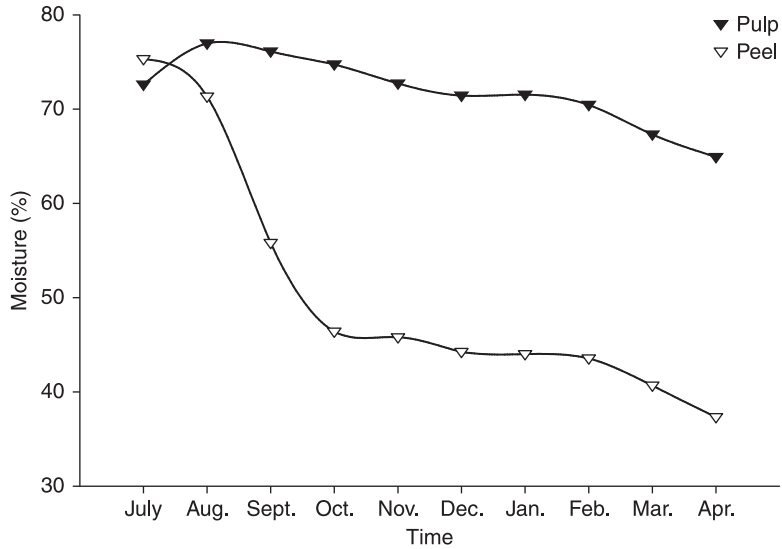

Fig. 9.4 Moisture changes during development and ripening. Note: line indicates time of ripening. Source: Roy (1975) (redrawn from original data).

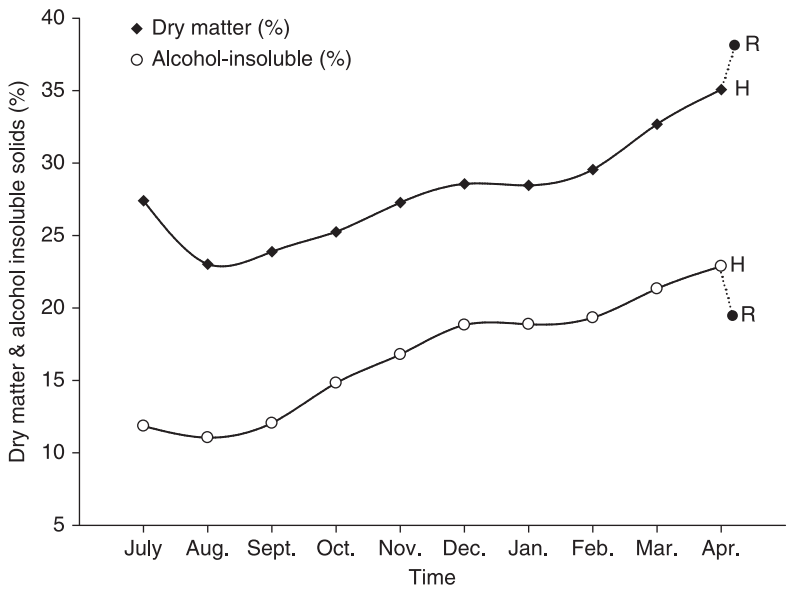

Fig. 9.5 Dry matter and alcohol-insoluble solids changes during development and ripening. Note: line indicates time of ripening. Source: Roy (1975) (redrawn from original data).

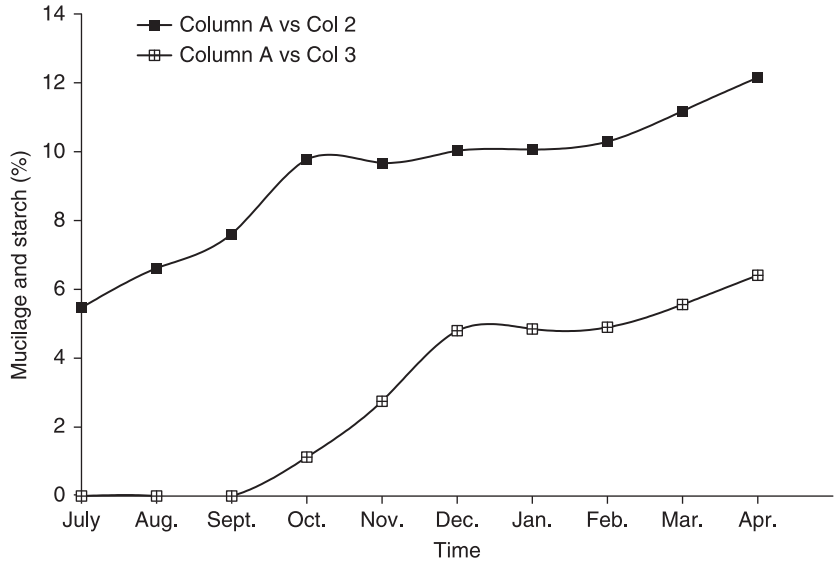

Fig. 9.6 Mucilage and starch changes during development and ripening. Note: line indicates time of ripening. Source: Roy (1975) (redrawn from original data).

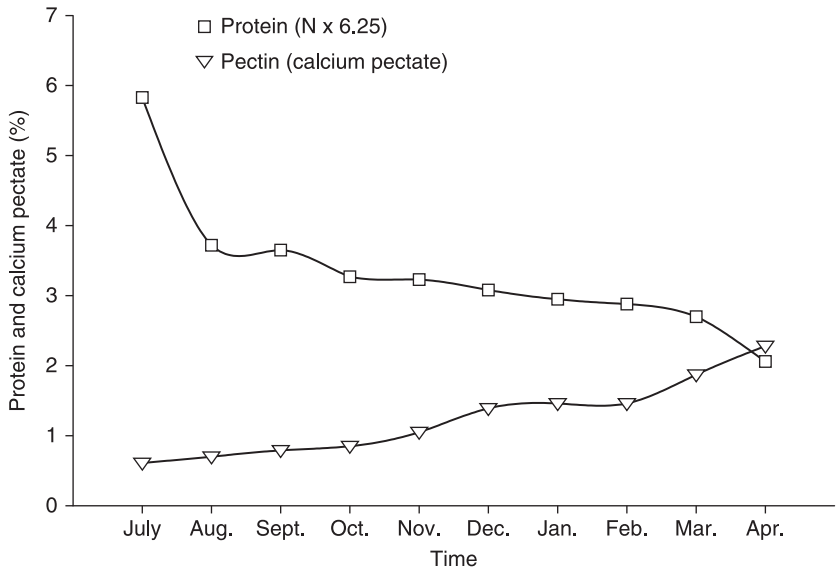

Fig. 9.7 Crude protein and calcium pectate changes during development and ripening. Note: line indicates time of ripening. Source: Roy (1975) (redrawn from original data).

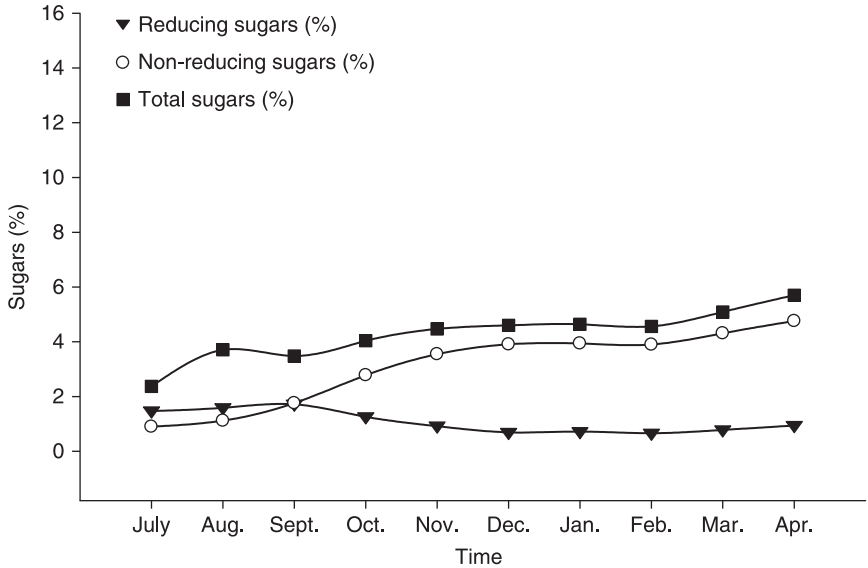

Fig. 9.8 Sugar changes during development and ripening. Note: line indicates time of ripening. Source: Roy (1975) (redrawn from original data)

from oblong to spherical. Misra *et al.* (1999) reported that growth pattern of different genotypes of bael showed a single sigmoid curve.

The specific gravity in bael fruit at the initial stage of development is very high, and then falls gradually until August, after which an increase is noticed from August to October (Roy, 1975). Thereafter, specific gravity remains more or less constant. Considerable reduction in specific gravity is marked at the time of ripening, declining from 1.0 to 0.82. No climacteric rise in respiration is noticed as long as the fruit is attached to the plant. However, an upsurge in respiration is noticed after harvest, which coincides with the optimum ripening condition of the fruit (Fig. 9.3).

The moisture content of bael fruit decreases during development and ripening, however, in the case of pulp moisture, initial increase is followed by a gradual decline. Peel moisture decreases rapidly until October, and thereafter decreases more slowly. With the decrease in peel moisture, the hardness of peel increases and it turns woody. During ripening, the peel turns very hard and brittle (Fig. 9.4).

Both the dry matter and alcohol insoluble solids (AIS) of the fruits increase during development after an initial fall. The rate of increase is more or less identical in both the constituents until harvest. During ripening the AIS is reduced due to disappearance of starch, and dry matter increases because hydrolysis of starch contributes to sugar formation (Fig. 9.5).

With the fall in the rate of increase in mucilage, starch appears and increases steadily until harvest, but disappears with ripening (Fig. 9.6). A progressive fall in

crude protein content is observed during fruit development, but there is a slight increase during ripening. Pectin, expressed as calcium pectate, increases during development and ripening of bael fruit (Fig. 9.7).

The total and non-reducing sugars (TS and NRS) of the fruit show an increasing trend during development. The initial level of reducing sugars (RS) is higher than non-reducing sugars, followed by a gradual decrease. A rising trend during ripening is noticed in all the three sugars (Fig. 9.8). The inherent low acidity of the fruit (0.75%) shows a downward trend during development (to 0.4% by April) and with ripening (to 0.3%).

Roy (1975) reported that both the total phenolic and leucoanthocyanin content of the bael fruit decrease during development and ripening. Total phenolics decreased from 7700 mg/100 g to 2500 mg/100 g, and leucoanthacyanins decreased from 0.48 to 0.16 (absorbance at 550 nm). Studies conducted by Pande *et al.* (1986) on the biochemical changes in bael fruit also revealed similar findings.

9.2.3 Preharvest factors affecting fruit quality

There is very little systematic information available on the preharvest factors affecting the crop. However, there have been studies regarding the effect of pH, soil salinity and soil alkalinity on bael fruit. Shukla and Singh (1996) reported delayed and poor seed germination and reduced plant growth in response to increased sodicity. Satisfactory performance of bael with respect to seed germination and plant growth was observed in sodic soils up to 29.0 exchangeable sodium percentage (ESP) without the application of any chemical amendments.

Shukla and Singh (1998) also demonstrated marked reductions in the contents of leaf nitrogen, phosphorus, potassium and calcium in response to increases in salinity and sodicity levels in the soil in which plants are grown. Salinity causes significant increases in leaf magnesium, while sodicity decreases leaf magnesium. Leaf sodium is at toxic levels in both saline and sodic soils.

Hore and Sen (1995) demonstrated the effect of pre-sowing seed treatment on longevity, germination and seedling growth of *A. marmelos* cv. Mirzapuri. The number of days required for germination to commence and the number of days required to complete germination were reduced by GA (200 ppm) and nutrient + GA treatments.

9.2.4 Preharvest treatments

Misra and Jaiswal (2001) reported the effect of plant bio-regulators and potassium nitrate on seedling quality of bael. Quality was maximized with foliar sprays of GA at 1000 ppm, while the number of fibrous roots per seedling, length of tap root and dry weight of roots were found to be maximized with foliar sprays of IBA (1000 ppm). The shoot:root ratio was found to be maximized with GA (1000 ppm) and a minimum with IBA (1000 ppm) treatments.

9.3 Postharvest physiology

9.3.1 Maturity indices

Mature green fruits are ideal for harvesting. Fruits become fully mature eight months after fruit set. Fruits take about three months after maturing to ripen on the tree. At this stage the tree becomes defoliated and fruits are completely exposed (Fig. 9.9).

The studies on changes during development in bael fruit showed that practically no change takes place in physical appearance and chemical constituents from December to February under North Indian conditions. This is possibly because the low temperatures prevailing during the period result in very slow physiological activity. Only slight changes in physical appearance and chemical constituents take place after February until harvest, and considerable changes take place after harvest during ripening. The bael fruit matures in the month of December with peel and flesh colour becoming light green and deep yellow respectively. The seeds become very hard with the full formation of the kernel and hairy growth on the surface. The mucilage becomes very thick. A considerable amount of starch formation, a reduction in phenolics and an increase in sugars take place (Roy, 1975).

Fig. 9.9 Defoliated bael fruit tree with fruits exposed (April, 2010).

Changes in the fruits during development, maturity and ripening were studied by Roy and Singh (1980) in detail. The studies indicated that ripe bael fruits are available at 11 months after fruit set under North Indian conditions.

Regarding the maturity of the fruit, it has been reported that biochemical parameters such as total soluble solids, total soluble solids:acid ratio, ascorbic acid and carotenoids are higher at the ripe stage, while acidity, crude protein, crude fibre, pectin, total phenols, tannins and marmelosin are higher at the green stage (Kaushik *et al.*, 2000). In a similar study, Kaushik and Yamdagni (1999) reported that there was a continuous decrease in crude protein, fibre and phenol contents during fruit maturation. Pectin increased until January, followed by a gradual decrease, and there was a more than four-fold increase in carotenoids.

9.3.2 Respiration, ethylene production and ripening

The rate of respiration in bael fruit at the early stage of development is very high. With growth, the respiration rate declines. No climacteric rise in respiration is measured as long as the fruit is attached to the plant. However, an upsurge in respiration occurs after harvest that coincides with the optimum ripening condition of fruit. This characterizes the bael fruit as climacteric in nature (Roy, 1975).

Temperature plays an important role in the availability of tree ripe bael fruit. For instance under Delhi conditions in North India, although the fruit matures in December or January, because of low ambient temperature it ripens in April when temperatures begin to rise (Roy and Singh, 1980). However, in warmer parts of India the fruit starts ripening on the tree in February or March.

Pal and Singh (2006) reported that bael fruits of smaller size (400 to 600 g) have higher levels of ethylene evolution and respiration rate with high acid content compared to larger fruits (800 to 1000 g).

The inherent low acidity of the fruit shows a downward trend during development and ripening. With the ripening of bael fruit, the peel turns yellowish. The stem end detaches easily from the fruit. The pulp becomes soft and sweet with full formation of sugar; starch disappears, phenolic content decreases considerably and a pronounced ripe bael fruit aroma develops (Roy, 1975).

In bael fruit the levels of compounds with cytokinin-like activity are high during the early phase of development but they decrease during subsequent fruit growth. Activity resembling that of cytokinin glucoside increases with maturation (Ghosh *et al.*, 1983).

9.4 Quality components

9.4.1 Physical factors: size, shape and colour

Roy and Singh (1978) studied the physical characteristics of 24 cultivars in India from the point of view of processing. Various shapes and sizes of Bael fruit were observed (Plate XVI: see colour section between pages 244 and 245). The range of physical characteristics is described in Table 9.1.

Table 9.1 Range of physical characteristics of bael fruit cultivars

Particulars	Range
Shape	Flat to oblong, spherical, pear and cylindrical
Transverse diameter (cm)	8.52–16.82
Polar diameter (cm)	6.65–17.78
Weight (g)	360–1850
External colour	Greenish to yellowish
Internal colour	Various shades of orange and yellow
Peel (%)	20.54–36.11
Seed (%)	0.81–5.55
Fibre (%)	1.31–4.10
Edible portion (%)	56.12–74.80
Thickness of peel (cm)	0.18–0.31
Number of seeds	32–104

Maiti *et al.* (1999) conducted a physicochemical analysis and found the cultivars with type II fruit (which was oblong with rounded base and flattened apex) were most promising with respect to fruit quality. Mukhopadhyay *et al.* (2002) conducted a study in West Bengal and reported that the fruits that were greenish yellow and oblong, with a smooth surface and obtuse stalk and stylar ends, have the highest percentage of edible matter content (74.98%), pulp dry weight (36.49%), ascorbic acid content (17.038 mg 100 g^{-1}), total sugar content (11.83%), non-reducing sugar content (8.79%), ratio of total sugar to titratable acidity (13.69) and protein content (2.20%).

9.4.2 Chemical factors

Roy and Singh (1978) studied the chemical characteristics of 24 bael fruit cultivars in India from the point of view of processing. The range of chemical characteristics in bael fruit cultivars is listed in Table 9.2.

The percentage of pectin on the fresh weight basis of fruits is 2.66 (Roy and Mazumdar, 1989). Ram and Singh (2003) studied the chemical characteristics of bael cultivars NB 5, NB 9, NS 1 and Kagazi. NB 9 had the highest average weight (2.09 kg) and contents of ascorbic acid (17.25 mg 100 g^{-1}), carotene (97.00 IU 100 g^{-1}), non-reducing sugar (15.52%) and total sugar (19.44%). NB 5 had the highest pulp content (68.13%) and reducing sugar content (4.87%). NS 1 had the highest total soluble solids (38.50%) and acidity (0.40%). Kagazi had the highest seed (3.47%) and fibre (9.91%) contents, shell percentage (29.50%) and contents of moisture (66.67%) and phenolics (2.87%).

Various chemical constituents such as alkaloids, coumarins, steroids and others have been isolated and identified from different parts of the bael tree. Chatterjee and Bose (1952) isolated skimmianine and a sterol, aegelin ($C_{18}H_{18}H_4$) from the leaves. Further studies on aegelin were conducted by Dasgupta and

Table 9.2 Range of chemical characteristics in bael fruit cultivars

Particulars	Range
Moisture (%)	59.37–62.70
Total soluble solids (%)	31.0–35.5
Reducing sugars (%)	2.08–5.68
Non-reducing sugars (%)	9.56–14.72
Total sugars (%)	12.50–17.92
Mucilage (%)	12.78–19.57
Acidity (%)	0.31–0.42
PH	5.0–5.3
Ascorbic acid (mg 100 g^{-1})	7.68–18.20
Crude protein (%)	2.26–3.22
Total phenolics (mg 100 g^{-1})	1755–3000
Organoleptic score	5.6–8.5

Chakravarti (1958). A free sterol, v-sitosterol ($C_{29}H_{50}O$), was isolated from the leaves by Chakravarti and Dasgupta (1956, 1958). The presence of aegelenine ($(C_{14}H_{10})_{12}N_2$), an alkaloid, was reported in the leaves by Chatterjee and Roy (1957). Four new alkaloids were also isolated from the leaves and their structural properties confirmed by synthesis (Mannandhar *et al.* 1978). In fruits, coumarins like alloimperatorin, imperatorin and *β*-sitosterol have been identified by Saha and Chatterjee (1957). Chakraborty *et al.* (1978) reported that marmolide, a tyrosinase-accelerating compound, and tryptophan pyrolase, which inhibits furocoumarin, were isolated from ripe fruits. Chatterjee and Roy (1959) isolated and identified three compounds from the heartwood: marmesin ($C_{14}H_{14}O_4$), *β*-sitosterol ($C_{29}H_{50}O$) and dietammine ($C_{12}H_9NO_2$). The young bark of the tree contains a coumarin, marmin ($C_{12}H_{26}O_5$), according to Chatterjee and Choudhary (1955). Compounds like auroptins, marmin, umbelliferone, lupeol, skimmianine and *β*-sitosterol have also been found in the bark (Chatterjee and Bhattacharya, 1959; Patra *et al.*, 1979). Occurrence of auroptin, umbelliferone, marmin, lupel and skimmianine has also been reported in roots (Chatterjee and Choudhry, 1960). In addition, psoralen, xanthotoxin, scopoletin and tembamide have been isolated from the roots (Shoeb *et al.*, 1973). Another coumarin, aegelinol, has been isolated from the root and stem-bark of bael fruit (Chatterjee *et al.*, 1978).

Badar-ud-Din (1950) studied the physical properties of bael fruit gum. Haksar and Kendurkar (1961) reported that bael fruit yielded 2% of dried, water-soluble gum. The gum can be used to prepare adhesives, water-proofing and oil emulsion coating. Bael fruit mucilage upon hydrolysis showed the presence of the three reducing sugars galactose, arabinose and rhamnose (Parikh *et al.*, 1958). A water-soluble polysaccharide is isolated from the bael fruit pulp and on hydrolysis it produces 20.4% D-glucose, 10.7 L-arabinose, 25.2% uronic acid and a trace of L-rhamnose. The uronic acid is characterized as D-galacturonic acid (Haq and Awal, 1977).

9.4.3 Organoleptic factors

It has been observed that the organoleptic quality of bael fruit depends upon the balance of three factors: mucilage, sugar and total phenolics. A high amount of sugars, particularly non-reducing sugars, and low amounts of phenolics and mucilage make bael fruit more palatable. The bael fruit contains a substantial amount of phenolics, which contributes to its astringent taste.

It has been observed that the bigger fruits have better quality attributes compared to smaller ones, having a high percentage of pulp, thinner peel, fewer seeds, higher sugar, lower phenolics, and less mucilage. For these reasons large-sized fruits also have the most desirable processing characteristics.

9.5 Postharvest handling

9.5.1 Harvesting operations

Bael fruits are likely to be damaged if proper care is not taken during harvesting. At the time of harvest, the tree is in a leafless condition and the fruits are completely exposed. The fruits should be picked individually from the tree and should not be allowed to drop to the ground, as even a minor crack in the shell can lead to spoilage during transport and storage. Harvesting by shaking the tree is discouraged since the fruits are likely to develop cracks on impact, as the peel is highly brittle. Bael fruit should be harvested with a small portion of stalk attached, since it is firmly attached in unripe fruits and provides a useful signal for ripening. On ripening, the attachment of the stalk on the fruit loosens and it can be detached without any effort. The stem end of the fruit, once the stem is detached, becomes vulnerable to infection.

9.5.2 Packaging, transportation and storage

There is no recommended practice for packing bael fruits. In India, the fruits are packed in gunny bags, sacks, baskets, or wooden crates and sometimes they are transported in bulk loads without any packing. It is highly desirable that some cushioning material, such as straw, shredded paper or leaves, be used when packing bael fruits. Development of cracks due to impact during packing, transportation and marketing of fruits has to be avoided, or heavy fungal infection will take place.

Bael fruit itself has a fairly good storage life compared to other tropical fruits, but unfortunately very little information is available in the literature on storing bael fruits. The only information available is on the application of cool storage to enhance the storage life of bael fruit (Roy and Singh, 1979e). The storage life of bael fruits could be increased from two weeks at ambient temperature (27 to 33°C) to 12 weeks at a cool storage temperature of 9°C. Marked physiological breakdown is noticed when the storage temperature is below 9°C, indicating that bael fruits are chilling-sensitive.

Ghosh and Mitra (2004) conducted storability and quality analysis of thirteen local types of bael fruit grown in West Bengal, India. They indicated that the edibility of fruits declined gradually during storage. Most varieties of bael fruit can be stored

up to 18 days. The physiological loss in weight of fruits increases progressively with storage. The total soluble solids, total sugar, reducing and non-reducing sugars of the fruits all increase gradually with storage. The titratable acidity initially increases slightly, but declines considerably thereafter. The ascorbic acid content of fruits increases up to the twelfth day of storage, and declines thereafter.

Bhadra and Sen (1998) studied the effects of some chemicals (NAA at 100 or 200 ppm, GA at 50 or 100 ppm, 200 ppm ascorbic acid, 250 ppm cobalt nitrate or stannous chloride) and wrapping materials (liquid paraffin coating, perforated polyethylene bags, butter paper or blue cellophane) in prolonging the storage life of bael. All the treatments, with the exception of the paraffin coating, increased the storage life of fruits. Fruits treated with chemicals could be stored for up to 18 days. Fruits in different wrappings could be stored for up to 24 days with little spoilage (Fig. 9.10). Fruits treated with hot water (52° ± 2°C) could be stored for up to 21 days. Fruits ripened uniformly and were reported to have pulp of good colour after treatment and subsequent ripening.

9.5.3 Control of ripening and senescence

The ripening of bael fruit can be accelerated by a combination of high temperature and exogenous application of ethylene. It has been found that ethylene-induced ripening is not effective at lower temperatures. The rate of respiration during

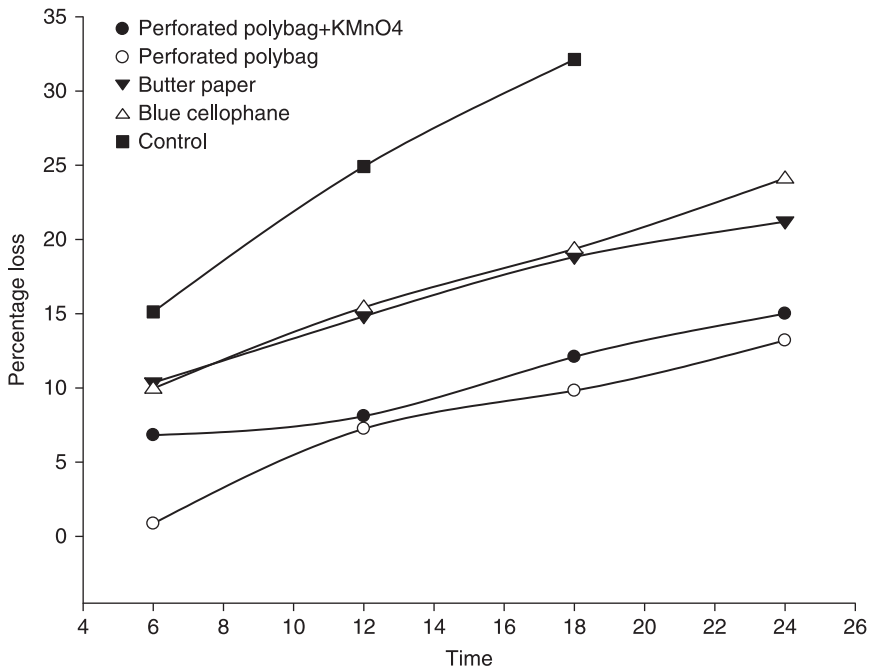

Fig. 9.10 Effect of bael fruit wrappings on physiological loss in weight (PLW%).

Table 9.3 Composition of naturally and artificially ripened bael fruits

	Moisture (%)		Starch (%)	Sugar (%)		Acidity (%)	Total phenolics (mg 100 g^{-1})
Bael fruit	**Peel**	**Flesh**		**Reducing**	**Total**		
Naturally ripened	30.37	59.88	nil	2.49	13.87	0.31	2412
Artificially ripened	30.26	60.97	nil	2.83	12.16	0.31	2401

induced ripening increases with elevation in temperature and more concentrated ethrel treatment. Ripe bael fruits can be made available two to three months ahead of schedule by using a treatment of 1000 to 1500 ppm ethrel and keeping the fruits at 30°C after harvesting them in January. It takes 18 to 24 days for the fruit to be artificially ripened. The composition of bael fruit, whether ripened artificially or naturally, does not vary much; only the accumulation of sugars is slightly lower in artificially ripened fruits compared to the naturally ripened ones (Roy and Singh, 1981; Singh and Roy, 1984).

The moisture content of both peel and pulp is reduced during storage at different temperatures, with the rate of moisture loss being higher at higher storage temperatures. In general, an increase in total sugars and a greater accumulation of reducing sugars on both a fresh and a dry weight basis were found after storage. Less increase in total sugars and lower accumulation of reducing sugars at a lower temperature is probably due to slower biochemical activity at lower temperatures. The increase in total sugars after storage is caused by hydrolysis of some polysaccharides into sugars. Similarly, higher accumulation of reducing sugars after storage is possibly due to inversion of non-reducing sugars. According to Roy and Singh (1979e) the percentage acidity remains more or less the same with a slight increasing trend after storage, while phenolic contents show a downward trend (Table 9.3).

9.5.4 Recommended storage and shipping conditions

There is no recommended practice for storage of bael fruits. However, studies show that the storage life of bael fruits could be increased from two weeks at ambient temperature (27 to 33°C) to 12 weeks at a cool storage temperature of 9°C (Roy and Singh, 1979a). No studies have been conducted regarding effects of shipping conditions. It is recommended that the fruits should be transported in a container with proper liners and a partition that restricts movement of the bael and prevents impact cracking. A recyclable ventilated fibreboard carton (CFB) developed by Joshi and Roy (1986) provides the recommended support and protection.

9.6 Processing

Mature green bael fruit has been used widely for traditional food processing. It has already been mentioned that the fresh ripe bael fruit is not consumed more

widely because of eating difficulty, but it may become more popular if suitably processed.

9.6.1 Pulp extraction method

Extracting pulp from the ripe bael fruit presents the main hindrance to processing. Conventional methods adopted to extract fruit pulp are not applicable in the case of bael fruit, because of the mucilaginous texture of the pulp and the tendency of the pulp to develop off-flavours and colours rapidly due to activity of peroxidase and several other enzymes. The factors considered important for ideal extraction of pulp are incorporation of water with the pulp and inactivation of enzymes by the application of heat and pH adjustment (Roy and Singh, 1979b).

The fruits are opened by striking against a hard object. The pulp along with the seeds and fibre is removed with the help of a stainless steel spoon and the peel is rejected. Water is added to the extracted pulp (with seeds and fibre) while kneading. The best results are obtained by adding water equal to the amount of the pulp (with seeds and fibre). The pH is adjusted to 4.3 with citric acid (titratable acidity 0.5%) and the mass is heated to 80°C for one minute. Adding water and applying heat dilutes the mucilage considerably and makes it possible to extract the pulp commercially using a pulping machine. The enzyme peroxidase is inactivated by the combined application of heat and the addition of citric acid. The loss of peroxidase activity in a blanched food product is taken as an indication of the loss of activity of all other deteriorative enzymes (Eskin *et al.*, 1971). The advantage of adjusting the pH to 4.3, in addition to being organoleptically acceptable, is that the pulp can be safely heat-processed and preserved with sulphur dioxide without further adjusting the pH. The pulp extraction process is shown in a flow chart in Fig. 9.11.

Similar work was done by Tarsem and Gehlot (2006) and they reported that pulp with 30% TSS, 0.5% acidity and 0.07% potassium metabisulfite was the most acceptable.

The bael fruit pulp obtained by the method standardized above is almost of the same consistency and colour as that of mango pulp. There is a possibility of preparing different bael fruit products and also blending bael fruit pulp with that of mango or any other fruit pulp.

9.6.2 Preparation of different processed products

The bael fruit pulp extracted by the standardized process has an acidic taste (Brix 16.5°, acidity 0.5%) and is less sweet compared to the original fruit (Brix 32.5°, acidity 0.32%). It was considerably improved by adjusting the Brix of the pulp to 25° by the addition of sugar without altering the acidity of the pulp. Adding sugar beyond this limit makes the product too sweet for most consumers. The pulp can be preserved by canning, freezing and adding sulphur dioxide. The preserved pulp can also be used in ice cream and confectionery preparations.

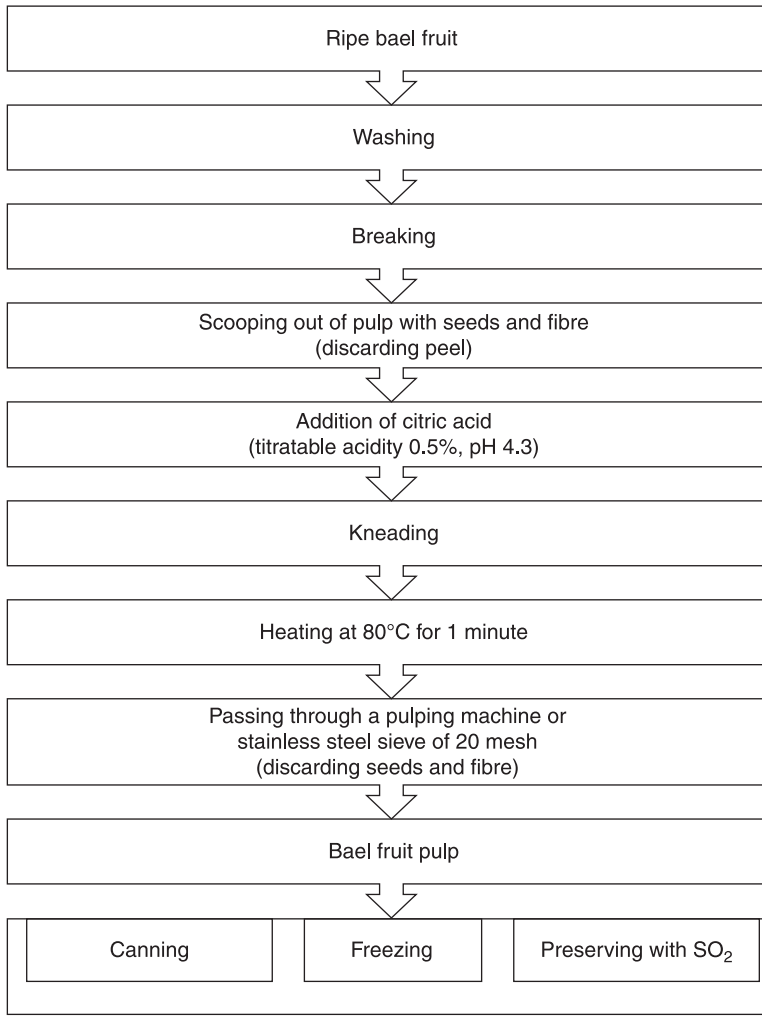

Fig. 9.11 Flow chart of the pulp extraction process.

Bael fruit nectar can be prepared like mango nectar by blending fruit pulp with sugar, acid and water. Bael fruit nectar of the composition 35% pulp, Brix 25° and 0.3% acidity produces a highly acceptable product. However, pulp content in the nectar could be altered according to any commercial requirement. The mucilage of the pulp provides a very good body to the nectar. Roy and Singh (1979c) and Verma and Gehlot (2006) also standardized the technology for processing nectar from bael fruit. Apart from canning, the bael fruit nectar is pasteurized in bottles. Bael nectar prepared with 20% bael pulp, 15% total soluble solids and 0.25% acidity is found to be most acceptable. A bael fruit squash drink is made by mixing sugar, acid, pulp and water. A composition of

50% pulp, 50° Brix and 1% acidity is found to be suitable for squash. The acidity of the bael fruit squash is low and the Brix high compared to citrus and most other fruit squashes, because the fruit itself is not acidic. The mucilage, which is a water-soluble polysaccharide, contributes toward the high soluble solids of the pulp. The bael fruit squash is preserved by addition of 300 ppm SO_2 (Roy and Singh, 1979c). Verma and Gehlot (2007b) recently standardized the technology for bael squash and reported that squash prepared with 35% bael pulp, 50% total soluble solids and 1.20% acidity was the most acceptable among all the treatments.

Bael fruit slab is prepared like mango slab. The bael fruit slab tastes acidic when made using the pure bael fruit pulp (16.5° Brix and 0.5% acidity). Addition of sugar up to 10% greatly improves the organoleptic quality of the bael fruit slab. It is found that addition of SO_2 up to 1500 ppm before drying improves the quality. The slab is dried to a moisture content of about 14.5% (Roy and Singh, 1979c).

Bael fruit toffee is successfully prepared by mixing 40 parts of sugar, 4.5 parts of glucose, 10 parts of skimmed milk powder and 6 parts of hydrogenated fat to every 100 parts of bael fruit pulp extracted by the process mentioned earlier. The proper moisture content of the bael fruit toffee is 8.5%; above this the product is too soft and, below this it is too hard. Bael fruit toffees are highly nutritious besides having medicinal properties (Roy and Singh, 1979c).

For preparation of bael fruit powder, 2000 ppm SO_2 is added to the bael fruit pulp, which is then dried in the form of a thin sheet to about 10% moisture. The dried bael sheets are cut into pieces and further dried to below 4% moisture in a cabinet drier at 60 ± 5°C. The pieces are ground into powder in a grinding machine (Roy and Singh, 1979c).

Protein enrichment of a bael fruit beverage was attempted by using partially denatured whey protein concentrate (WPC) complexed with acidic polysaccharides, i.e. carboxymethylcellulose (CMC) and pectin. A beverage base with 25% bael fruit pulp, 16° Brix, and pH 3.9 was found optimum and was fortified with WPC polysaccharide complex. The products with CMC and WPC complex were rated superior (Singh and Nath, 2004).

Bael fruit powder can be mixed with an equal quantity of milk powder and reconstituted when required. Bael fruit flakes are prepared by making a thin sheet of pulp with 12% moisture and further drying it to a moisture level below 5% and then breaking it up into flakes. Pure and clear bael fruit juice (liquid bael fruit) is prepared by treating the extracted pulp with 1% enzyme liquid concentrate for 24 hours at 37°C. The juice is extracted by basket press and clarified by treating the extracted juice with 0.4% gelatine and holding at 3°C for 48 hours. The acceptability of the clarified juice can be improved by adding cane sugar and adjusting the Brix to 35° with the original acidity 0.5% (Singh and Roy, 1984). Methods have also been standardized for preparing green bael fruit jam as well as mixed fruit jam by incorporating apple pulp (Rahman, 1983).

Bael wine is prepared following the same basic steps employed for the preparation of a typical fruit juice wine. The only major modification employed is

in the extraction step, as bael yields a rather viscous pulp. Wines are prepared from pulps obtained by both hot and cold extraction. The analysis showed the hot-extracted pulp is found to be better, and that wine from mash of 25% pulp content was the best (Verma and Gehlot, 2006).

9.6.3 Packaging and storage of processed products

During storage of bael fruit products, there is a reduction in non-reducing sugars and an increase in reducing and total sugars, Adding SO_2 not only improves the initial quality of the bael fruit slab, toffee and powder but also prevents non-enzymatic browning reaction during storage of all the bael fruit products. The optimum relative humidity for the storage of bael fruit slab, toffee and powder is found to be 63, 58 and 5% respectively. Practically no change in organoleptic quality is noticed in frozen pulp after six months and for other products stored at 37°C, the organoleptic quality remains well above the acceptable level (Roy and Singh, 1979d).

Singh *et al.* (2006) carried out an investigation to study the effect of pH on bael fruit wine storage. The minimum fermentation time for wine production was 88 h at pH 5.5. Storage of wine increased browning and organoleptic rating but decreased phenol content.

Tarsem and Gehlot (2006) assessed the physicochemical changes and organoleptic quality of bael pulp. The total sugar and reducing sugar contents, acidity, and browning increased, whereas ascorbic acid and total phenol levels decreased during storage.

Verma and Gehlot (2007a and 2007b) evaluated the changes in chemical constituents and organoleptic quality during the storage period of bael fruit nectar and bael fruit squash respectively and Verma and Gehlot (2006) reported the changes in chemical composition and organoleptic quality during storage. The results showed that in both the products, total sugars, reducing sugars and browning were increased whereas acidity and total phenols decreased during storage. The overall acceptability of bael fruit nectar decreased during storage; however, their organoleptic scores remained above the acceptable level in all the treatments after storage.

It was reported that the changes in the chemical composition of bael preserve during storage at room temperature showed maximum acceptability after three months of storage. The organoleptic scores of bael preserve remained above the acceptable levels even after six months of storage (Kaushik *et al.*, 2002).

9.6.4 Other potential uses and by-products

Bael has always been regarded as an extremely useful tree and has many other uses. The gummy substance, mucilage in which the seeds are embedded is used as an adhesive, in cementing mixture and varnishes. The rind of unripe fruits yields a yellow dye (Nadkarni 1988; Jain, 1968). As already stated, a preserve made using the green fruit is widely consumed. In spite of its beneficial properties the

ripe fruit is not very popular in the fresh form, particularly with the modern generations, since it is difficult to eat. However, it has tremendous possibilities for processing.

Saini *et al.* (2002) reported that the waste from processing bael fruit such as pomace and peel could be used as animal feed. The results indicated that bael waste was a potential source of nutritive animal feed which would substitute at least 25% of the animal feed. The use of these wastes as animal feed would not only reduce feed cost but would also prevent health hazards and environmental pollution.

9.7 Physiological disorders

9.7.1 High and low temperatures

The type of spoilage observed in bael fruit at higher temperature is quite different from that which occurs at low temperature storage. At high temperature (above 14°C) brown-to-black patches appear on the surface of the fruit together with heavy fungal growth inside the fruit, which indicates fungal spoilage (Roy, 1975). In the case of low-temperature storage (below 9°C), brown spots appear on the surface, which gradually increase in number, size, and colour intensity, indicating chilling injury, with symptoms similar to those found in other citrus fruits.

9.7.2 Other physiological disorders

The storage life of bael fruits could be increased from two weeks at ambient temperature (27 to 33°C) to 12 weeks at a cooler storage temperature of 9°C. A marked physiological breakdown is noticed when stored temperature is below 9°C (Roy and Singh 1979e).

9.8 Pathological disorders

Fungal growth can take place inside the fruits without showing evidence on the surface. The fungal infection of bael fruit occurs only as a result of cracking of the fruit surface or through entry at the stem end (Roy and Singh 1979e).

The bacterium *Xanthomonas bilvae* causes bacterial shot hole in bael fruit leaves. The pathogen also infects twigs and thorns and causes fruit canker (Patel *et al.*, 1953).

9.9 Conclusions

Bael fruit is one of the most nutritious fruits of India, and its medicinal properties have long been known. It can grow under adverse agro-climatic conditions, unlike other tropical fruit trees. The fruit is presently under-utilized but has an important

role to play in satisfying the demand for nutritious and delicious natural foods of high therapeutic value.

Investigations have clearly indicated that a number of acceptable processed products can be prepared from bael fruit. Methods have been standardized, and storage requirements have also been formulated to enable commercial utilization of this fruit and its processed products. However, the bael fruit's quality and flavours are entirely unknown in the world market and need to be popularized. A lack of processing technology is not the main hindrance for promoting bael fruit consumption. The main problem is lack of market awareness, as to date there has been no serious effort regarding the marketing and export of processed products of bael fruit. Kiwifruit was practically unknown in the world market 30 years ago, but has come to the forefront in the field of international fruit trade. This was achieved by the untiring efforts of the New Zealand Kiwifruit Marketing Board. This fruit was made popular among consumers the world over, particularly the developed nations, by highlighting the qualities of this nutritious fruit and its thirst-quenching properties. The constant campaign for this fruit has appealed to the modern lifestyle and it has become particularly popular with health and image-conscious people. There is no reason why processed products of bael fruit could not achieve a similar success.

The present chapter on bael fruit will serve to bring attention to this nutritious fruit, as yet unknown in the world market, and help to create awareness and increased interest in the commercial development of processed bael fruit products.

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Plate XV Section of bael fruit showing seed cavity.

Plate XVI Different sizes and shapes of bael fruit. Source: Central Institute of Subtropical Horticulture, Lucknow, India (2006).

10

Banana (*Musa* spp.)

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Abstract: Bananas and plantains form a major component of the economies and food security of many countries especially some with fragile economies. An enormous amount of research and commercial development has been invested into the crops with the result that high-quality fruit is delivered to the consumer. Bananas and plantains are both climacteric fruit that respond well to temperature, controlled atmosphere storage and modified atmosphere packaging. This has ensured that they have an adequate postharvest life. They are delicate and susceptible to disease, and comprehensive systems have been developed to address these challenges. However, there remains the fact that some of these technologies may have deleterious effects of the environment that represent challenges to sustaining current systems.

Key words: *Musa*, botany, diseases, harvesting, packaging, pests, postharvest, physiology, processing, taxonomy, transport.

10.1 Introduction

10.1.1 Botany

Botanically the fruit is a parthenocarpic berry. It probably originated in South-East Asia and grows best in the humid lowland tropics within 30 degrees of the equator. It is also grown commercially within the subtropics and at altitudes of 1000 m or higher in the tropics but growth is much slower and cropping lighter. The plant has a basal corm, the true stem, which has an apical meristem in the form of a flattened crown from which grow the spirally arranged leaves whose bases form a pseudostem. The flower is produced from the corm in the centre of the leaves and emerges at the top of the pseudostem. Only one flower is produced from one pseudostem. It takes about a month from formation to emergence of the inflorescence. The inflorescence is borne on a stout peduncle and consists of male and female flowers borne on nodes in two rows of nodal clusters with bracts in

between. The top five to fifteen nodal clusters produce female flowers, and below this at the distal end, male flowers. There may be hermaphrodite flowers between the male and female. The root system is adventitious with individual roots up to about 8 mm in diameter with primary roots producing short thinner lateral roots. They are white and fleshy later becoming somewhat corky and can spread up to 5 m laterally but mostly in the top 15 cm and to a depth restricted by the water table.

10.1.2 Taxonomy

Bananas and plantains belong to the section *Eumusa* of the genus *Musa*. Many authors use the Linnaean classification, e.g. *Musa paradisiaca, M.* x *paradisiaca* and *M. sapientum* and many others. However, Cheesman (1947–1949) defined the two species, *M. balbisiana* and *M. acuminata* as the basis for almost all cultivated bananas and plantains. Simmonds and Shepherd (1955) and Stover and Simmonds (1987) confirmed this, and reported that many edible varieties are derived from *M. acuminata*, some being diploid and a few being tetraploid but most being triploid. *M. balbisiana* has also contributed to the origin of edible bananas and plantains by hybridization with *M. acuminate*. They recommended that in place of the species name, an A genome or a B genome should be used showing the origin and contribution of the two species. So a triploid variety whose origin is *M. acuminate*, e.g. the Giant Cavendish and Gros Michel varieties, would be referred to as *Musa* AAA. Where the triploid has one-third *M. bulbisiana* and two-thirds *M. acuminate*, as in most plantain varieties, it would be referred to as *Musa* AAB.

10.1.3 Varieties

Since the edible varieties are parthenocarpic and often female or male sterile, seeds are rarely found in their fruit, which has made it difficult to improve bananas and plantains by conventional breeding. Almost all varieties used commercially have arisen from mutations selected in the field. Gros Michel was the fruit that dominated the international trade from its beginnings in the mid-nineteenth century until the late 1940s. It is a tall heavy bearing variety, but is susceptible to Panama disease (Fusarium root rot) caused by the fungus *Fusarium oxysporum* f. sp *cubense*. It was reported as early as 1928 in Trinidad that there was concern about the susceptibility of Gros Michel to Panama disease (Wardlaw, 1937). In the coffee zones of Colombia, Gros Michel is still grown commercially and is preferred to Cavendish and achieves a higher price locally. It is also grown in parts of Thailand and receives a high price when exported to Japan. Three races of Panama disease have been described that can affect bananas. Race 1 caused the epidemics on Gros Michel and also affects some other varieties and tetraploids. Race 2 affects cooking bananas, e.g. Bluggoe and some tetraploids while Race 4 affects race 1- and race 2-susceptible varieties as well as the Cavendish varieties. Race 4 has been shown to consist of a subtropical and a tropical race. The tropical Race 4 can attack unstressed plants while the subtropical Race 4 usually only attacks when plants are in a stressed condition.

Giant Cavendish has been the main variety of international trade since the late 1940s and selections include: Grand Nain, Lacatan, Poyo/Robusta, Valery and Williams, which are largely distinguished by the size of the pseudostem. The largest is Lacatan (up to 5.5 m) followed by Robusta and Giant Cavendish (up to 5 m) and the smallest is the Dwarf Cavendish (1.2 to 2.1 m). In addition Dwarf Cavendish is tolerant to a wide range of climates including cool conditions and Grand Nain responds well to optimum growing conditions. The Sucrier/Pisang Mas/Honey varieties are very sweet and have small fruit, thin skin, yellowish flesh and small bunches (up to about 13 kg). Plants are up to 3.5 m high, prefer light shade and are not well adapted to cooler temperatures.

Breeding programmes have developed tetraploid bananas and plantains, starting in 1922 at the Imperial College of Tropical Agriculture in Trinidad and subsequently at the banana breeding programme at Bodles in Jamaica (producing Bodles Altafort which is *Musa* AAAA), the Centro Nacional De Pesquisa De Mandioca e Fruticultura Tropical in Brazil and Fundacion Hondureña De Investigacion Agricola (FHIA). However, there is concern about tetraploids that possess the B genome. This is because the banana streak virus (BSV) is integrated in the B genome and may be activated, especially if they are exposed to stress or are propagated *in vitro*. The FHIA-21 (*Musa* AAAB) cooking banana with plantain in its pedigree is reported to be resistant to Black Sigatoka disease, and total fingers per bunch and bunch weights at maturity are about double those of False Horn. They have a higher fruit moisture content and a softer ripe texture than False Horn. FHIA-01, also called Goldfinger, (*Musa* AAAB) is a desert banana that has been bred to be high yielding and resistant to Black Sigatoka. Seberry and Harris (1998) showed that Goldfinger, harvested at 36–39 mm grade, had an adequate green life. Ripening at 16°C with >96% rh, in 1 ppm ethylene, gave fruit of the best appearance and colour and had longer shelf life after ripening than Williams, but Goldfinger fruit softened more rapidly than Williams or Lady's Finger (*Musa* AAB). It has not replaced the Cavendish varieties in international trade as was hoped.

10.1.4 Worldwide importance and economic value

Estimated world production has risen from just over 20 million tonnes in 1960 to just over 70 million tonnes in 2007. India is by far the largest producer (Table 10.1) and Ecuador the largest exporter (Table 10.2).

Some countries, particularly those in Latin America, are very efficient banana producers with a good infrastructure and optimum inputs giving high yields. Many banana plantations in these countries are foreign-owned. Many of the African Caribbean and Pacific (ACP) countries have economies that rely on tourism and banana exports, and because of factors such as comparatively high labour costs or lower capital investment they are unable to compete with other countries on banana price. Organic production and 'Fair Trade' have enabled many ACP countries to supply niche markets economically. The World Trade Organization (WTO) ruling in 1997 against trade preferences between ACP

Table 10.1 Banana production in 2007, 2008 and 2009 in million tonnes

Country	2007	2008	2009
India	21.77	23.20	Not available
China	8.04	8.04	8.20
Philippines	7.48	8.69	9.01
Brazil	7.10	7.12	7.19
Ecuador	6.00	6.70	7.64
Indonesia	5.46	5.74	6.27
Tanzania	3.50	3.50	Not available
Costa Rica	2.08	1.88	2.13
Thailand	2.00	2.00	1.53
Mexico	1.96	2.16	Not available
Colombia	1.82	1.99	2.02
Burundi	1.60	1.85	Not available
Guatemala	1.57	1.57	Not available
Vietnam	1.36	1.36	Not available
Kenya	1.19	0.59	Not available
Bangladesh	1.00	0.88	Not available
Honduras	0.91	0.91	0.69
Egypt	0.88	1.06	1.10
Papua New Guinea	0.87	0.94	Not available
Cameroon	0.86	0.86	0.82
Uganda	0.62	0.62	Not available
World total	72.5	90.7	95.6

Source: Food and Agriculture Organization of the United Nations, Statistics division 2, September 2010. Available http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor, accessed January 2011.

Table 10.2 Value of exports in US$ million per year by country of the 11 leading exporters

Year	2005	2006	2007	2008
World	6,317	6,607	7,483	8,812
Ecuador	1,085	1,214	1,303	1,639
Costa Rica	490	648	702	712
Colombia	506	511	558	644
Philippines	363	404	397	398
Guatemala	262	233	325	344
Honduras	136	132	154	171
Côte d'Ivoire	94	116	127	118
Panama	96	106	110	97
Brazil	33	39	44	36
Mexico	24	31	20	48
Peru	18	27	31	46

Source: UN Comtrade and Global Trade Atlas. Online at http://www.wto.org/english/news_e/pres09_e/pr591_e.htm, accessed January 2010.

Table 10.3 Agreed progressively reducing tariffs on non-ACP banana exports to Europe

Year	Tariff €/tonne
2010	148
2011	143
2012	136
2013	132
2014	127
2015	122
2016	117
2017	114

Source: World Trade Organization, WT/L/784, online at http://docsonline.wto.org/DDFDocuments/t/wt/l/784.doc, accessed January 2010.

countries and the European Union (EU) has been a potential problem in these fragile economies. The EU is the principle importer of bananas in the world (in 2008 it imported 49% of the world banana exports). A settlement of the disputed WTO ruling over tariffs on imports into the EU was achieved in December 2009. The WTO brokered an agreement with the non-ACP banana producers and the USA that ACP suppliers can continue to export to the EU duty-free and quota-free under the 2008 EU Economic Partnership Agreements. The EU will continue to apply a duty on the import of non-ACP bananas called the Most Favoured Nations Duty. There are some provisos with the regulations but, in brief, they are that the non-ACP banana exports to Europe will attract progressively reducing tariffs (Table 10.3).

10.1.5 Culinary uses, nutritional value and health benefits

Bananas are mainly ripened and eaten fresh but are also used in cooking and both green and ripe plantains are cooked before being eaten. Amyl esters give bananas their distinctive flavour and aroma and butyl esters give them a fruity flavour and aroma but other esters and aldehydes, alcohols and ketones have been associated with flavour and their production rates can increase during ripening (Tressl and Jennings, 1972).

Lee (2008) reported that bananas have a high potassium content and an average-sized banana had 450 to 467 mg potassium. He also reported that potassium is essential for keeping human blood pressure normal and also helps in proper functioning of the heart. Bananas are also high in fibre and a medium sized banana has about 6 g of fibre. They also contain vitamins C, B and A as well as other minerals. Wall (2006) reported that bananas contained higher concentrations of lutein than of the provitamin A pigments, α- and β-carotene. She also showed that different varieties of banana could contain different levels of nutrients. Hawaii Apple bananas had almost three times more vitamin C (12.7 mg 100 g^{-1}

fresh weight) than Williams (4.5 mg 100 g^{-1}) and Apple bananas had an average of 96.9 μg β-carotene and 104.9 μg α-carotene 100 g^{-1}, whereas Williams bananas averaged 55.7 μg β-carotene and 84.0 μg α-carotene 100 g^{-1}. Apple bananas also had higher P, Ca, Mg, Mn, and Zn concentrations than Williams.

10.2 Postharvest physiology

10.2.1 Respiration

Bananas and plantains are climacteric and, like other climacteric fruit, ripening initiation is through ethylene biosynthesis via ACC (1-aminocyclopropane 1-carboxylic acid) biosynthesis. The initiation of ripening in bananas and plantains occurs when a threshold level of ethylene is reached within the fruit cells. It is marked by a rapid rise in respiration rate to a peak, after which the rate gradually falls as ripening progresses. During ripening the fruit softens, starch is converted to sugars, the skin colour changes from green to yellow, they lose their astringency and develop their characteristic flavour. Pathak *et al.* (2003) concluded, 'ethylene induced ripening of banana is characteristically different from that of other climacteric fruits and that ethylene biosynthesis may have more than one mechanisms operating during ripening which are tightly controlled at various levels.'

10.2.2 Colour

The pigments in the peel of bananas and plantains are chlorophylls and carotenoids. The change in colour of ripening fruits is associated with the breakdown of chlorophylls, with carotenoid levels remaining relatively constant (Seymour, 1985). Cavendish banana cultivars can fail to completely degreen when they are ripened at 25°C and above (Seymour *et al.*, 1987; Semple and Thompson, 1988). This can result in bananas that are ripe in every other respect, having green peel; the higher the temperature the more obvious the effect. With plantains it was shown that complete chlorophyll destruction could occur even at 35°C (Seymour, 1985; Seymour *et al.,* 1987). Studies on the reason for this effect of temperature on degreening of Cavendish bananas have shown that it appears to be related to the thylakoid ultrastructure of the chloroplasts (Seymour, 1985, Blackbourn *et al.*, 1990).

Colour changes during ripening of bananas have been used as a rough guide to the stage of ripeness. It is commonly used commercially in the form of colour matching charts based on the degree of peel yellowing where colour index 1 is allocated to fruit that are dark green and colour index 6 is for fruit that are fully yellow (Von Loesecke, 1949, Lizada *et al.*, 1990). Examples of these colour charts are supplied by commercial banana companies, and can also be found in Stover and Simmonds (1987), Abdullah and Pantastico (1990) and Thompson (1996). Advanced stages of banana ripeness are characterized by the appearance of brown flecks or spots on the skin. The brown flecks usually appear at colour index 6 but

conflicting reports dispute this. For example in *Musa* AAA, Miem (1980) reported colour index 5.5, whereas Ng and Mendoza (1980) reported that they occur at colour index 3.5 to 4.

10.2.3 Softening

Softening of bananas during ripening appears to be associated with two or three processes (Smith, 1989). The first of these is the breakdown of starch to form sugars, since starch granules could have a structural function in the cells. The second is the breakdown of the cell walls due to the solubilization of pectic substances and even the breakdown of cellulose. He also found evidence of increased activity of cellulase during banana ripening. The possible third is the movement of water from the peel of the banana to its pulp during ripening. This latter process could affect the turgidity of the skin that would be enhanced by transpirational losses. Fernandez *et al.* (1996) reported that in plantains the pulp:peel weight ratio increased from 1.23 in green plantains to 1.60 when fully ripe. This change in the moisture status of the fruit also contributes to the ease of which the peel can be detached from the pulp. Agoreyo *et al.* (2007) showed that the cell wall degrading enzyme polygalacturonase in plantains was more active in the pulp than in the peel for all the ripening stages, with the activity increasing from the unripe stage through to the over-ripe stage. Yang *et al.* (2008) found that enhanced production of hydroxyl radical and hydrogen peroxide could participate in the formation of oxidative products that are involved in the initiation of banana fruit softening.

10.2.4 Phenols

The presence of tannins can impart an unpleasant flavour to the fruit. As the fruit ripens the tannins polymerise and they loose their astringency (Von Loesecke, 1949). Mura and Tanimura (2003) also reported loss of astringency during ripening of bananas and found that it was by the polymerizing of polyphenol compounds with a molecular weight of 2×10^5.

10.2.5 Acidity

Bananas and plantains, like most other fruits, are acid with a pulp pH below 4.5 (Von Loesecke, 1949). Palmer (1971) showed that the main acids in bananas were citric, malic and oxalic and the levels of these acids normally increase during ripening. Ascorbic acid content of Dwarf Cavendish, Rasabale and Rajabale increased during ripening at 20°C for 21 days and then decreased slightly up to 35 days (Desai and Deshpande, 1975).

10.2.6 Carbohydrates

Starch accumulates during maturation and as they ripen there is a reduction in starch content in bananas from around 15 to 25% to 0 to 5% in the ripe pulp,

coupled with increases of similar magnitude in total sugars (Barnell, 1943; Lizada *et al.*, 1990). During the early part of ripening sucrose is the predominant sugar, but in the later stages glucose and fructose predominate (Barnell, 1943). Starch content for green plantains was 27.10 and 8.21% for ripe fruits and total sugars were 1.13 and 19.91%, respectively (Fernandez *et al.*, 1996). It has been shown that the onset of the starch to sugar conversion is influenced by harvest maturity, with more mature fruits responding earlier. In bananas the breakdown of starch is usually completed during ripening, but in plantains this breakdown is not complete even when the fruit is fully yellow and soft (George, 1981). In Apple bananas the fruit still has residual starch when it is fully yellow and needs to be ripened further before being eaten (Wei and Thompson, 1993).

10.3 Maturity and quality components and indices

As bananas and plantains mature on the plant they increase in size and width and they become less angular and more rounded in cross-section. The width of individual fingers can be used to determine their harvest maturity. Usually a predetermined finger from the bunch is used and its maximum width is measured with callipers, hence it is referred to as the 'calliper grade' (Thompson, 1996). The length of the same finger may also be measured for the same purpose. The cross-section angle is also used to describe harvest maturity. In the West Indies light three-quarters, three-quarters and full correspond approximately to 37 to 41, 41 to 45 and over 45 mm diameter respectively.

For the export of bananas harvest maturity must be very precise, and so the time after the flower shoot appears in each plant is recorded. At anthesis a plastic cover is placed over the bunch to protect the fruit as it is developing. In order to identify exactly when anthesis occurs a coloured plastic ribbon is attached to the bunch, hence the process is called 'ribbon tagging'. The same colour is used for one week throughout the plantation (or even for the whole country in the Windward Islands) and changed to another colour the following week and so on. This means at the harvest time the age of each bunch is precisely known. Wilson Wijeratnum *et al.* (1993) showed that the Ambul (*Musa* AAB) variety grown in Sri Lanka reached physiological maturity eight to nine weeks after anthesis. For Giant Cavendish in Ecuador the maximum time from anthesis to harvest is usually 12 weeks and for Giant Cavendish in the Windward Islands it is 13 weeks.

In plantains, increasing fruit maturity at harvest significantly increased their postharvest ripening rate (Ferris *et al.*, 1993). Optimum harvest time can vary with variety and the best harvesting stages, in weeks before ripeness of the first finger on the bunch, were given by Tchango *et al.* (1999) as: one week for French Clair with a flowering to harvesting interval of 79 days, one to two weeks for Big Ebanga with a flowering to harvesting interval of 71 to 78 days and two to three weeks for Batard with a flowering to harvesting interval of 68 to 75 days.

10.4 Preharvest factors affecting quality

If bananas are allowed to mature fully before harvest and harvesting is shortly after rainfall or irrigation, the fruit can easily split during handling operations, allowing microorganism infection and postharvest rotting (Thompson and Burden, 1995). Ahmed *et al.* (2001) found very strong evidence that in Robusta bananas the fruit had much better organoleptic properties the more mature they were when harvested.

Growing conditions can also affect postharvest characteristics. Chillet and De Lapeyre De Bellaire (2002) found a weak correlation between the manganese concentration and wound ethylene production in lowland bananas in the West Indies. They also showed that in the wet season lowland fruit was more fragile and produced more wound ethylene than highland fruit. In Thailand, Williams and Grand Nain grown under low chemical production systems tended to have higher levels of sugars and acids but were softer and there was some indication that they contained less starch than those from a conventional production system (Ambuko *et al.*, 2006). In a survey of fruit quality of Philippine bananas from non-chemical production, the problems highlighted all related to management practices and none to the effects of organic production on postharvest aspects (Alvindia *et al.*, 2000). However, in Britain Nyanjage *et al.* (2000) found that imported organically grown Robusta bananas ripened faster at 22 to 25°C than non-organically grown bananas as measured by peel colour change, but ripe fruit had similar total soluble solids levels from both production systems. The peel of non-organic fruits had higher nitrogen and lower phosphorus contents than organic fruits.

10.5 Postharvest handling factors affecting quality

10.5.1 Physical damage

The effects of different types of bruise on the ripening of plantains showed that the greatest effect was caused by abrasion. Ripening rate of French, True Horn and False Horn in ambient conditions, averaging 28°C and 82% RH, was increased when fruit had been damaged by abrasion, more so in less mature fruits, and also by impact, but only in immature fruits (Ferris *et al.*, 1993). For some local markets damage and blackening of the peel did not adversely affect banana marketability (Silvis *et al.*, 1976). A study carried out in Ghana showed that even plantain fruit that had been crushed to a pulp were readily saleable and often had specialized markets (Ferris, 1991).

10.5.2 Temperature

Bananas and plantains suffer from chilling injury to an extent that is proportional to the time they are exposed to chilling temperatures. Recommended storage conditions for green bananas include the following: 12 to 14°C and 90 to 95% RH for two to three weeks (Mercantilia, 1989), 13.3 to 14.4°C and 90 to 95%

RH for all cultivars except Gros Michel, which is 11.7°C (Hardenburg *et al.*, 1990), 14.4°C and 85 to 95% RH for seven to 28 days (SeaLand, 1991).

Recommendations for specific varieties include:

- Cavendish: 12.8 to 14.4°C with 85 to 90% RH (Pantastico, 1975) and 13°C in 85 to 90% RH for ten to 20 days (Snowdon, 1990).
- Dwarf Cavendish: 11.5 to 11.7°C (Wardlaw, 1937), 12.2°C for transport from Trinidad to Britain (Simmonds, 1966) and 11.4°C for transport from West Africa to Europe (Simmonds, 1966).
- Gros Michel: 11.5 to 11.7°C (Wardlaw, 1937), 11.7°C for transport from tropical America and West Africa to Europe and USA (Simmonds, 1966), 12.2°C for transport from Trinidad to Britain (Simmonds, 1966) and 13°C and 85 to 90% RH for ten to 20 days (Mercantilia, 1989).
- Lacatan: 14 to 14.4°C (Wardlaw, 1937), 13.1°C for transport from Jamaica to Britain (Simmonds, 1966), 12.2°C for transport from Trinidad to Britain (Simmonds, 1966), 13°C (Purseglove, 1975), 12.8 to 15.6°C with 85 to 90% RH for 4 weeks (Pantastico, 1975) and 13 to 15°C and 85 to 90% RH for one month (Snowdon, 1990).
- Latundan: 14.4 to 15.6 with 85 to 90% RH for three to four weeks (Pantastico, 1975). For Robusta/Poyo 11.1 to 11.7°C for transport from Samoa to New Zealand (Simmonds, 1966), 13°C and 85 to 90% RH for ten to 20 days (Snowdon, 1990), 13°C (Purseglove, 1975) and 13°C and 85 to 90% RH for ten to 20 days (Snowdon, 1990).
- For bananas that have been initiated to ripen: 13°C for three to six days (Mercantilia, 1989), 20°C for one to two days (Mercantilia, 1989) or 13 to 15°C and 85 to 90% RH for five to ten days (Snowdon, 1990) were recommended.

Storage recommendations for plantains include: 10°C and 85 to 90% RH for green fruit for five weeks with 6% loss (Pantastico, 1975), 7.2 to 10°C and 85 to 90% RH for ripe fruit for ten days (Pantastico, 1975), 10°C and 85 to 90% RH for five weeks (Snowdon, 1990), 11 to 15.5°C and 85 to 90% RH for coloured fruit for one to three weeks (Snowdon, 1990), 14.4°C and 85 to 95% RH for ten to 35 days (SeaLand, 1991) and 12 to 14°C and 85 to 95% RH for 15 days for green mature fruits (Tchango *et al.*, 1999).

10.5.3 Ethylene

Bananas and plantains are initiated to ripen when they are fully mature and their internal ethylene reaches a threshold level. They can be initiated to ripen before this point is reached by exposure to exogenous ethylene at a critical level for sufficient time, if the environmental conditions are conducive. Quazi and Freebairn (1970) showed that high CO_2 and low O_2 delayed the production of ethylene to levels associated with the initiation of ripening in bananas, but the application of exogenous ethylene was shown to reverse this effect. Wade (1974) reported that bananas could be ripened in atmospheres of reduced O_2, even as low as 1%, but the peel failed to degreen, which resulted in ripe fruit which were still green.

Similar effects were shown at O_2 levels as high as 15%. Since the degreening process in Cavendish bananas is entirely due to chlorophyll degradation (Seymour *et al.*, 1987), the controlled atmosphere storage treatment was presumably due to suppression of this process. Hesselman and Freebairn (1969) showed that ripening of bananas, which had already been initiated to ripen by ethylene, was slowed in low O_2 atmospheres.

Treatment with 1-Methylcyclopropene (1-MCP) can inhibit the action of ethylene. Pinheiro *et al.* (2005), Jansasithorn and Kanlavanarat (2006) and Jiang *et al.* (2004) reported that treatment with 1-MCP increased postharvest life of bananas and Klieber *et al.* (2003) showed that treatment with 1-MCP did not affect eating quality. However, bananas treated with 1-MCP were shown to result in some uneven degreening (De Martino *et al.*, 2007). Moradinezhad *et al.* (2010) reported that 1-MCP treatment at 300 nl l^{-1} on Williams had no effect on ethylene production of preclimacteric fruit stored at 10°C but it increased their shelf life. Firmness of 1-MCP-treated fruit decreased significantly compared to the control when fruit were stored at 5 or 15°C prior to ripening (and 1-MCP application), but had no effect on fruit stored at 10°C before ripening.

10.5.4 Controlled atmosphere (CA)

There are very wide variations in recommendations for optimizing CA conditions for bananas (Table 10.4) and perhaps it would be safe to use 3% O_2 + 5% CO_2 at 14°C. In some cases higher levels of CO_2 and lower levels of O_2 have shown beneficial effects, but these levels have also been reported to have detrimental effects.

Madrid and Lopez-Lee (1998) stored Grand Nain green bananas in 3% O_2 or air for 15 days at 14°C and 95% RH in a flow-through system to simulate sea freight transport. After storage, the fruit was ventilated in air for two days at 14°C and then exposed to 300 µl l^{-1} ethylene for 24 hours at 16°C then stored at 16°C after treatment with ethylene. They found that the CA-stored fruit were firmer and had lower total soluble solids for the first three days after ethylene treatment, but these differences disappeared as fruit reached commercial ripeness. They found no significant differences in colour. Agoreyo *et al.* (2007) found that ethylene production in CA conditions was not detected and CA storage increased the postharvest life when compared to fruit stored in air.

There was one controlled atmosphere storage recommendation for plantains, which was 14.4°C and 85 to 95% RH with 2 to 5% CO_2 and 2 to 5% O_2 (SeaLand, 1991).

10.5.5 Modified atmosphere packaging

Modified atmosphere packaging is very commonly used in various forms in the banana industry. One example is where individual clusters of six fingers are packed individually in small polyethylene film bags that are then packed together into a large carton. These are transported by sea freight then ripened and marketed while still in

Table 10.4 Recommended conditions for controlled atmosphere storage of bananas

CA conditions	Reference
15°C in 2% O_2 + 8% CO_2	Smock *et al.* (1967)
5% CO_2 or lower + 2% O_2	Woodruff (1969)
20°C 3% O_2 + 5% CO_2 for 182 days for Williams (*Musa* AAA), Australia	McGlasson and Wills (1972)
15°C in 5–8% CO_2 + 3% O_2 for Bungulan (*Musa* AAA), Philippines	Pantastico (1975)
20°C in 1.5–2.5% O_2 + about 7–10% CO_2	Anon (1978)
20°C in 1.5–2.5% O_2 + 7–10% CO_2 for Williams (*Musa* AAA), Australia	Sandy Trout Food Preservation Laboratory (1978)
Maximum of 5% CO_2	Fellows (1988)
5% CO_2 + 4% O_2	Hardenburg *et al*. (1990)
15°C in O_2 as low as 2% if the CO_2 level is around 8% for Lakatan (*Musa* AA), SE Asia	Abdullah and Pantastico (1990)
2–5% CO_2 + 2–5% O_2	SeaLand (1991)
12–16°C in 2–5% CO_2 + 2–5% O_2	Kader (1993)
12–16°C in 2–5% CO_2 + 2–5%O_2	Bishop (1996)
11.5°C in 7% CO_2 + 2% O_2, South Africa	Van der Merwe (1996)
14–16°C and 95% rh in 2–5% CO_2 + 2–5% O_2	Lawton (1996)
14°C in 4 or 6% O_2 + 4 or 6% CO_2 for Robusta (*Musa* AAA)	Ahmad *et al*. (2001)
12°C in 3% O_2 + 9% CO_2 or 5% O_2 + 5% CO_2 for Prata (*Musa* AAB)	Botrel *et al*. (2004)
12.5 ± 0.5°C and 98% ± 1.0% rh in 2% O_2 + 4% CO_2 or 3% O_2 + 7% CO_2 for Prata Ana (*Musa* AAB)	Santos *et al*. (2006)

the same bags. Banavac is a patented system that uses large 0.04 mm thick polyethylene film bags in which typically 18.14 kg of green bananas are packed, and then a vacuum is applied and the bags are sealed and transported in cartons (Badran, 1969). Nair and Tung (1988) reported that Pisang Mas bananas had an extension in their postharvest life of four to six weeks at 17°C when they were stored in evacuated collapsed polyethylene film bags by applying a vacuum not exceeding 300 mm Hg. There are many other reports of the positive effects of modified atmosphere packaging on different varieties of banana in different films from different countries including: Shorter *et al.* (1987), Tiangco *et al.* (1987), Tongdee (1988), Abdullah and Pantastico (1990), Marchal and Nolin (1990), Satyan *et al.* (1992), Wei and Thompson (1993), Chamara *et al.* (2000) and Chauhan *et al.* (2006). However, Wills (1990) mentioned that an unsuitable selection of packaging materials could accelerate the ripening of

fruits or enhance CO_2 injury when ethylene accumulated. Thompson *et al.* (1972) showed that plantains stored in modified atmospheres had a considerably longer postharvest life than those stored unwrapped. The degree of perforation in the bag had a large effect on the atmosphere inside the bag.

Including potassium permanganate inside the bags can increase the positive effects of modified atmosphere packaging (Chamara *et al.*, 2000), as does gas flushing (Chauhan *et al.*, 2006) and some other chemicals (Ranasinghe *et al.*, 2005).

10.6 Physiological disorders

10.6.1 Chilling injury

Bananas and plantains are subject to chilling injury at temperatures well above freezing. At temperatures at, or below, 12°C the green fruit develop a dull, grey skin colour, starch is no longer converted to sugar and they subsequently fail to ripen properly (Wardlaw, 1937). They eventually become black and decay. To avoid this problem bananas are shipped at 13 to 14°C. A milder form of chilling injury is under peel discolouration, which can occur after prolonged storage even at 13°C. This takes the form of browning of the vascular bundles in the peel and can be seen as faint brown lines just below the peel surface. It is more obvious when the fruit are cut longitudinally (Plate XVII: see colour section between pages 244 and 245). However, Zhang *et al.* (2010) reported that immersion of harvested fruit in iced water for one hour reduced their ethylene production and respiration rates and inhibited peel degreening and pulp softening during storage or ripening at 20°C. Low-temperature injury can occur where fruit are exposed to temperatures below about 10°C in the field, e.g. in the banana producing areas of the Sudan the night temperature is often low in winter and poor quality deformed bunches can be produced.

10.6.2 Other physiological disorders

Cream pulp or *pulpa crema* occurs on Cavendish bananas when the fruit have initiated to ripen on the plant. This is when the ambient temperature is above 25°C: the pulp ripens but the chlorophyll in the skin is not fully broken down. It commonly occurs when the plant is under stress from lack of water or fungal infections of the leaves and may not be obvious at harvest but shortens the postharvest life of the fruit.

Sunscald is where fruit have been exposed to direct sunlight, especially where bunches are enclosed in transparent polyethylene film sleeves. Peel cells are killed leaving a brown stain. Damaged fruit can be graded out at harvest so it is not a major problem.

10.7 Pathological disorders

With such large monoculture areas, especially for bananas, there are usually accumulated pest and disease problems that require an integrated control programme.

10.7.1 Sigatoka leaf spot

Generally if a crop has suffered an infection during development its storage or marketable life may be adversely affected. Bananas may ripen prematurely or abnormally after harvest because of leaf infections by fungi during growth, which cause stress and therefore shorten their storage life. This can be manifest on the crop before harvesting or it may only be observed as a postharvest 'physiological disorder'. Fungicide applications in the field to control Yellow Sigatoka leaf spot (*Micosphaerella musicola*) were shown to reduce premature ripening (Thompson and Burden, 1995). Black Sigatoka is also a leaf spot or leaf streak disease caused by infection with *Mycosphaerella fijiensis*, which is endemic to most banana-exporting countries. It does not infect the fruit but damages or kills leaves. This reduces the photosynthetic area of the plant, which can lead to a reduction in yield. This leaf damage in turn causes stress to the plants and a reduction in the green life of the harvested fruit. It has been found that the fruit of infected plants behave as though they were physiologically one to two weeks older than those of uninfected plants of the same age. In trials reported by Turner (1997), reducing leaf numbers from twelve to seven during fruit growth, as can occur with leaf infections, did not affect bunch weight, but reduced green life by six days. Ramirez *et al.* (2008) also found that in Grand Nain, grown in tropical commercial banana plantations, it was possible to defoliate the plants to seven leaves at flowering without causing a reduction on the green or yellow life and quality of fruit. With fewer leaves there was no further reduction in green life, but bunch weight was reduced by 8%. Ramsey *et al.* (1990) found that plants with less than five viable leaves (that is five leaves not greatly affected by Sigatoka) at harvest produced lighter bunches, due to smaller fingers. All bunches from plants with fewer than four leaves were field ripe, which in Cavendish means that the pulp is ripe but the peel remains green.

Control of *Micosphaerella* is achieved by spraying with chemicals as often as every seven to ten days in the case of *M. fijiensis*. In Guadeloupe this method of chemical control has resulted in the appearance of strains resistant to the active ingredients used for postharvest disease control (De Lapeyre De Bellaire and Chillet, 2000). They also reported growing consumer resistance to chemical use.

10.7.2 Anthracnose

Anthracnose (*Colletotrichium musae*) gives latent fruit infections, the symptoms of which generally only become clear as the fruit ripens. The time taken between infection and the symptoms of the disease developing can be over five months (Simmonds, 1941). This used to be a common disease but is rare now owing to the extensive field sprays used to control *Mycosphaerella* spp. Anthracnose was a problem when bananas were shipped as bunches with prolonged shipping times, or when ripened at temperatures above 18°C. It is rarely seen in hands packed in boxes.

10.7.3 Crown rot

The cut surface of the banana or plantain hands is liable to infection by fungi, which cause a disease known as 'Crown Rot'. Since the shipment of bananas as hands packed in fibreboard boxes began in the late 1960s, Crown Rot has been the principal postharvest disease problem. If not treated with fungicide these infections develop during ripening in the importing country and cause decay of the crown tissue, which may spread into the fruit stalk or even the fruit itself during marketing. Several different fungi have been found to be associated with crown rot (Griffee and Burden, 1976), the most common being the banana anthracnose fungus *Colletotrichum musae*, which often occurs in mixed infections with *Fusarium semitectum* (Knight *et al.*, 1977). Control is by postharvest treatment with a fungicide, usually thiabendazole or imazalil. Postharvest dips with *Pseudomonas* sp. isolates, associated with the skin of bananas, significantly reduced Crown Rot (De Costa and Subasinghe, 1998). Banana crowns coated with Semperfresh (sucrose esters of fatty acids and carboxy methylcellulose) showed delayed development of Crown Rot and this effect could be enhanced by including organic acids in the coating material (Al-Zaemey *et al.*, 1989). Bastiaanse *et al.* (2010) also investigated the control of Crown Rot without fungicides and found that the most effective control (53%) was a combination of yeast (*Candida oleophila* strain O at 1.10^7 colony forming units per ml), calcium chloride and modified atmosphere packaging in non-perforated polyethylene film bags.

10.7.4 Other fungal diseases

Several other fungi cause postharvest diseases of banana and plantain fruit including: *Botryodiplodia theobromae* stalk and fruit rot, *Ceratocystis paradoxa* stem end rot, *Pyricularia grisea* pitting disease and *Verticillium dahliae* cigar end of fruit. Most of these diseases are only occasionally serious where infection levels are high and favourable conditions occur; none are as widespread as Crown Rot. Pitting disease, however, is a serious field problem in some areas in both bananas and plantains. It can also be serious on fruit after harvest due to the development of latent infections, which are not controlled by postharvest treatments (Meredith, 1963; Stover, 1972).

All postharvest disease organisms are widespread in the field, growing and sporulating on decaying banana or plantain flowers, bracts and leaves. The spores are blown by wind or splashed by rain on to the fruit and are also carried on bunches to contaminate packinghouse environments, including the washing water.

10.7.5 Viruses

Banana bunchy top virus (BBTV)-infected plants are stunted with pale yellow margins and a characteristic dot-dash pattern of dark-green flecks along the leaf veins. Leaves at the top are narrower, closer together and upright. Infected plants do not produce fruit: bunches either fail to form, or fail to emerge from the pseudostem depending on the time of infection. Transmission is by vegetative

propagation or aphids. Control is by using planting material from non-infected sites or propagating by tissue culture, locating new plantations away from old ones and removing infected plants. Aphid control has little effect.

Banana streak virus (BSV) is an endogenous pararetrovirus, which infects by releasing virions in interspecific hybrids. Symptoms include chlorotic streaks on leaves that become necrotic and sometimes also narrower and thicker. Plants may be stunted with a constriction of the bunch on emergence (choking) and detachment and splitting of the outer leaf sheaths of the pseudostem. It has a deleterious effect on the yield and could result in *pulpa crema*. Transmission is genetic in *Musa bulbisiana*.

10.8 Insect pests and their control

10.8.1 Thrips

Thrips attack the developing fruit, causing unsightly damage that may result in their being downgraded in export markets. Where thrips are a problem it is essential to protect the fruits as they emerge by covering bunches early with plastic 'sleeves' impregnated with a suitable insecticide. There are two main types of thrips that attack banana fruit: flower thrips (*Frankliniella parvula*) and rust thrips (*Chaetanaphothrips signipennis*).

10.8.2 Nematodes

Several species attack bananas but the most common is *Radopholus similis*. They invade the roots, feed and reproduce still inside the root. This causes cells within the roots to die and turn brown, which has the effect of damaging the roots so that plants fall over more easily in the wind and they reduce the amount of water and fertilizer the plant can take up. Nematodes enter the roots and establish feeding sites. They then lay eggs that remain near the adults and hatch in 12 to 14 days, usually migrating to new feeding areas by swimming through the soil water. The usual method of control is to treat the soil with a nematicide often up to twice a year.

10.8.3 Borers

The banana borer/weevil (*Cosmopolites sordidus*) is an insect up to about 12 mm long that feeds on the corm, weakens the plant and increases the chance of it breaking at ground level and falling over in the wind. The damage also allows fungi to enter the tunnels causing rotting of the corm, and reduces yield. The adult hides in banana trash or in the plant during the day and crawls out at night and lays eggs singly in holes made at ground level at the base of the plant. The eggs hatch into larvae, which tunnel into the corm. To control the borer, at planting ensure all planting material is free from borer and pare around the corm to remove all tunnels and signs of borer and any trash or dead leaves from the planting material. After

trimming spray the planting material and the area to be planted with an appropriate insecticide.

10.9 Postharvest handling practices

10.9.1 Harvest operations

Harvesting practices vary between countries and size of operation. Field dehanding and manual transfer of hands to a packinghouse and overhead cableways for transporting bunches to the packinghouse are two methods.

Field dehanding starts with placing two clean banana leaves flat on the ground with their mid-ribs facing upwards. The pseudostem is partly cut so the bunch can be pulled down and each hand is cut off with a piece of stalk attached starting from the bottom of the bunch, working upwards, and the hands of fruit are placed on banana leaves (Fig. 10.1). Considerable skill is required in cutting the crowns evenly and selecting only the clusters that are suitable for the market. The hands are cut into clusters of four to eight fingers, the crowns are trimmed neatly and they are left for some ten minutes on the leaf to allow the latex to stop draining. Any cluster not reaching the required standard should be rejected.

The polyethylene film sleeves that were used to protect the bunches should be placed in at least a double layer at the bottom of a plastic packing tray as padding to protect the clusters from damage or alternatively pieces of banana leaves (Plate XVIII: see colour section between pages 244 and 245). The clusters are placed in the tray with the crown downwards, inter-laying each row with at least a double layer of polyethylene between each row of clusters. The clusters should not be

Fig. 10.1 Placing cut clusters on fresh cut banana leaves to drain the latex.

placed on top of each other in the tray. The tray full of clusters is then carried to the field packinghouse on the head of the worker.

The most successful method of minimizing damage during the movement of bananas or plantains from the point of harvesting to the packinghouses is by overhead cableways. The bunches are joined together in groups by 1.2 m-long spacing rods, which reduce damage to the fruit by preventing the swinging bunches from striking each other. The trains of bunches can be pulled to the packinghouse manually, by a small tractor or a donkey. Some plantations have used a suspended motor hanging on the cableway to haul the bunches, but this method is not common, possibly because there is heavy wear on the driving pulleys and the cable. The layout of the cableway is based on a regular shaped planting of bananas with a centrally located packing station. It involves a central primary cableway running the length of the plantation with secondary lateral branches serving the whole plot. These secondary branches are ideally spaced 100 m apart so that harvesters need carry the bunches no more than 50 m to hang them on the rolling hooks. Bunches are brought right to the dehanding site still suspended from the rolling hook on which they were placed when harvested.

This method has been applied for several decades in areas of large-scale banana production in Latin America and elsewhere. The cableway involves high capital investment to install and maintain, and its viability depends on the use of a high-yielding production system. For successful operation the cableway must be included in the original planning of the plantation, so that its layout can be coordinated with other features such as drainage ditches, irrigation, roads and packing station location. The topography of the land is important with a slope of less than 0.2%, especially for the lateral branches, where it will be difficult to restrain the train of rolling hooks for the bunches to be attached. The cableway remains in place for the life of the planting. A version of this type of cableway, including modifications to recover bananas from hillsides, was designed for use in the Windward Islands (Kemp and Matthews, 1977). The overhead cable is a single strand high tensile steel wire suspended about 2.25 m above ground from arches fabricated from galvanised pipe. The cableway serves as a runway for roller conveyor hooks, from which bunches of fruit are suspended. The rolling hooks carrying bunches from the field to packing station are made up into trains totalling up to 30 bunches (Fig. 10.2).

In Martinique and Guadeloupe bunches are placed on padded shelves in trailers that are parked alongside the plantation. When full the trailers are towed by a tractor to the packinghouse. In a study in Jamaica in 1971 bunches were stacked horizontally in lorries padded with banana leaves. It was found that almost all damage caused to the fruit occurred during the loading and unloading operations.

10.9.2 Packinghouse practices

Where cableways are used the hands are cut from the bunch while it is still suspended from the cable and placed directly into water to prevent latex staining. When dehanding, the crown should be evenly cut close to the main stem of the bunch leaving as much as possible of the crown attached to the hand, otherwise its

Fig. 10.2 Overhead cableway in a plantation in Ecuador.

Fig. 10.3 Delatexing tank in a packinghouse in Ecuador.

outer fingers may be detached during subsequent handling. The design of the knife or chisel used for dehanding varies considerably in different countries, but in all cases the tool must be very sharp to give a clean smooth cut in a single movement. As soon as the hands of fruit are removed from the bunch they are placed in the wash tank to remove dirt and the latex, which exudes from the cut surface of the crown (Fig. 10.3). There should be a flow of water through the tank

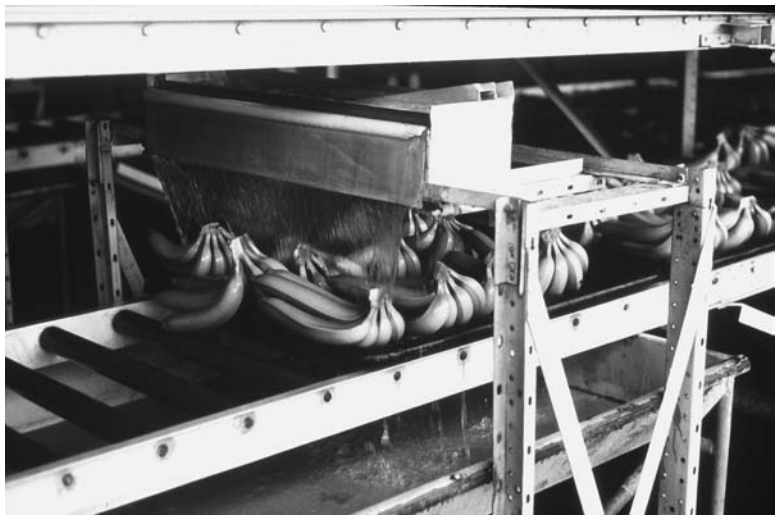

Fig. 10.4 Cascade fungicide applicator in a packinghouse in Ecuador.

to avoid the accumulation of dirt and fungal spores that may infect the crown. At the packing station, an inspector checks for: minimum finger length, calliper grade and different types of damage. Any cluster below standard is rejected. Fungicide is commonly applied in a cascade (Fig. 10.4). The crowns should be uppermost since they are the part most susceptible to attack.

Tanks containing alum (potassium aluminium sulphate at 10 g litre^{-1}) used for delatexing and tanks of fungicide may be used in field packinghouses and sometimes in large packinghouses where flowing water is not available.

In packing fruit for export, most exporters use polyethylene film liners inside the cartons to help reduce moisture loss from the bananas and provide some protection from damage during handling and transport. This procedure varies with different producers and the distance the bananas must be transported. Some fold sheets of polyethylene around the fruit; others pack all the box contents in a sealed bag under partial vacuum, and a few use individual small bags, each containing a single cluster of fruit. Vacuum packing is commonly used where the transport time is long because it can modify the carbon dioxide and oxygen levels around the fruit, which is said to extend their green life. The final handling of the bananas in the packing station involves packing the hands in the boxes in which they are to be marketed. Since the 1960s virtually all bananas exported outside their production region have been packed in fibreboard boxes holding a minimum weight of 18.14 kg each, although other sizes are used.

10.9.3 Local transport

For local transport in countries such as the Sudan and Eritrea banana bunches are packed in lorries padded with banana leaves and transported from the field to the

ripening rooms. In various studies by the author it was found that they had extremely high levels of damage, but since the price was the same whether they were damaged or not very little effort had been made to improve the system. In the Sudan packing the bananas in plastic boxes for transport greatly reduced these losses (Silvis and Thompson, 1974). In Ghana plantains are transported to the market in a similar way and the damage does not seem to matter since even fruit that are crushed almost to a pulp still find a ready market at similar prices to fruit with little damage. In Colombia plantains are usually cut into fingers and stacked in the back of lorries padded with plantain leaves for transport to the market.

10.9.4 International transport

History

The first commercial export shipment of bananas was from Jamaica and was reported to be 500 'stems' to Boston in 1866 which took 14 days, and the fruit were said to have been sold at a profit (Sealy *et al.*, 1984). There was no indication of temperature control during this or subsequent shipments in the latter part of the nineteenth century. In 1879 steam ships as well as schooners were used to transport bananas from the Caribbean Islands and Central America to the USA. In 1901 the vessel Port Morant carried 23,000 'stems' of bananas from Jamaica to Britain using mechanical refrigerated holds for the company Elder and Fyffes (Sinclair, 1988).

Reefer ships

Ships with refrigerated holds are used to transport almost all bananas that enter international trade. 'Break bulk' refers to a system of transport where individual boxes or pallets of produce are stacked directly in the hold of the ship. Almost all shipments are now palletized before shipping and maintained on the pallets throughout the marketing chain; in some cases this is right up to the retail outlet. Palletization reduces handling and therefore labour costs and damage to produce. The standard international pallet is 1000 mm × 1200 mm, on which produce is commonly stacked to some 2100 mm high. The holds of ships are commonly 2200 mm high and reefer containers are the same or higher so that pallet loads can fit in with an adequate clearance to allow for air circulation.

Reefer containers

Refrigerated containers are stacked on specially designed ships and are more expensive than break bulk and can only be used economically where the trade is subsidized, as in Martinique and Guadeloupe through the EU Common Agricultural Policy, or where a higher price is obtained for the fruit as in Ghana through the Fair Trade Organization.

Air freight

This is even more expensive. It is used in Thailand to export Gros Michel, which have started ripening in the field, to a lucrative specialized market in Japan. Some

very small quantities of Matoke are air freighted from Uganda to UK for the ethnic market.

10.10 Processing

The high standards imposed on the appearance of fresh bananas by importing countries results in a high proportion of the fruit being judged not to be of export quality, which has resulted in a surplus of fruit in producer countries. Thompson (1995) reviewed the various processed products from bananas, which included flour, starch, powder, puree, alcohol, juice, jams, crisps and dehydrated fruit and gave details of processing methods. A couple of the more important examples are given below.

10.10.1 Purée

Several large factories have been set up to produce banana purée. The method used for processing at a factory in Ecuador was that bananas were ripened to colour stage six. The hands were cut into individual fingers from which the two extreme ends were cut off; then they were spray washed and loaded into peeling machines. Considerable problems were encountered with these machines, and it was concluded that manual peeling was more appropriate. The peeled fruit were fed into a hopper and pump, through a homogenizer and duplex filter and into a vacuum de-aerator. The puree was then pumped through a series of votators (scrape heat exchangers) where it was flash pasteurised to a Fo value of 4 (71.5 to 74°C for 15 to 30 seconds) and immediately cooled. It was then fed into fibreboard cartons each lined with a laminated plastic bag with a capacity of 57 litres. Filling and sealing of the bags was done in aseptic conditions under a high-pressure steam. Banana purée is used for baking, dairy, beverages and baby food products. It has a shelf life of 18 months after the date of manufacture when stored at 15°C or for 12 months at room temperature but it must be used immediately after the bag is opened. Several manufacturers now make this product and market it in sizes from 20 to 26 kg for bag-in-a-box to 220 to 230 kg for bag-in-a-drum.

10.10.2 Crisps

On a commercial scale the production of crisps (or chips as they are called in the USA) uses green unripe bananas or plantains. They are peeled and cut into slices 0.8 to 1.2 mm thick. The slices need to have a smooth surface with minimum cell fracture or maceration and to be of an even thickness. They are then washed under pressure to remove surface starch and separate the slices and then they are dried by blowing compressed air over them to remove surface moisture and thus reduce the frying time (Fig. 10.5). Frying is either on a batch or continuous basis (Fig. 10.6) using soybean, maize, groundnut, palm oil or cotton seed oil whichever is the cheapest. Input temperatures are 177 to 190°C and at the finishing

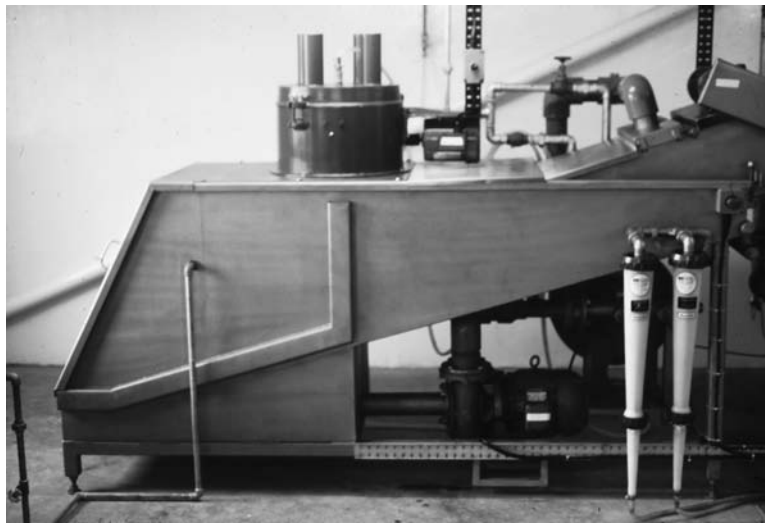

Fig. 10.5 Slicer and washer used for the production of banana crisps in Ecuador.

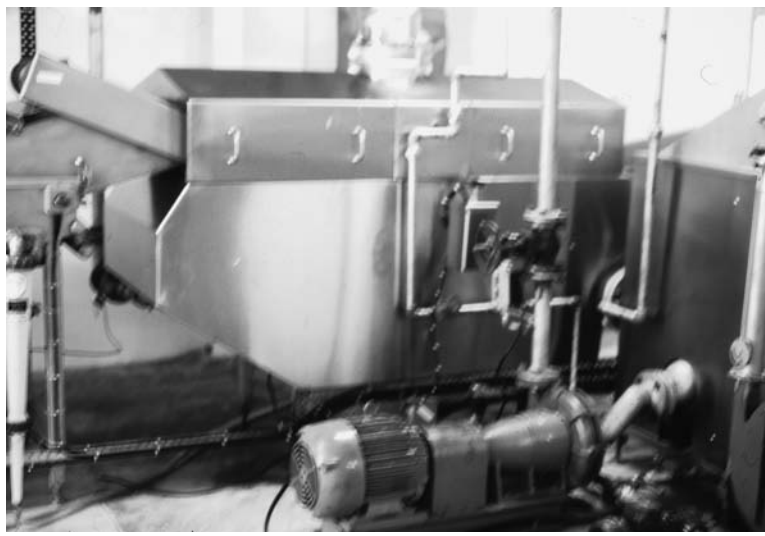

Fig. 10.6 Small continuous fryer used for the production of banana crisps in a banana plantation in Ecuador.

end 160 to 174°C. Time/temperature exposure of the slices to the oil is judged at the factory, but the frying time is usually a few minutes. Crisps must be packed in moisture proof bags to prevent them taking up moisture and losing their crispness usually in an atmosphere of 100% nitrogen to prevent rancidity.

10.11 Conclusions

The importance of bananas in the human diet and its importance in the economies of many countries have resulted in cutting-edge technology development. Production and postharvest technologies have been developed and applied that give high and consistent yields of good quality fruit. With the challenges of diseases, exacerbated with bananas being produced as a monocrop on the same land for decades, work needs to be done on breeding cultivars that are resistant to pests and diseases. The market is conservative and there is little scope to vary the flavour and appearance. The main challenges are therefore to produce a cultivar that is resistant to diseases, especially Sigatoka and Crown Rot, and pests, especially nematodes, which have a good flavour and texture and an adequate postharvest life. Extending the use of controlled atmosphere and modified atmosphere packaging to address postharvest disease and physiological changes need to be developed to replace or reduce chemical use. The chemicals and technology currently used in production and postharvest have some deleterious effects, which can affect the environment and climate. This represents a challenge to sustaining current production.

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Plate XVII Underpeel discolouration four days after ripening initiation with ethylene Photo: Allen Hilton.

Plate XVIII Clusters of bananas dehanded and placed in plastic trays in the field in preparation to be carried to a field packinghouse in the Windward Islands.

11

Black sapote (*Diospyros digyna* Jacq.)

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Abstract: Black sapote (*Diospyros digyna* Jacq.) is a climacteric fruit, popular in Mexico, that is consumed fresh as well as in other processed forms. The fruit is greatly valued for its excellent organoleptic characteristics, but unfortunately not enough information is available on its postharvest physiology and handling. Therefore guidance on optimum conditions for handling is not available and needs to be developed. The fruit is very sensitive to chilling injury, and its very soft texture when ripe makes its handling and shipping somewhat difficult.

Key words: *Diospyros digyna*, black sapote, postharvest, ripening, nutrition, processing.

11.1 Introduction

Although is sometimes believed that black sapote (*Diospyros digyna*) belongs to the Sapotaceae family because of its common name, it actually comes from a different family, the Ebenaceae. It is a climacteric fruit (Yahia, 2004) and is widely accepted in regional markets due to its organoleptic characteristics. It has excellent potential for commercialization as an exotic fruit, yet in spite of this, information on its postharvest biology and physiology necessary to establish optimum storage and transport conditions is limited.

11.1.1 Origin, botany, morphology and structure

Black sapote is native to the coasts of Mexico and Central America, where it is usually found as a cultivated crop. It is also known in Spanish as *sapote, sapote negro, matasano de mico, sapote de mico*, or *ebano*, while in Hawaii people know it as black persimmon. The black sapote tree is an evergreen that reaches a height of up to 25 m. Fruit are bright green and shiny when young (Plate XIXa: see colour section between pages 244 and 245), nearly round with a diameter of 5 to

12.5 cm and present a pronounced four-lobed, undulate calyx. When ripe, the fruit's skin becomes olive-green and then muddy-green (Plate XIXb: see colour section between pages 244 and 245). The pulp is glossy, brown to very dark brown or black, with a jelly-like consistency and sweet and mild flavor. Although the fruits are mostly seedless, sometimes up to 10 to 14 seeds can be found (Morton, 1987).

11.1.2 Worldwide importance

Black sapotes are found in tropical and subtropical areas of Mexico with the states of Tabasco, Guerrero, Chiapas and Puebla being the main areas of production. In 2001, production of black sapote in Mexico reached more than 700 tons with a total value of 1.35 million pesos (SAGARPA, 2001).

11.1.3 Culinary uses, nutritional value and health benefits

Black sapote pulp can be eaten fresh, served as a dessert accompanied with milk, made into ice cream, or mixed with orange juice, liquor, or wine and served as a dessert. It is also made into liquor in Central America. Some of the medicinal benefits attributed to black sapote include the decoction made with the leaves, which is used as an astringent and febrifuge. Other preparations from black sapote are used to treat skin rash and leprosy (Morton, 1987). The nutritional composition of black sapote is presented in Table 11.1.

It contains mainly carbohydrates and minerals and is an important source of ascorbic acid, calcium and phosphorus (Miller *et al.*, 1997). Although Morton (1987) reported an ascorbic acid concentration of 191.7 mg $100g^{-1}$, recent analysis

Table 11.1 Nutrient composition of black sapote (100 g of fresh fruit)

Constituent	Approximate value
Water content	79.46–83.1%
Protein	0.62–0.69 g
Carbohydrates	12.85–15.11 g
Fat	0.01 g
Ash	0.37–0.6 g
Calcium	22.0 mg
Phosphorus	23.0 mg
Iron	0.36 mg
Total carotenoids	399.4 μg
β-carotene	64.7 μg
Riboflavin	0.03 mg
Niacin	0.20 mg
Ascorbic acid	24 mg
Vitamin E	2064 μg
Total soluble phenols	247 mg

Source: Morton (1987), Corral-Aguayo *et al.* (2008).

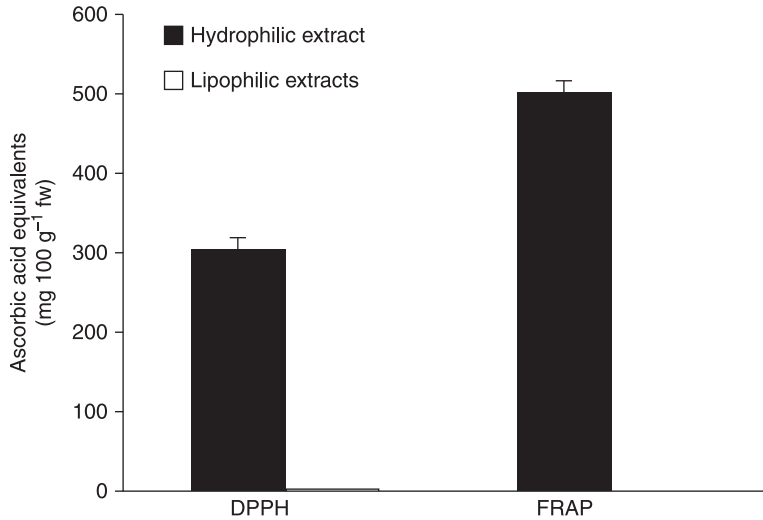

Fig. 11.1 Antioxidant capacity of hydrophilic and lipophilic extracts of black sapote measured by DPPH and FRAP assays. Source: Yahia et al., 2010.

by HPLC reported 24.1 mg per 100 g fruit (Corral-Aguayo *et al.*, 2008). Vitamin E content in black sapote (2,064 μg 100 g^{-1} fw) is higher than that of other tropical fruits such as strawberries and mango, and was found to be mainly in the form of α-tocopherol (Corral-Aguayo *et al.*, 2008). The content of total phenols in black sapote has been reported as 247 mg equivalents of gallic acid per 100 g fresh weight (Corral-Aguayo *et al.*, 2008). HPLC-DAD-Mass Spectrometry (HPLC-MS) analyses revealed major phenolics are sinapic acid, myricetin, ferulic acid, and catechin (110.7, 85.0, 81.9, and 79.941 mg 100 g^{-1} dw, respectively) (Yahia *et al.*, 2010).

The antioxidant capacity (AOC) of black sapote hydrophilic (HPE) and lipophilic (LPE) extracts has been evaluated using the DPPH (2,2′-diphenyl-1-picrylhydrazyl) and FRAP (ferric ion reducing antioxidant power) assays. AOC of the HPE was much higher than that of the LPE using the two assays (HPE: 302.734, LPE: 2.180 mg AAE 100 g^{-1} fw by DPPH; and HPE: 501.478 mg ascorbic acid equivalents (AAE) 100 g^{-1} fw, while AOC was not detected in the LPE by FRAP) (Fig. 11.1) (Corral-Aguayo *et al.*, 2008; Yahia *et al.*, 2010).

11.2 Fruit development and postharvest physiology

11.2.1 Fruit growth, development and maturation

Fruit takes about four months from anthesis to maturity. The firmness of black sapotes decreases during ripening with a more pronounced decrease three days

after harvest, which corresponds to an elevation of ethylene synthesis (Arellano-Gómez *et al.*, 2005). After the same period of time, total phenolics presented a reduction of more than 80%, while the activity of polyphenol oxidase increased significantly. Total carotenoids were lower at the end of ripening as well as ascorbic acid, which presented a reduction of about 62%. This decrease in ascorbic acid and the increase in polyphenol oxidase activity could explain the darkening of the pulp during ripening (Arellano-Gómez *et al.*, 2005).

11.2.2 Respiration, ethylene production and ripening

Black sapotes are climacteric fruits (Yahia, 2004). The maximum production of CO_2 was reported by Arellano-Gomez *et al.* (2005) on day six after harvest (about 367.3 mL $kg^{-1}h^{-1}$), and that of ethylene is reached on day five (480 μL kg^{-1} h^{-1}). Due to this respiratory behavior, this fruit is considered to be highly perishable. The total soluble solids content in fully mature fruit is in the range of 17.9 to 21.5°Brix, while their water content is 77.5% (Corral-Aguayo *et al.*, 2008).

11.3 Maturity and quality components and indices

The unripe fruit of the black sapote has a golden yellow colored pulp [skin? – see comment] that turns brown-black when ripe (Ledesma and Campbell, 2001). The external and internal color of fully ripe black sapote fruit has been characterized and is presented in Table 11.2.

The color paramenters of black sapote pulp correspond to a dark brown color (Corral-Aguayo *et al.*, 2008). Fruits should be harvested when fully mature but still unripe, or when they present a bright green color. When harvested at this stage, they become ripe in about ten days if kept at room temperature. Fruits harvested later, when they are olive-green, will ripen in two to six days. Fully ripe black sapotes (Plate XX: see colour section between pages 244 and 245) are very soft and they can be kept in the cold for only a very few days, but their handling becomes difficult due to their excessive softness (Morton, 1987; Yahia, 2004).

Table 11.2 Color characteristics of fully ripe fruit of black sapote

Parameter	Skin	Pulp
L	41.2	22.6
a	4.5	16.5
b	6.2	2.9
Chroma	7.8	16.8
Hue	53.1	10.2

Source: Adapted from Corral-Aguayo *et al.* (2008).

11.4 Postharvest handling factors affecting quality

11.4.1 Temperature management

Black sapote fruit held at 15, 20 or 25°C for up to seven, ten, or 15 days and then transferred to 25°C ripened normally (Yahia, 2004). The same was observed when the fruit were kept at 10°C for seven days and then transferred to 25°C. However, some fruit held at 10°C for ten or 15 days had abnormal ripening, and most fruit stored at 1 or 5°C did not ripen normally or failed to ripen regardless of the storage duration (Miller *et al.*, 1997; Yahia, 2004).

11.4.2 Physical damage

Fully ripe fruits of black sapote are extremely soft (Plate XIXb: see colour section between pages 244 and 245), and therefore very prone to physical damage.

11.5 Physiological disorders

Black sapote is chilling sensitive (Yahia, 2004). Some of the fruit held at 10°C for ten or 15 days showed abnormal ripening, and most fruit stored at 1 or 5°C did not ripen normally or failed to ripen regardless of storage duration (Yahia, 2004).

11.6 Pathological disorders

Janick and Paull (2008) indicated that black sapote is not commonly affected seriously by diseases.

11.7 Insect pests and their control

Although no important pests are reported in black sapote, it is a fruit fly host (Janick and Paull, 2008).

11.8 Postharvest handling practices

11.8.1 Harvest operations

The harvest season of black sapote in Mexico is from August to January. A cutting pole with a cloth bag attached is used to harvest the fruits when they are mature green or olive green (Morton, 1987).

11.8.2 Control of ripening and senescence

Black sapote will tolerate irradiation at 0.15 kGy, but abnormal ripening will likely occur in fruit treated at 0.3 kGy (Miller *et al.*, 1997; Yahia, 2004).

11.8.3 Recommended storage and shipping conditions

Storage of black sapote fruits at 13 to 15°C and 85 to 90 percent RH will extend their shelf life for up to two to three weeks (McGregor, 1989; Yahia, 2004). Modified and controlled atmospheres are not practiced, but they could help (especially modified atmosphere packaging) in extending the storage and shipping life (Yahia, 1998; 2008).

11.9 Processing

Black sapote is mainly eaten fresh, but also processed into several products. The fruit is peeled and the pulp is placed in bottles or frozen, and also used to make ice cream (SDR, 2010). The fresh pulp of black sapote is used to prepare puddings, cakes and mousse.

11.10 Conclusions

Black sapote presents a climacteric behavior and its postharvest handling is difficult, especially due to the lack of adequate information. This fruit has potential for commercialization as exotic fruit due to its excellent organoleptic properties and multiple uses, especially processed. However, very limited information exists on their postharvest biochemistry, physiology and handling and thus it is difficult to establish the optimum conditions for storage and transport to extend their shelf life. The fruit needs to be harvested and transported while still unripe because once it reaches full ripeness, it becomes soft and handling becomes unsuitable. It is consumed fresh and made into preserves and several other processed products, which gives an added value and would facilitate its commercialization.

11.11 References

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(a)

(b)

Plate XIX (a) Black sapote fruit on the tree; (b) Black sapote fruit at different stages.

Plate XX Overripe black sapote fruit as it is mostly marketed in Mexico.

12

Breadfruit (*Artocarpus altilis* [Parkinson] Fosberg)

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Abstract: Breadfruit (*Artocarpus altilis* [Park.] Fosb.) is a starchy staple, which has been domesticated over millennia in the Pacific Basin, where some 130 cultivars are recognised today. This starchy fruit is unusual in that it is typically eaten at the mature, unripe stage, usually after it is cooked. The commodity is a climacteric fruit with a high respiratory rate but a relatively low rate of ethylene production, even though it is quite sensitive to ethylene. After harvest the bright green skin of the fruit undergoes browning especially under refrigerated conditions. Film wrapping as well as waxing of the fruit helps retard this deleterious process. The fruit suffers chilling injury if stored below 12°C and is best stored at 13 to 16°C, ideally film-wrapped. Controlled atmosphere storage of breadfruit at high humidity and 16°C in an atmosphere of 5% O_2 and 5% CO_2 has been shown to delay ripening and skin browning dramatically.

Key words: Breadfruit, *Artocarpus altilis*, postharvest, maturity, ripening.

12.1 Introduction

12.1.1 Origin, botany, morphology and structure

The genus *Artocarpus* of the family Moraceae comprises almost sixty species native to India, South East Asia and Australasia (Zerega *et al*., 2004). Only three species are of widespread commercial importance, namely the breadfruit (*A. altilis* [Parkinson] Fosberg), the breadnut (*A. camansi* Blanco) and the jackfruit (*A. heterophyllus* Lamarck). The latter two are treated in individual chapters in this book although previously the breadnut was viewed as a seeded form of the breadfruit within a broader species concept of *A. altilis*. It should also be noted that in Africa the name breadfruit is also applied to another member of the Moraceae, *Treculia africana* Descaine ex Trécul, a distinct species altogether.

Breadfruit was domesticated over millennia in the Pacific Basin where over one hundred documented cultivars persist to this day. In that wider definition of breadfruit, molecular data suggest the crop is a monophyletic complex of three species (Zerega *et al*., 2005). The first of these, *A. camansi*, produces large, seed-filled fruit and is probably indigenous to New Guinea, while the second, *A. mariannensis*, is native to a geographically distinct group of islands of western Micronesia and bears smaller fruit containing both seeds and starchy pulp. Both of these are diploid ($2n = 2x = 56$). The last of this trio is *A. altilis*, which comprises cultivars bearing seedless as well as few-seeded fruit. This species seems to be derived from *A. camansi* but can hybridise with *A. mariannensis* and evolved over the last four thousand years with human migrations across Micronesia and into the remote eastern atolls of Polynesia (Zerega *et al*., 2004). While seeded forms of *A. altilis* are known and are exploited in Oceania, it is the restricted range of vegetatively propagated, triploid, seedless cultivars, that are the familiar breadfruit cultivated worldwide today. This review will focus on this widespread breadfruit of commerce.

Breadfruit is an evergreen tree up to 30 m high with alternate, 12 to 60 cm long leaves, typically pinnately lobed, although leaves of some Pacific cultivars are almost entire (Zerega *et al*., 2005). Trees bear separate male and female inflorescences. Male inflorescences are club-shaped and 10 to 30 cm long but pollen of the typically cultivated seedless form tends to show poor staining and viability and, not surprisingly, fruit develop without pollination (Hasan and Razak, 1992). The syncarpous fruit develops from the perianth parts of the many flowers of a single globular female inflorescence, fusing and becoming fleshy to form this edible, starchy fruit. There is great variety in the shape of the fruit (Plate XXI: see colour section between pages 244 and 245), the fruit skin topography and leaf dissection (Ragone and Wiseman, 2007). A web-based database of the National Tropical Botanical Garden, Hawaii, provides a useful tool to compare known cultivars of breadfruit (National Tropical Botanical Garden, 2009).

12.1.2 Worldwide importance

Breadfruit has been exploited as a food crop for more than 3000 years in Oceania where the greatest diversity resides (Ragone and Caveletto, 2006). While over 130 cultivars are recognized in the Pacific, ten or fewer cultivars were successfully introduced to the Caribbean and Mauritius in the late eighteenth century, essentially seedless, sterile cultivars as well as the breadnut (Ragone and Caveletto, 2006). From the latter an even more restricted number of cultivars have been spread around the tropics, often distinguished simply as white-fleshed ('white heart') and yellow-fleshed ('yellow heart') forms. Despite this worldwide spread, the Pacific and Caribbean remain the main producing regions.

A breadfruit tree can bear over 300 fruit per year but production is largely from scattered, backyard trees and pure stand production is small-scale and unproven. With this production base it is not surprising that recent annual exports are limited to around 100 t for both Samoa (Tuivavalagi and Samuelu, 2007) and Fiji (Stice

et al., 2007) and just over 1000 t for the entire Anglophone Caribbean (Roberts-Nkrumah, 2007). Despite current food security concerns and an acknowledgement that breadfruit can provide staple food with minimal inputs, the crop is underexploited and relegated to a backyard tree. Furthermore, lifestyle changes have seen the younger generation in the Pacific rejecting breadfruit in favour of other staples like rice (Taylor and Tuia, 2007), a similar trend seen in the Caribbean. Ironically, the fact that breadfruit thrives with next to no care seems to add to its perceived low value in the Caribbean, despite the environmentally friendly nature of its production (Roberts-Nkrumah, 2007).

12.1.3 Culinary uses

While unripe breadfruit is eaten cooked, either baked, roasted, fried or boiled, there are other modes of preparation, especially in Oceania with its wide diversity of breadfruit, which are specific to particular cultures and unlikely to become widespread. As examples, in times of plenty, for consumption later, Polynesians fermented breadfruit in leaf-lined pits while Melanesians developed a drying technique whereby fruit portions were dried over an oven pit to a biscuit-like hardness (Taylor and Tuia, 2007).

In the West Indies, breadfruit is used as a starch to complement meat or fish dishes. It can simply be served boiled, roasted or fried like potato but it also is a major component of several iconic Caribbean dishes like pickled breadfruit, the one-pot 'Oil-Down', and slurry-like breadfruit 'coucou'. In this category, breadfruit roasted in an open fire is probably one of the most casual, traditional modes of preparation. In Sri Lanka, cubes of breadfruit are cooked with coconut milk and eaten as a curry (Medagoda, 2007) while Filipinos enjoy the cooked fruit with coconut and sugar. In Hawaii, under-ripe fruits are diced, boiled and made into a chowder, while in the Bahamas, boiled under-ripe chunks of breadfruit are made into a soup (Morton, 1987: 56).

12.2 Fruit development and postharvest physiology

12.2.1 Fruit growth and development

Flowering and fruiting vary with cultivar but the widespread seedless cultivars typically fruit twice yearly in the Caribbean (Roberts-Nkrumah, 2007) and four times per year in Ghana (Gamedoagbao and Bennett-Lartey, 2007). In a study of a white-fleshed, seedless cultivar (probably equivalent to the Tahitian *Rare*), Worrell *et al*. (1998) found that fruit typically reached a maximum size 14 to 16 weeks after first detectable, growing in a single sigmoidal fashion up to about 20 cm in diameter. However, when monitoring dry and fresh weight they noted a biphasic growth pattern with a 'rest' period halfway through development. The first phase is associated with size generation and the second stage is the period of major dry weight increase, largely through starch accumulation. Mature fruit typically weigh about 1 kg but can be up to 2 kg, depending on the cultivar.

12.2.2 Respiration, ethylene production and ripening

Breadfruit was first characterised as a climacteric fruit by Biale and Barcus (1970). The fruit shows the typical climacteric rise in carbon dioxide (CO_2) production, which coincides with peak ethylene (C_2H_4) generation. Worrell *et al*. (1998) showed CO_2 production to be in the high range (200 to 300 mL kg^{-1} h^{-1}) while C_2H_4 production was relatively low (max. 1.6 μL kg^{-1} h^{-1}). They also showed that in less mature fruit the climacteric was delayed by two to three days and maximum CO_2 and C_2H_4 production were almost twice that measured for fully mature fruit. In each case, these climacteric peaks coincided with softening of the fruit. Despite the fruit's relatively low rates of C_2H_4 emission it is, nonetheless, quite sensitive to C_2H_4, a five minute dip in 500 ppm Ethephon being sufficient to hasten the onset of the climacteric and accelerate ripening (Paull, 2009).

12.2.3 Browning reactions and control

Prior to harvest, breadfruit show no sign of browning, however, upon harvesting and storage under ambient or refrigerated conditions, skin browning develops. Brown fruits lose their aesthetic appeal to customers so this is an important problem to address.

Skin browning is accelerated by low temperature storage and occurs before the onset of ripening. It is believed that browning occurs when polyphenol oxidase (PPO) catalyses the oxidation of soluble, colourless phenolic compounds to highly coloured polymeric phenolics (Kader and Barrett, 2005). Conceivably, this browning response occurs in epidermal cells when these undergo water loss or other forms of cell damage bringing PPO into contact with soluble phenolics (Worrell and Carrington, 1997). Submersion of breadfruit in water, a traditional short-term storage measure, maintains bright green skin colour as does fruit waxing and film-wrapping, all of which reduce water loss. Fruit stored in water at 13°C showed little browning, unlike fruit in air at 13°C (Worrell, 1994), indicating it is not a form of chilling injury but triggered by water loss. Both Samsoondar *et al*. (2000) and Maharaj and Sankat (2004) reported on reduced external browning of breadfruit at 16°C when fruits were shrink-wrapped with 15-μm polyethylene film. Browning was also dramatically retarded in CA storage of 5% O_2 and 5% CO_2 for up to 25 days when compared to untreated or shrink-wrapped fruit (Maharaj and Sankat, 2004).

12.3 Maturity and quality components and indices

12.3.1 Maturity indices

Breadfruit is typically consumed at a mature, firm but unripe stage. However, certain modes of preparation will require differing degrees of maturity; fruit for boiling are typically at a less mature stage than fruit for baking or roasting (Worrell and Carrington, 1997). Furthermore, it has been shown that smaller, less mature fruit have a longer postharvest life than larger, more mature fruit (Marriott *et al.*,

1979). This can be attributed to a delayed onset of the climacteric in early mature fruit (Worrell *et al.*, 1998).

Breadfruit attain full size 13 to 21 weeks after first detectable, with fruit typically reaching their maximum size at an age of 14 to 16 weeks (Worrell *et al.*, 1998). Full size is one measure of maturity but this varies considerably. There is a slight paling of the skin but this is too subtle to be reliable. More reliable is the flattening of the polygonal skin segments and the decreased prominence of the spike at the centre of each, rendering the skin smoother to the touch. Usually at this stage small droplets of latex are spontaneously exuded onto the skin surface. This combination of full size, skin smoothness and surface latex signal maturity and correlated well with taste test results, which identified fruit 15 to 19 weeks old as being most acceptable. In contrast, neither fruit density nor measurements of induced latex flow by pricking fruit or their peduncles showed any useful correlation (Worrell *et al.*, 1998). These maturity indices cannot be applied to all cultivars: for example, the maturity of hybrid cultivars is more difficult to discern as there is usually no dried surface latex and very slight separation between the skin segments (Ragone and Caveletto, 2006). In Sri Lanka, it is claimed that if the fruit emits a dull, hollow sound when tapped with a finger this is a good indicator of the mature, unripe stage (Medagoda, 2007).

12.3.2 Chemical composition

The mature fruit has a water content of 65 to 74% and starch levels of around 20% of fresh weight or about 60% of dry solids (Worrell *et al.*, 1998; Huang *et al.*, 2000). A range of sugars is found in the mature fruit with sucrose, glucose, galactose and arabinose predominating but at very low concentrations, representing mg amounts per 100 g fresh weight (Golden and Williams, 2001). The fruit emits a subtle but complex mixture of volatiles. Alcohols predominate in these volatiles with *cis*-3-hexenol responsible for the strong green note of fresh fruit while esters are the main volatiles of the cooked fruit (Iwaoka *et al.*, 1994).

In a survey of fourteen staples, breadfruit had the highest level of dietary fibre, 4.9 g per 100 g edible portion (Bahado-Singh *et al.*, 2006), suggesting that a 500 g portion of breadfruit can supply the current recommended human daily intake of fibre (Ragone and Caveletto, 2006). Nutritionally, it compares favourably with other tropical staples especially with respect to calcium, iron, magnesium, potassium, niacin and thiamine; potassium levels are ten-times that found in white rice (Ragone and Caveletto, 2006). It also contains all the essential amino acids with relatively large amounts of leucine and lysine and, atypical of plants, mainly saturated free fatty acids (Golden and Williams, 2001). Its one drawback nutritionally is its relatively low protein level (Bahado-Singh *et al.*, 2006) although this can apparently be improved by fertilizer treatment (Tumaalii, 1983, cited in Tuivavalagi and Samuelu, 2007). While one study has claimed that boiled breadfruit has a lower glycaemic index than many other starchy staples including yam and dasheen (Bahado-Singh *et al.*, 2006) another failed to find such marked differences (Ramdath *et al.*, 2004).

In terms of nutraceuticals, the flesh of the fruit contains antifungal stilbenes and arylbenzofuran as well as sitosterol (Amarasinghe *et al.*, 2008). The latter is a phytosterol used as dietary supplement to reduce blood levels of cholesterol but its level in breadfruit is probably too low to have a physiological effect. Decoctions of the leaves of the breadfruit tree have a long tradition of medicinal usage (Mitchell and Ahmad, 2006) and further validation of this may bolster cultivation of the tree beyond that of a fruit crop. To date, breadfruit leaves have yielded prenyl flavanoids with potential use against osteoporosis (Patil *et al.*, 2002) as well as prostate (Shimizu *et al.*, 2000) and other human cancers (Wang *et al.*, 2007).

12.4 Preharvest factors affecting fruit quality

In Australasia, where bilateral quarantine agreements exist, there is usually a systems approach to quality management that allows traceability to individual growers. The Fiji–New Zealand agreement is the prime example of such an approach (Tirimaidoka *et al.*, 2007). Breadfruit growers are registered and agree to certain standards of field hygiene including scheduled application of protein bait spray for fruit fly control, tree pruning and the prompt removal of ripe fruit. Compliance is checked by site visits by extension officers (Tirimaidoka *et al.*, 2007). This ensures a common standard of production and then fruit are sorted for uniformity on receipt at the packinghouse. Uniformity of shape, size, and weight are important as quality factors, especially for export markets. Most important of all, for maximum storage life for the export trade, fruit should be at the early mature stage, i.e. full-sized, with the first signs of surface latex and without any skin yellowing (Worrell *et al.*, 1998).

12.5 Postharvest handling factors affecting quality

12.5.1 Physical damage

Harvested fruit should be free from decay, sunscald, cracks, bruises, and mechanical damage. It is recommended that harvesting be done early in the morning or late in the afternoon under cool conditions to avoid heat build-up in the fruit and 'sunburn' damage (Nauluvula, 2007). The method of harvest (section 12.9.1) is of prime importance in minimising physical damage. It has been shown that breadfruit hand-picked or caught has a significantly longer postharvest life than those that were simply dropped to the ground (Marriott *et al.*, 1979).

12.5.2 Temperature management

Breadfruit is a highly perishable commodity, softening and deteriorating rapidly under ambient tropical conditions, often within two to three days of harvest. Like other tropical fruits, the shelf life of breadfruit can be extended by refrigeration,

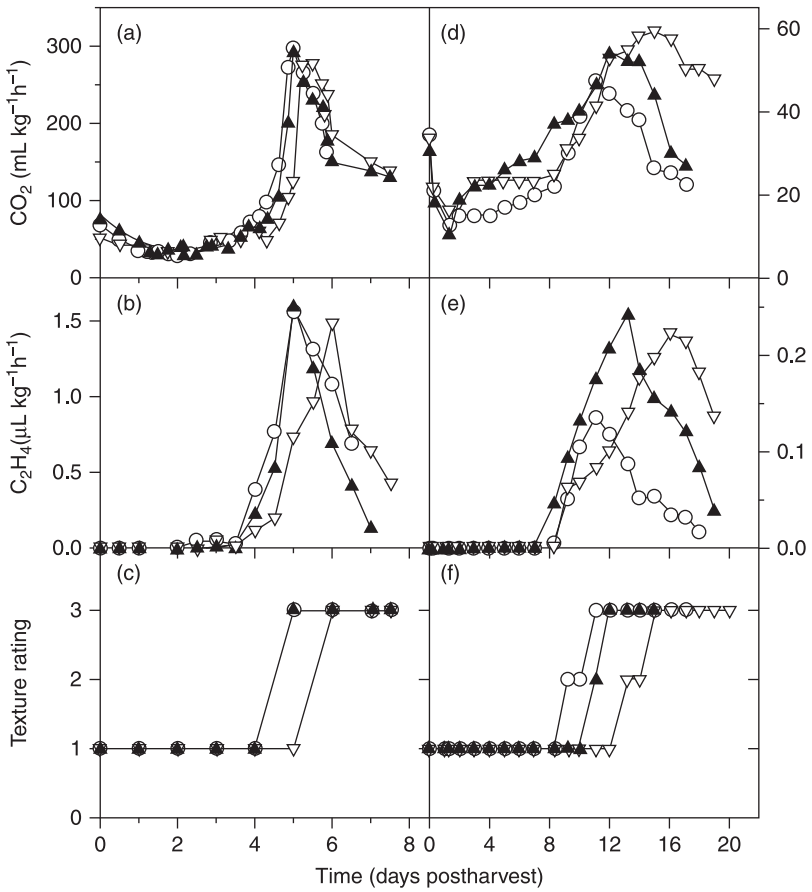

Fig. 12.1 Postharvest changes in respiration (a, b), ethylene production (c, d) and texture (e, f) in breadfruit stored at ambient temperature (a, c, e) or 13°C (b, d, f). Each symbol represents a single fruit. A texture rating of 1 represents a firm fruit and a rating of 3 a fully soft fruit. Source: Worrell and Carrington, 1997.

12 to 13°C being optimal (Thompson *et al.*, 1974; Maharaj and Sankat, 1990; Worrell *et al.*, 2002). The lower storage temperature slows down metabolism and more importantly delays the climacteric by at least a week (Fig. 12.1). Below 12°C breadfruit exhibits chilling injury, failing to ripen when returned to ambient temperature and displaying water-soaked tissue and internal browning discoloration. Off-flavour development and susceptibility to decay are also symptoms of chilling injury. Rapid pre-cooling to the optimal storage temperature can further enhance shelf life but must commence in the field to be effective. Maharaj and Sankat (1990) reported benefits from pre-cooling freshly harvested breadfruit in chipped ice in the field but Worrell *et al.* (2002) found no extension of shelf life by hydro-cooling fruit in a 13°C water bath following their transport to the laboratory. While temperature

management is critical, refrigeration must be combined with maintenance of high humidity, as water loss can be extremely deleterious.

12.5.3 Water loss

Breadfruit at maturity, despite being a hard, dense, starch-filled fruit, still contains over 65% water by weight which is gradually lost in storage. Fresh weight of breadfruit stored at ambient tropical temperatures of 25 to 30°C can decline 25% in five days and 17% at 13°C, mainly due to water loss (Worrell *et al.*, 2002). Not surprisingly, a traditional storage method in the Caribbean is to submerge fruit in water although this can lead to fruit splitting and is a very short-term method (Thompson *et al.* 1974). Water loss affects the marketable weight of the commodity and adversely affects appearance leading to shrivelling and skin browning. Removal of field heat by pre-cooling also reduces water loss but thereafter it is important to maintain a high relative humidity. This can be achieved by applying treatments to the commodity such as waxes and other surface coatings or by wrapping with plastic film or otherwise manipulating the storage environment.

Worrell *et al.* (2002) in a comparison of four coatings (chitosan derivatives, a sucrose polyester and a fruit wax) found that all delayed ripening, reduced weight loss and retarded skin browning in breadfruit stored at ambient. Sta-Fresh MP©, a fruit wax, was most effective, especially at maintaining green skin colour, supporting previous work by Sankat and Maharaj (1993) which showed the efficacy of a paraffin wax at improving ambient shelf-life of breadfruit. These results contrast with early work by Thompson *et al.* (1974) who found no extension of ambient storage life of breadfruit coated with an oxidised polyethylene emulsion. It should also be noted that under refrigerated storage at 13°C, Worrell *et al.* (2002) found that coatings were not effective at retarding softening and did not help maintain green skin colour except in the case of the fruit wax. Such coated fruit also suffered from internal discoloration and off-flavours.

Early work by Thompson *et al.* (1974) showed that bagging breadfruit in 38 μm polyethylene bags markedly reduced water loss and extended storage life to seven days at ambient temperature and 12 days at 12.5°C. Maharaj and Sankat (1990) further confirmed that polyethylene films (25 μm) strongly reduced water loss in breadfruit, especially at 12 and 16°C, with fruit still acceptable after two weeks' storage. Worrell (1994) looked at the effect on harvested breadfruit of three gauges each of high-density and low-density polyethylene film as well as four other speciality films. At ambient temperature, all of these films drastically reduced water loss to 3 to 5% weight loss over three weeks compared to 20% weight loss after one week for unwrapped fruit. For fruit stored at 13°C, weight loss was 1 to 2% over three weeks versus 35% for unbagged fruit. Films also delayed the onset of ripening and skin browning (Plate XXII: see colour section between pages 244 and 245). At ambient, films delayed the start of softening and skin browning by one week, while fruit showed no softening at 13°C even after three weeks, and little skin discoloration. One major drawback of film wrapping was that the high internal humidity often encouraged fungal growth on the fruit surface by the second week of ambient storage

and by the third week of storage at 13°C. Internal flesh discoloration developed in some films and from this comparison, only the 40 μm high-density polyethylene film maintained acceptable internal flesh colour over three weeks of storage at 13°C. Taste tests on cooked flesh from these film-wrapped fruit found that none of the fruit stored at 13°C for three weeks was acceptable but, after one week's storage, fruit in all three low-density polyethylene films were closest to fresh fruit while, after two weeks at 13°C, fruit in 40- or 60-μm high-density polyethylene film was acceptable.

While one major effect of coatings and films is to reduce water loss from fruit, this is but one explanation for their role in extending postharvest life. Their second effect is to alter the concentration of physiologically important gases within the fruit during storage.

12.5.4 Atmospheric modification

Storage atmospheres with reduced oxygen (O_2) and/or elevated carbon dioxide (CO_2) levels supplement refrigeration and are known to extend the postharvest life of fruits and other commodities. Where specific concentrations of these and other gases are precisely maintained, e.g. in storage chambers, this is referred to as controlled atmosphere (CA) storage, whereas where these levels develop internally as a result of packaging or coating a commodity this is termed modified atmosphere (MA) storage (Kader, 1992).

The coating of breadfruit was found to lead to low internal O_2 concentrations of 8 to 16% and elevated CO_2 concentrations as high as 16% at ambient temperature (Worrell *et al.*, 2002). These altered internal gas levels may explain the effect of coatings to double the time for coated fruit to become fully soft relative to controls. At 13°C, the rise in internal O_2 concentration and the fall in internal CO_2 concentration was less than at ambient, reflecting the lower respiratory rate of the fruit at this temperature. Nonetheless, fruit softening at 13°C in uncoated and coated fruit is very similar despite stark differences in internal O_2 and CO_2 concentrations, suggesting this modified atmosphere is not the overriding factor influencing ripening here.

Internal gas composition of breadfruit was sampled in unbagged, control fruit stored at 13°C as well as fruit bagged in one of seven types of film (Worrell and Carrington, 1997). Control fruit began softening and browning rapidly compared to bagged fruit, in which such changes began in the third week of storage, if at all. In the bagged fruit, internal O_2 concentrations rapidly and consistently fell to less than 5% while unbagged fruit were relatively aerobic (18 to 20%). In contrast, internal CO_2 concentrations rose and saturated at quite different levels between 12% and 30%, depending on the film type. Film-wrapped fruit behaved similarly, showing virtually no softening during storage, correlating with the low, shared internal O_2 concentrations rather than the elevated and varying CO_2 concentrations. This suggests that low internal O_2 concentrations may be more important in breadfruit in delaying the onset of ripening.

Compared to MA storage, there has been less work done on CA storage of breadfruit. Ramlochan (1991) investigated the effect of a range of O_2 (2.5 to 5.0%) and CO_2 (2.5 to 10.0%) concentrations on breadfruit in storage chambers at high

relative humidity. By assessing skin colour, weight loss, texture and taste it was concluded that a combination of 2 to 5% O_2 and 5% CO_2 at 12°C were optimal for maintaining marketable fruit over 21 days. Maharaj and Sankat (2004) also reached similar conclusions storing 'Yellow heart' breadfruit at 16°C and high relative humidity. In this case, 5% O_2 and 5% CO_2 were viewed as optimal, based on maintenance of green skin colour, delay in the onset of softening and the rise of total soluble solids (TSS) and enhanced storage life up to 25 days (Fig. 12.2).

Breadfruit would be classified as a low ethylene-producer but is, nonetheless, quite sensitive to ethylene. A 6 h exposure of late mature breadfruit to 50 or 500 ppm accelerated softening while 5 ppm C_2H_4 had no effect (Worrell and Carrington, 1997). Interestingly, the synthetic ethylene antagonist 1-methylcyclopropene (1-MCP) alone did not extend postharvest life of breadfruit at 17°C, but when used

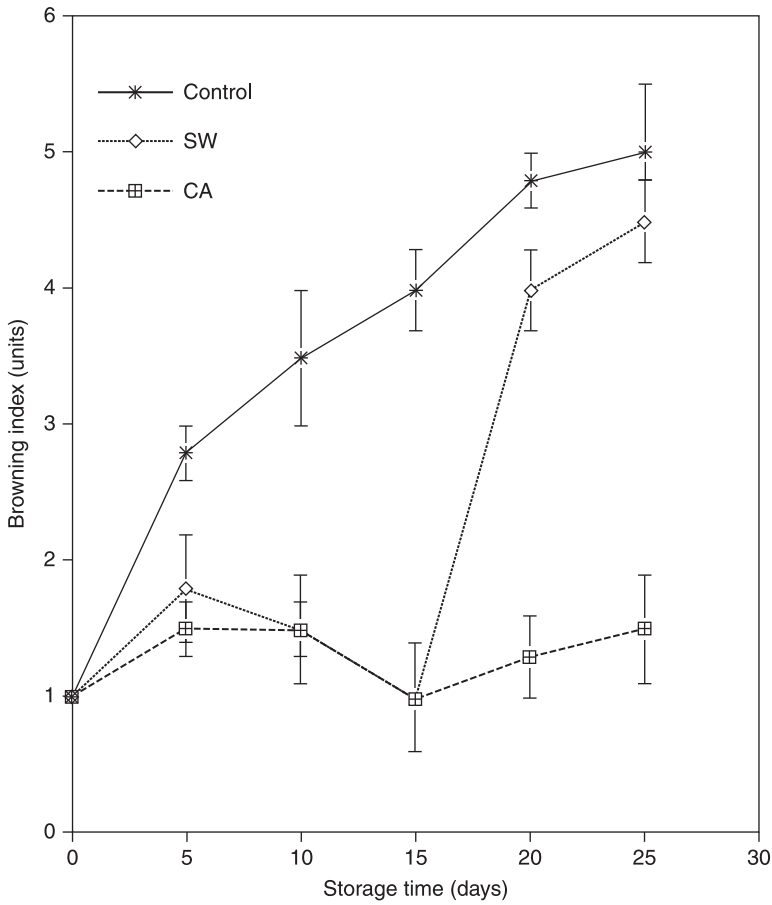

Fig. 12.2 Browning rating values (1 = no browning, 5 = greater than 75% browning) of control, shrink-wrapped (SW) and 5% O_2/5% CO_2 controlled atmosphere (CA) breadfruit, all stored at 16°C. Source: Maharaj, 1990.

in combination with perforated polyethylene wrapping this doubled the time to softening (Paull, 2007).

12.5.5 Microbial control

Microbial growth on the surface of stored breadfruit can usually be prevented by effective washing of the freshly harvested fruit. Dipping of fruit (two minutes) in 0.05% Benomyl solution has been used as a preventative measure (Maharaj and Sankat, 1990) but is not widely practised. Fungal contamination has been noted in bagged fruit after one week at ambient temperature or sometimes after two to three weeks at 13°C (Worrell, 1994). Bagged storage is therefore not used commercially at ambient temperature but can certainly be employed at 13°C as fungal contamination is not a consistent problem at this temperature and is prevalent with only some types of film. Fungal growth on coated fruit can be a problem but is restricted to carbohydrate-based coatings and is not seen with fruit waxes.

12.6 Physiological disorders

12.6.1 Temperature-related injury

Chilling injury occurs when commodities of tropical and subtropical origin are held at temperatures above their freezing points and below a particular critical temperature. Chilling injury is influenced by storage temperature and the duration or time at that temperature. This relationship can vary with the variety, preharvest conditions, stage of maturity and postharvest treatments (Shewfelt, 1986; Crisosto *et al.*, 2008). Below 12°C, chilling injury symptoms develop in breadfruit within seven days (Thompson *et al.* 1974; Marriott *et al.*, 1979). These symptoms are a brown, scald-like discolouration of the skin, pulp browning, failure to fully soften, poor flavour development and an increased susceptibility to decay (Paull and Chen, 2004). It should be noted that symptoms of chilling injury become evident shortly after fruit are removed to ambient temperature. Thompson *et al.* (1974) noted that when fruit were removed to ambient temperature after storage at low temperature (2.5 or 7°C), softening occurred in small circular areas over the surface of the fruit, increasing in number and size with time compared to fruit that were stored at higher temperatures, where softening was more uniform. Worrell *et al.* (2002) also reported similar results when fruit were transferred from 7°C to ambient storage. Such fruit did not ripen normally and exhibited water-soaked tissue and browning of the pulp, symptoms consistent with chilling injury.

12.7 Pathological disorders

In Fiji, the main breadfruit diseases are fungal, namely fruit rot (*Phytophthora palmivora*), leaf anthracnose (*Colletotrichum gloeosporoides*) and brown stem/root rot (*Phellinus noxius*) (Stice *et al.*, 2007). Brown stem rot can kill entire trees and

can be particularly dangerous in orchards. Planting trees at least 12 m apart is thought to help reduce the spread of this disease in such settings (Stice *et al.*, 2007). In hot and humid climates, Rhizopus rot, a soft rot of the fruit has been reported by Sangchote *et al.* (2003). Lesions develop as soft, watery brown spots and expand rapidly. The application of copper fungicides or dithiocarbonates to young fruit have reduced losses in breadfruit. On immature breadfruit, anthracnose may develop in association with injuries that are caused by insects. Lesions also develop on mature fruit. Small, round, dark brown spots develop on the rind and expand gradually coalescing to form larger lesions. Sprays such as mancozeb have been found to reduce the incidence and severity of anthracnose (Sangchote *et al.* 2003).

Breadfruit production in Jamaica has in the past suffered from Slow Decline Disease, which leads to death, especially of older trees. This appears to be caused by a root rot involving nematodes, mainly *Pratylenchus* spp., and has been successfully treated by solarisation of the soil just beyond the edge of the tree canopy (Coates-Beckford and Pereira, 1997).

Pathological disorders usually follow mechanical damage and/or chilling injury of breadfruit. Decay may be caused by *Phytophthora palmivora, Rhizopus artocarpi* or *Botryobasidium salmonicola*. Several fungi of varying pathogenicity have been isolated from harvested breadfruit stored at room temperature in polyethylene bags, viz. *Aspergillus flavus, A. niger, Botryodiplodia theobromae, Mycovellosiella fulva, Penicillium* sp. and *Rhizopus stolonifer* (Amusa *et al.*, 2002). However, storing bagged fruit at room temperature for extended periods, as in this study, is not a recommended commercial protocol and fungal contamination is not normally seen during refrigerated storage of one to two weeks except on carbohydrate-based coatings (Worrell *et al.*, 2002).

12.8 Insect pests and their control

The fruit flies *Bactrocera xanthodes* and *B. passifloae* are important pests in Fiji, damaging the flesh (Tirimaidoka *et al.*, 2007). As breadfruit is a fruit fly host, it requires quarantine treatment if it is to be exported fresh to New Zealand from Fiji and neighbouring areas of production. Key to this is high temperature forced air (HFTA) treatment. The fruit are slowly heated (typically 4.5 h) to 47.2°C and held at this temperature for 20 minutes to kill fruit fly eggs and larvae and then rapidly cooled to 15°C over 30 to 90 minutes (Stice *et al.*, 2007). Subsequent storage must also be under pest-proof conditions to prevent reinfestation (Tirimaidoka *et al.*, 2007). HFTA is not employed in the Caribbean, and the only insect problem is the development of dark brown sunken areas on the skin, referred to as 'bee sting' and believed to be caused by pre-harvest insect damage (Roberts-Nkrumah, 2007).

12.9 Postharvest handling practices

The traditional method of harvesting breadfruit consists of harvesters climbing the trees (typically about 20 m in height) and breaking the fruit stalk with a

forked stick so that the fruit will fall to the ground. Other devices used to harvest the fruits consist of a sharp scythe or curved knife attached to the end of a long, sturdy pole or a picking pole with a net. Just as fruit should not be injured while being detached from the tree using a picking pole, postharvest injury should be avoided at all costs. Fruit striking the ground should be rejected and falling fruit should ideally be caught by hand or individually in a stretched tarpaulin to cushion the impact of the fall. Bruising and premature softening will result if multiple fruit are allowed to accumulate in a taut tarpaulin or if fruit are piled into sacks for transport from the field (Stice *et al.*, 2007). For export, surface latex is unsightly and should be avoided rather than removed by washing. As fruit are caught, they should be gently placed stem-down in the shade until sap flow ceases and then packed directly into suitably partitioned crates (Stice *et al.*, 2007).

12.9.1 Packinghouse practices

Sap management

Latex should be drained from the cut peduncle after harvest and before washing in water to avoid latex stain. Harvested fruit should be placed fruit stem down in the shade for ten to 20 minutes or until the oozing sap flow stops, in order that it does not drop onto the fruit surface and before fruit are transported in crates to the packinghouse. Tissue paper can also be wrapped around the end of the fruit stem to absorb the oozing sap before the fruit are placed in sturdy reusable plastic crates for transportation (Nauluvula, 2007).

Pre-cooling

Ideally, fruit should be pre-cooled after harvest in the field and during transport prior to arrival at packinghouse or final destination since transportation times may vary depending on where fruit were harvested. Chipped ice or an iced-water bath are simple methods for pre-cooling breadfruit. Maharaj and Sankat (1990) reported a positive response to immediate precooling of the fruit in chipped ice in the field to an internal temperature of 16°C, measured using a thermocouple inserted into the centre of a fruit. Transportation of harvested and packed fruit on rough roads must be with the utmost care to prevent the product suffering any physical damage. Paull and Chen (2004) advocate room-cooling to 12°C, but not hydro-cooling as this can lead to skin browning.

Washing and sanitization

In the packinghouse, breadfruit should be washed in large water troughs to remove excessive sap. Sap stains are washed or scrubbed off using a soft cloth or sponge. Washing also removes physical and microbial contamination from the fruit. Gentle wiping with a soft sponge or brush is a convenient method to remove insects and foreign matter from base of fruit stems and around the fruit surface (Nauluvula, 2007).

Selection and grading

Handling of fruit after harvest is important. Fruit needs to be inspected for damage and defects. Fruit maturity needs to be assessed by the large fruit size, large segment size and green colour with the exudates from the cut stem being noted and used as a criterion for fruit selection. There are no US or International grade standards. Selection and grading of breadfruit can be used based on these subjective criteria as described by Nauluvula (2007):

i. Appearance – fruit should be whole, well formed and firm and free from surface moisture, contaminants and any sign of fresh physical damage. Furthermore, fruit with skin defects from excessive sap, sunburn, bruises, contaminants, foreign matter and healed physical damage are not acceptable. Fruit should be handled properly and should not be dropped onto the ground at anytime from harvest to the shelves. Dropped fruit will show signs that they are bruised after high temperature forced air treatment (HTFA).
ii. Pest and diseases – fruit should be free of any visible sign of insects and diseases and any sign of fruit rot.
iii. Maturity – only mature green fruit should be packed. Soft and yellowish-green fruit which indicate ripening are not acceptable. Fruit with the same shape and size that is typical of the variety should be packed together. Fruit could be graded as: Large > 14 cm diameter; Medium = 12 cm–14 cm diameter; and Small = 10 to 12 cm.
iv. Labeling – Fruit should be manually packed in sturdy cartons with no more than 8 to 12 fruit per case. The carton should be labelled with adequate information such as variety, size, weight, location/country of origin and name and address of the grower or exporter.

12.9.2 Recommended storage and shipping conditions

Breadfruit typically ripen and soften within one to four days after harvest under ambient Caribbean conditions, however, there are Pacific Island cultivars that remain firm for as long as ten days at ambient conditions (Ragone, 1997: 63). A range of storage temperatures from 12 to 16°C has been recommended for enhancing storage life of breadfruit. The commodity suffers chilling injury if stored below 12°C so storage should always be at or above this temperature. In conjunction with refrigerated storage, fruit should also be sealed in plastic film if green fruit colour, an important quality factor, is to be maintained (Sankat and Maharaj, 2007). Including an ethylene-oxidizing agent within the film wrapping does not significantly improve storage (Marriot *et al.*, 1979; Passam *et al.*, 1981, Worrell *et al.*, 2002) and cannot be recommended. Sankat and Maharaj (2007) recommend that fruit be individually sealed in a 15-μm cling wrap film and stored at 16°C and high relative humidity (>85%) and report a shelf-life of 15 to 17 days. Worrell and Carrington (1997) recommend a storage temperature of 13°C and sealing the fruit in 40 μm high-density polyethylene bags. Fruit stored in this way for two weeks were acceptable when cooked and assessed by a taste panel. Their preliminary trials did not find storage at temperatures above 13°C to effectively retard ripening (Worrell *et al.*, 2002) and this difference might reflect an inability to maintain high relative humidity in the storage chambers.

If CA facilities are available, storage of unwrapped breadfruit at high humidity and 16°C in an atmosphere of 5% O_2 and 5% CO_2 has been shown to delay ripening and skin browning dramatically (Maharaj and Sankat, 2004). This approach can achieve a storage life of 25 days, superior to the two week-plus storage with film wrapping and refrigeration.

There is less consensus on recommending waxes and other coatings to extend storage life of breadfruit. Sankat and Maharaj (1993) reported that applying a high-solids, food-grade wax (Fresh Wax 51V) gave breadfruit a shelf life of about 14 days at 16°C. Other groups found no benefits of fruit waxes (Thompson *et al.*, 1974) and other coatings, and in some cases these even caused deleterious effects such as the development of off-flavours (Worrell *et al.*, 2002).

12.10 Processing

12.10.1 Minimal processing

The USDA and FDA definitions for 'fresh' and 'minimally-processed' fruits and vegetables imply that fresh-cut (pre-cut) products have been freshly-cut, washed, packaged and maintained with refrigeration to deliver to the consumer a fresh-like product (Beaulieu and Gorny, 2005). Passam *et al.* (1981) cut wedge-shaped segments (approximately 15 g each) from peeled and cored breadfruit of the 'White heart' cultivar. These segments were boiled for one to ten minutes, air-cooled, wrapped in foil packages and frozen at –15°C for as long as 11 weeks. They reported that segments boiled for two to five minutes, possessed the flavour, colour and texture comparable with that of fresh-cooked breadfruit when presented to a taste panel. After ten weeks in frozen storage, there was no quality deterioration of the product. However, segments that were frozen without pre-boiling discoloured on cooking after storage and had poor flavour.

Samsoondar and Sankat (1998) investigated the shelf life and cooking quality of minimally processed breadfruit slices (20 mm thick) that were blanched for five seconds at 100°C and packaged in styrotex trays and covered with 15-μm polyethylene film. They noted that fruit stored at 5 and 8°C had acceptable shelf lives of 13 and ten days respectively, with such slices cooking to a comparable quality to that of fresh breadfruit. Beyond this period, microbial spoilage was apparent. In contrast, slices stored at 0°C, upon thawing, appeared water-soaked and unacceptable, consistent with symptoms of chilling injury. John and Narasimham (1998) reported that peeled and diced breadfruit chips steeped in 1000 ppm SO_2 and packaged in 250-gauge (approximately 60 μm) polypropylene pouches with CO_2 and SO_2 head space gas had a shelf life of 30 and 120 days at 28 and 0°C respectively and showed acceptable sensory qualities after boiling or frying. Chips infiltrated in 500 ppm SO_2 and packaged in similar pouches, with CO_2 as the headspace gas, had a shelf life of 75 and 120 days at 28 and 0°C respectively. Breadfruit chips made from minimally processed mature breadfruit slices of both the 'Yellow heart' and 'White heart' cultivars (Bates *et al.*, 1991), after slicing and frying in partially hydrogenated soy oil at 165°C, consistently

produced a light-coloured, crisp chip. The amount of oil absorbed by the chip was reduced from 42 to 26% by first air-drying slices at 57°C for up to 40 minutes. The chips were packed into metallised, commercial 19 μm polypropylene/polyethylene bags and hermetically sealed in air. Packaged samples were stored at 2, 27 and 55°C and analysed at three-day intervals. Storage temperature clearly influenced the keeping quality of chips. Rancidity was detected in chips after 21 days at 27°C. Chips became rancid sooner at the higher storage temperature while those stored at 2°C showed little change in quality for the duration of the study.

12.10.2 Commercial processing

Traditionally, breadfruit are normally roasted, baked, fried or boiled before consumption. Canning fresh fruit in brine or freezing allows products to be used all year long. Other reported methods of preservation include sun-drying, artificial drying, pit fermentation, ambient and low-temperature storage, atmospheric modifications and freezing. Traditional drying of thinly sliced breadfruit is done by the sun or in a very slow oven (50°C). Processing of breadfruit through extrusion into flour, which can then be made into bread and other baked goods and snack products, is another method of preserving breadfruit. One area of interest to food manufacturers is that breadfruit can be dried and ground to produce gluten-free flour, high in protein and several vitamins, making it potentially useful as a food additive or supplement to wheat flour (Ducklow and Mortenson, 2008; Olaoye and Onilude, 2008). Breadfruit flour made from firm, mature breadfruit that were peeled, cored, cut and dried at 80°C for 24 hours, contained higher levels of amino acids, lysine and threonine, than wheat flour. Nochera and Caldwell (1992) reported that bread made from 10% breadfruit flour and 5% whey as well as biscuits containing 10% breadfruit flour and 5% soy protein were judged most acceptable in terms of colour, texture and flavour. Storage of breadfruit flour in PET jars for three months at room temperature showed no significant reduction in key nutrients except for crude fibre and colour attributes (Sharon and Usha, 2006), while Mafwila *et al.* (1991) reported a marked decrease in protein and fat content of breadfruit flour after four weeks in storage. Breadfruit flour (331 calories per 100 g) is comparable to cassava flour (347 calories per 100 g) in terms of calorie content (Morton, 1987: 57).

Breadfruit starch

Breadfruit starch was extracted from firm, mature breadfruit from Puerto Rico that were peeled, cored, cut and dried at 80°C for 24 hours and ground into flour (Loos *et al.*, 1981). The starch was then freeze-dried for 24 hours and pulverised into a fine powder. The resulting starch was 90% pure and contained 18.2% amylose. The intrinsic viscosity of the starch was higher than the reported values for wheat, cassava and arrowroot starches. At concentrations of 4 to 5% the viscosity held stable throughout a heating-cooling cycle. At higher starch concentrations (7 to 8%), the cooled gels exhibited a breakdown in viscosity during prolonged heating and stirring, comparable to potato starch.

Dehydrated breadfruit

Reeve (1974) studied the commercial dehydration potential of breadfruit. Firm, mature breadfruit was peeled, cored and the edible pulp cut into small cubes or slices and tunnel-dried for four hours at 60°C or freeze-dried overnight. Both forms reconstituted readily in cold or hot water and textural qualities were the same and comparable to that of freshly boiled, steamed and whole-baked breadfruit. No significant difference could be observed microscopically between freshly baked or boiled breadfruit and the tunnel-dried breadfruit. The keeping quality of both forms of dried breadfruit was good and no off-odour was detected in freeze-dried sections kept for six months at room temperature. When reconstituted in hot water, these made an excellent substitute for sliced potato in a scalloped-potato and cheese recipe. Both forms were suitable for grinding or crushing into flour, which, when boiled and sweetened, can be eaten as breakfast porridge. It should also be noted that the waste generated by the commercial dehydration of breadfruit by tunnel drying or freeze-drying constitutes a highly digestible stock feed.

12.10.3 Other uses

Soft-ripe fruits constitute a large part of the animal feed in many breadfruit-growing areas. Breadfruit has been investigated as potential material for chick feed but has been found to produce less weight gain than cassava or maize despite higher intake, and it also caused delayed maturity (Morton, 1987: 57). Breadfruit also has potential when combined with corn and peanuts to be used as a nutritious infant food (Nelson-Quartey *et al.*, 2007).

12.11 Conclusions

Only a very narrow range of the many Pacific breadfruit cultivars are being exploited worldwide. The development of *in vitro* propagation methods for this woody crop (Rouse-Miller and Duncan, 2000; Shi *et al.*, 2007) will facilitate the international distribution of this germplasm, and hopefully provide cultivars that will extend the traits available including an extension of the fruiting season.

Breadfruit is essentially a fruit that one does not wish to ripen at all, and so a desirable goal would be to delay, diminish or even eliminate ethylene production. ACC oxidase, the enzyme catalysing the final step in ethylene biosynthesis, has been purified from breadfruit (Williams and Golden, 2002), and one would have hoped by now the nucleotide sequence for this or another ethylene synthesis enzyme like 1-aminocyclopropane-1-carboxylate (ACC) synthase would have been determined for this fruit. None appears in GenBank, but ACC synthase has apparently been fully sequenced from ripening breadfruit and shows 78 to 80% homology with its homologue from pear, apple and papaya (Paull, 2007). The ability to regenerate breadfruit by tissue culture and this preliminary molecular work suggests that it should soon be possible to produce antisense transformants targeting the ethylene biosynthesis enzymes in which ripening would be delayed or even prevented.

Simpler approaches storing fruit with the ethylene antagonist 1-methylcyclopropene (1-MCP), have delayed ripening in the breadfruit's relative, jackfruit (Mata-Montes de Oca *et al.*, 2007), and it does appear that 1-MCP can delay ripening in breadfruit when used together with film wrapping (Paull, 2007). In the short term, optimising the film wrapping of refrigerated fruit in conjunction with 1-MCP treatment should further enhance current postharvest life of this extremely perishable commodity.

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Plate XXI Diversity in the shape of breadfruit (*A. altilis*) cultivars growing at the Breadfruit Institute, National Tropical Botanical Garden. 1. Puurea, 2. Kea, 3. Lipet, 4. Pulupulu, 5. Tuutouauena, 6. Puou. Details for each variety available at http://ntbg.org/breadfruit/database/search. Photograph © Jim Wiseman, courtesy of the Breadfruit Institute, National Tropical Botanical Garden.

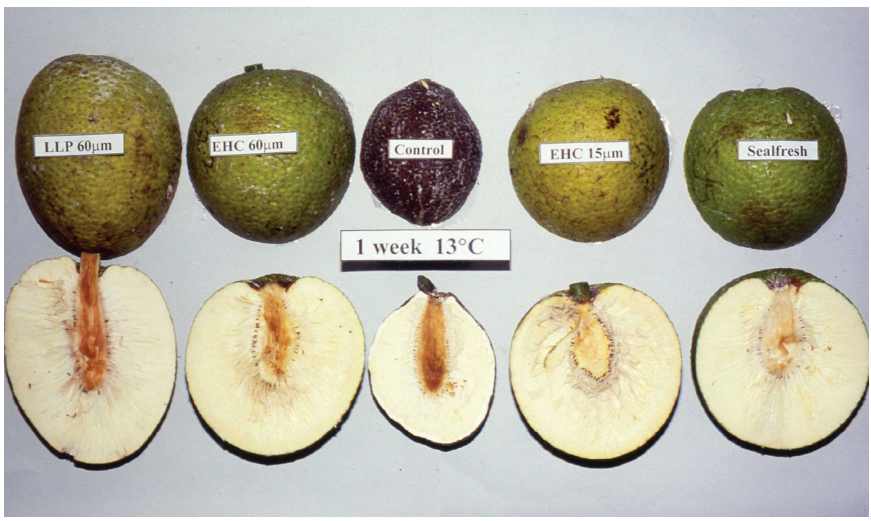

Plate XXII External and internal appearance of breadfruit stored for one week at 13°C either unwrapped (control) or wrapped in SealedFresh 15 µm film or in Clysar (DuPont) EHC 15 µm or EHC 60 µm or LLP 60 µm. Source: Worrell (1994).

13

Breadnut (*Artocarpus camansi* Blanco)

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Abstract: The breadnut or chataigne (*Artocarpus camansi* Blanco) qualifies as a commodity with a unique flavour, high fibre content, high percentage of complex carbohydrates and the ability to be utilized in a myriad of ways. Further, with its current use in ethnic cuisine and in traditional medicine, it is expected that it will increase in importance as an item in international trade. The breadnut is a member of the Moracaeae family, which consists of nearly fifty species of trees all native of Southeastern Asia and the Pacific islands. The fruit is a syncarp, with its rind covered with fleshly prickles or spines. It has a fibrous core with 50 to 100 nut-like seeds embedded in a white, flaky and spongy-like pulp. The fruit is highly perishable with a shelf life of not more than two days under ambient conditions. The breadnut rapidly transforms when harvested mature green. After two days it has a very soft texture, the milky-white seed develops a brown net-like hard rind while the flesh changes from a white colour to a light yellow colour. The fruit is very chilling sensitive. The combined effects of rapid softening and high susceptibility to chilling injury contribute immensely to its short shelf life.

Key words: *Autocarpus camansi*, breadnut, chataigne, chilling injury, ripening, maturity indices, flesh softening, senescence.

13.1 Introduction

13.1.1 Origin, botany, morphology and structure

The breadnut, also called chataigne, was brought by the French to the Caribbean ten years before the breadfruit was introduced by Captain Bligh (Coronel, 1990). It belongs to the genus Artocarpus and is a member of the Moracaeae family, which consists of nearly fifty species of trees, all natives of Southeastern Asia and the Pacific islands (Purseglove, 1974). Three known members of the genus cultivated and utilized throughout the Caribbean and Asia and exported to ethnic markets in Europe and America include: breadnut (*Artocarpus camansi*), breadfruit

(*Artocarpus altilis*) and jackfruit (*Artocarpus heterophyllus*). The breadnut is presently grown in India, Sri Lanka, Burma, Jamaica, Cuba, the lowlands of Mexico, and Central and South America. A few trees, all fairly recent introductions, can be found in New Caledonia, Pohnpei, the Marquesas, Tahiti, Palau and Hawaii (Ragone, 2006).

Beginning in the late 1700s the British and French propagated breadnut throughout the tropics, and it is now widespread in the Caribbean, where it is especially popular in Trinidad and Tobago, Guyana and Suriname (Wickham, 2001). In New Guinea, it is a dominant member of alluvial forests in lowland areas, and is one of the first species to appear on the tops of frequently flooded river banks. The trees grow widely scattered in the forest and the seeds are dispersed by birds. *Artocarpus camansi* has often been considered to be a form of seeded breadfruit, *Artocarpus altilis*. However, the breadnut and the breadfruit are separate species and hence the names *Artocarpus camansi* and *Artocarpus artilis* are given to them, respectively (Biale, 1964; Coronel, 1990). Breadfruit is thought to have developed from its wild seeded ancestor, breadnut (Ragone, 2006). The botanical differences that these two fruits exhibit are shown in Table 13.1. All trees of the Artocarpus genus produce sticky, white, milky latex that is present in all parts of the tree and contains a small quantity of rubber (Coronel, 1990).

The breadnut is a large monoecious tree with a spreading crown. It attains a height of 10 to 15 m or taller with a single trunk 1 m or more in diameter, often growing to a height of 5 m before branching. Canopy diameter generally measures about half of the tree height. The tree typically forms buttresses at the base of the trunk (Ragone, 2006).

The very large leaves are ovate to oblong ovate, coriaceous, 40 to 60 cm long, and 25 to 45 cm wide, bright dark green in colour, acuminate, deeply pinnate with four to six pairs of lobes that are ovate and acute with sinuses cut halfway to the

Table 13.1 Botanical differences between breadnut and breadfruit

Botanical characteristics	Breadnut (*A. camansi*)	Breadfruit (*A. artilis*)
Fruit	Seeded	Seedless
Anthocarps	Narrowly conical, prolonged	Flat or rounded, slightly projecting
Base of fruit	Rounded	Oblique
Male spike	Club-shaped	Narrowly, oblong, ovoid, thickened at middle
Stigma	Elongated	Very short
Leaves	Usually 4–5 lobes on both sides	Usually 3 lobes on both sides

Source: Quisumbing, 1940.

midrib. The leaves are densely pubescent, with many white or reddish-white hairs on upper and lower veins, lower leaf surface and petiole. The leaf blade is dark green with green veins. Two large green stipules enclose the bud, turning yellow before dehiscing (Barrau, 1976; Brown, 1943; French, 1988).

Breadnut trees can adapt to a wide range of ecological conditions. They require a tropical climate and will not grow where the temperature is below 50°C (Ochse et al., 1961). They grow best in equatorial lowlands below 600 to 650 m but are found at elevations up to 1,550 m. The trees prefer a rainfall of fairly equal distribution, but can tolerate short dry periods (Wester, 1920). An annual rainfall of 150 cm and a temperature of 21 to 30°C are ideal for growth and development. While the tree is tolerant to a wide range of soil types, it tends to perform best in deep, fertile, well-drained, sandy loam or clay loam soil. Seeds should be planted 5 cm apart and 1 cm deep. They start germinating in ten to 15 days after sowing. When seedlings are one year old they are ready for field planting. Plants are spaced 12 to 15 m apart. Trees begin producing at eight to ten years of age. The tree is fast growing in favourable conditions, growing 0.5 to 1.5 m in height for the first ten to 12 years. Small branches often die back at the tip after fruiting, but new shoots and branches continue to develop throughout the life of the tree.

Flowering is monoecious with male and female flowers on the same tree at the ends of branches, with the male inflorescence appearing first. The male inflorescence is club-shaped, rather spongy, curved at the base, cylindrical, greenish-yellow, 15 to 20 cm long and 3 to 4 cm in diameter (Plate XXIIIa: see colour section between pages 244 and 245). Thousands of tiny flowers with two anthers are attached to a central spongy core. Female inflorescences are ovoid with pubescent petiole and two-lobed elongated and prominent stigma and consist of 1500 to 2000 reduced flowers attached to a spongy core (Verheij and Coronel, 1991).

Fruits of the breadnut tree consist of a large fleshy syncarp, oval or ovoid, 13 to 20 cm long and 7 to 12 cm in diameter, weighing approximately 800 to

Table 13.2 Proximate analysis of breadnut pulp and seed

Components	Pulp	Seed
Moisture content (%)	56.0	20.0
Crude protein (%)	6.4	13.3
Crude fat (%)	6.4	6.2
Total carbohydrates(%)	74.6	76.2
Crude fibre(%)	18.0	2.5
Starch (%)	46.2	53.4
Alcohol soluble carbohydrates (%)	23.6	16.4
Ash (%)	1.8	3.7
Energy		434/100 g^{-1} edible portion dry weight

Source: de Bravo *et al*., 1983.

1200 g (Plate XXIIIa: see colour section between pages 244 and 245). The skin is dull green to green-yellow when ripe with a spiny texture from the pointed, flexible 5 to 12 cm long tips of individual flowers. The scanty pulp is yellow-whitish when ripe with a sweet aroma and taste. The fruit is not as solid or dense as other fruits in the family because the individual flowers forming the fruit are fused together only at their bases. The fruits contain numerous seeds, from 12 to as many as 150, each weighing an average of 7 to 10 g, comprising 30 to 50% or more of the total fruit weight. The seeds have little or no endosperm, no period of dormancy, germinate immediately, but lose their viability rapidly and are unable to withstand desiccation.

Roberts-Nkrumah (2005) reported on a study to determine fruit yield and seed yield and the relationship between fruit size and seed yield as well as the response of yield to pruning. Data for this study were collected from 1996 to 2002 from three seedling trees established at the University of the West Indies Field Station, Trinidad and Tobago in 1993, and the trees were pruned in 1998. From this investigation Roberts-Nkrumah (2005) reported that the highest fruit mass per tree was 139.7 kg, fruit number per tree was 126 and seed mass per tree was 59 kg in 5-year-old trees. Additionally, fruit seed yields were significantly lower in the years after pruning. Fruit mass per tree was positively correlated with fruit number ($r = 0.99$). The study also indicated that seed mass per fruit was positively correlated with seed number per fruit ($r = 0.87$) and both variables had strong, positive correlations with mean fruit mass ($r = 0.83$ and $r = 0.77$, respectively) and fruit volume ($r = 0.63$ and $r = 0.77$, respectively). Roberts-Nkrumah (2005) indicated that breadnut fruit and seed yield were larger than originally estimated and emphasized further that both are strongly related and therefore selection for high seed number per fruit with more effective pollination, disease control and proper tree height management may increase productivity. She concluded by confirming that estimated fruit volume is the most practical indicator of seed yield.

13.1.2 Worldwide importance and economic value

According to Roberts-Nkrumah (2005), the breadnut has remarkable potential as an alternative food source in the tropics based both on its nutritional content and on its level of seed production. There is also the potential for further improvement of fruit and seed yield via selection and by crop management to reduce constraints to productivity and marketability, including the effectiveness of pollination, disease and tree size. The fruit is generally available year round but usually the season extends from June to November in most Caribbean islands. In Trinidad and Tobago, the peak season is from October to November. Roberts-Nkrumah's (2005) study, conducted in Trinidad, showed that over a seven-year period, the mean total fruit mass per tree and per year was 52.7 kg and the mean fruit number per tree was 49. Mature breadnut trees in the Philippines have been reported to produce 600 to 700 fruits per season. Based on 100 trees/ha producing 200 fruits per tree, an average yield of 11 mt/ha of fresh seeds has been estimated (Ragone, 2006).

The breadnut is exported from several Caribbean islands including Trinidad, St. Vincent, Jamaica and Guyana to Canada, United States and Europe where Asians and West Indians reside.

13.1.3 Culinary uses, nutritional value and health benefits

Culinary uses

The breadnut is a very versatile fruit that can be utilized at horticultural maturity (Plate XXIIIb: see colour section between pages 244 and 245). In Trinidad and Tobago as well as many other Caribbean islands such as Guyana and Suriname in particular, mature green fruits including the pulp (Plate XXIIIc: see colour section) and immature seeds are cooked with curry, coconut milk and even meat, forming an exotic meal with roti or rice. The fruit is used at several functions such as weddings, religious festivals and is therefore required in large quantities (Brown, 1943).

Fruits harvested at the physiological stage of maturity have seeds that have already germinated with a light brown brittle-like seed coat. Underneath this seed coat is a thin papery-like lining surrounding the seed mesocarp of a similar colour. These fully developed seeds (Plate XXIIIc: see colour section), when separated from the soft light yellow pulp of a fresh ripened breadnut fruit and boiled for 30 to 40 minutes in water and salt, make a very tasty nutritious snack (Wickham and Mohammed, 1996). Since breadnut seeds are so similar in taste and texture to chestnuts, they could have commercial possibilities roasted, canned in brine, or processed into nut butter or nut paste or oil (Wickham, 2001). Seed from fresh ripened breadnut that are boiled could also be made into value-added products such as ground paste, which can be fried or baked and used in the formulation of palatable high-protein infant foods that fit into traditional culinary and child-feeding practices throughout the world (Nelson-Quartey *et al.*, 2007). The boiled or fried seeds can also be used as a substitute for chickpeas.

Nutritional value

The breadnut has a moisture content of 56%, which is lower than that of the breadfruit, hence it is more energy- and protein-dense. The edible pulp constitutes 33.2 to 46.8% of the fruit, while the seed constitutes 30.1 to 46.8% (de Bravo *et al*., 1983; Wickham and Mohammed, 1996). Compared to other published data for other tree nuts, the breadnut seed contains high quantities of calcium, phosphorus, potassium, iron and niacin. It is a good source of protein and low in fat compared to nuts such as almond, Brazil nut, and macadamia nut (Ragone, 2003). While the fibre content of the seed varies from 2.5 to 3.9 g, in the edible pulp it is 18.0 g (de Bravo *et al.*, 1983). The fat extracted from the seed is a light yellow, viscous liquid at room temperature with a characteristic odour similar to that of peanuts. It has physical properties similar to those of olive oil. A 100 g portion of dried seed consists of 13.3 to 20 g protein. Four amino acids, methionine (3.2 g), leucine (2.6 g), isoleucine (2.4 g) and serine (2.1 g) account for more than 50% of the amino acids (de Bravo *et al.*, 1983).

The breadnut can be made into flour, which is more concentrated in energy and proteins than wheat flour (McIntosh and Manchew, 1993). Oshodo *et al.* (1999) investigated the chemical composition, amino acid analysis and functional properties of breadnut flour and reported that this value-added product contained 55.1% high-quality proteins and amino acids, which is higher than the protein and amino acid levels of soy flour and egg. They elucidated that the dominant essential amino acids are valine, glutamic acid, aspartic acid, while the limiting amino acids are methionine and cystine. In the same study they also claimed that the breadnut protein has minimum solubility at pH 5 and maximum solubility at pH 8. Additionally, potassium is the most abundant mineral in the breadnut flour (0.7 g 1 00 g^{-1}), while magnesium (0.08 g 100 g^{-1}) is the least abundant. Overall, their results showed that breadnut flour is useful as a thickener and source of protein in diets. In other investigations Nwabueze (1999) examined the effect of blanching on the composition and characteristics of breadnut flour. Accordingly, Nwabueze (1999) observed that while the raw and blanched flours showed low protein (4.6%) but high carbohydrates (66.33%) and fat (14.25%), blanching did not improve the proximate composition of the flour except for the carbohydrate content, which increased to 70.45%. It was further highlighted that blanching improved the physical characteristics of the breadnut flour. In particular, it improved 'meat' extraction rate from 80.5% to 86.0%, wettability from 1.38 to 0.56 minutes and bulk density from 0.66 to 0.82 w/v due to the effect of heat on the components native to the breadnut.

In more recent studies, Fagbemi et al. (2005) reported on the effects of processing such as raw drying, boiling, fermenting, germinating and roasting on antinutritional factors and in vitro multienzyme protein digestibility of three tropical seeds including breadnut seeds. The seeds from breadnut, cashew nut and fluted pumpkin subjected to the various processing options listed above were dried at 50°C, ground and sieved, and evaluated for trypsin inhibitor activity, tannin, phosphorus compounds and in vitro multienzyme protein digestibility. Their results indicated that processing significantly affected the antinutritional factors in the flours. Breadnut flours contained 2.8 to 5.3 g kg^{-1} phytic acid, 5.9 to 9.2 g kg^{-1} tannin and 0.9 to 8.1 mg g^{-1} of trypsin inhibitor activity. Fermentation proved to be the most effective processing method to reduce phytic acid and trypsin inhibitor activity, while boiling was most effective in reducing the tannin content. Their results also confirmed that in vitro multienzyme protein digestibility of seeds generally showed that the boiled samples were the most digestible followed by the fermented samples while the raw/germinated samples were the least.

Medicinal properties

Medicinal properties of parts of the breadnut tree other than the flesh and seeds have been exploited. The flowers, for example, are roasted in Java and rubbed on infected gums to reduce toothache. The yellow senescing leaves can be boiled and used to alleviate diabetes and hypertension. The reduction in blood pressure is due to the presence of amino-butyric acid in the yellow leaves. In the West Indies, the sap is used as a plaster to assist in healing dislocated joints.

13.2 Breadnut physiology

13.2.1 Fruit growth and development

Growth and development of the breadnut fruit showed a typical sigmoid shape (Fig. 13.1). In the investigation conducted by Wickham and Mohammed (1996), they reported changes in the breadnut fruit growth from six weeks after flowering, where the fruits were noticeably small with an average weight of 455.33 g, until 12 weeks, where the fruits were significantly larger with an average weight of 1240 g (Fig. 13.1). Fruits examined six weeks after fruit set had seeds that were undeveloped, soft internally, with a jelly-like appearance and having an eating quality rated as poor (Fig. 13.3). Although fruit weight increased by another 100 g by the end of the seventh week post-anthesis, fruits were still considered as immature, once more based on poor eating quality. Fruit weight increased rapidly from week eight to week 12 (Fig. 13.1). Fruits harvested between weeks eight and ten, which ranged between 718.6 g and 1100.5 g were horticulturally mature (Plate XXIIIb: see colour section between pages 244 and 245) with excellent cooking and eating quality (Table 13.3).

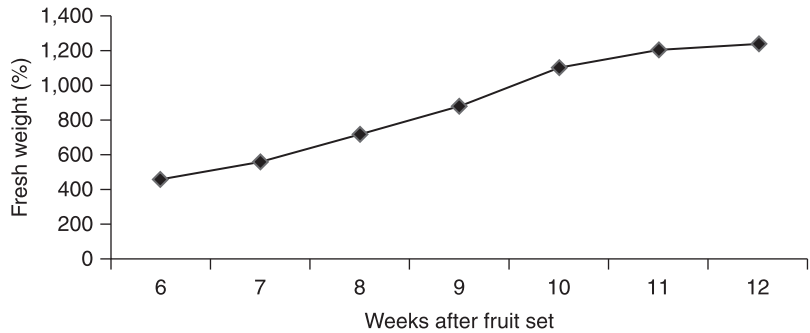

Fig. 13.1 Percentage fresh weight of breadnut from weeks 6 to 12 after fruit set.

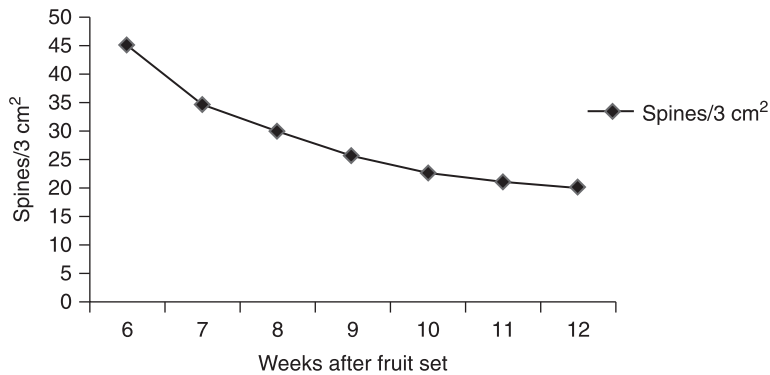

Fig. 13.2 Spacing of spines 3 cm^2 on fruit skin surface.

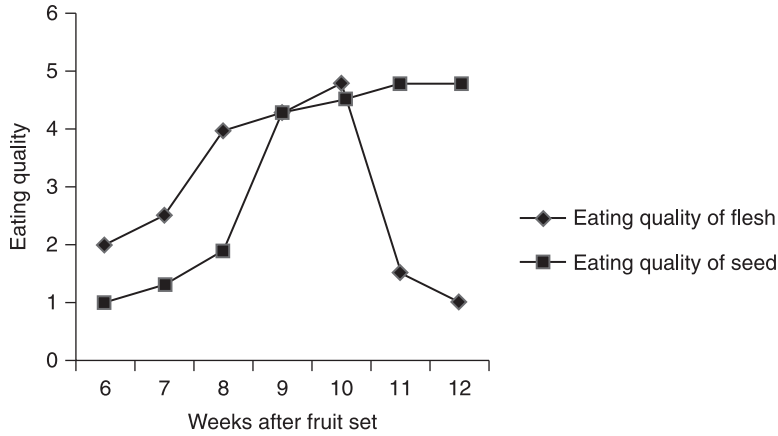

Fig. 13.3 Changes in breadnut flesh and seed eating quality when cooked over weeks 6 to 12 after fruit set.

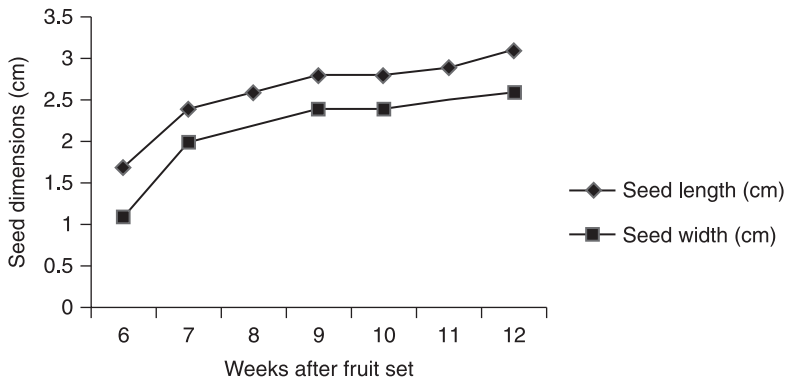

Fig. 13.4 Changes in seed dimensions of breadnut from weeks 6 to 12 after fruit set.

At weeks 11 to 12 fruit fresh weight measured between 1200.1 and 1240.0 g, reaching a plateau indicative of attaining physiological maturity (Table 13.3). Coinciding with increasing fruit weight was a similar increase in firmness up to week 11 postanthesis (Figs 13.1 and 13.8). Noteworthy, was the relatively small increase in firmness from weeks nine to 11 (Fig. 13.8). However, from week 11 to 12 the breadnut fruit demonstrated a dramatic decline in firmness accompanied by fruit ripening (Fig. 13.8). During fruit development, increasing fruit weight was accompanied by a decrease in the number of spines per 3 cm^2 on the fruit skin from weeks six to 12 after fruit set (Figs 13.1 and 13.2). Fruit mass after six weeks following fruit set is two-fold greater three weeks later and nearly three-fold more by week 12. Meantime the number of spines at week six, which amounted to 45 per 3 cm^2, decreased to 20 per 3 cm^2 at week 12 thereby confirming an inverse relationship between fruit weight and number of spines on the fruit surface (Figs 13.1 and 13.2).

Table 13.3 Physicochemical and sensory quality attributes of breadnut at horticultural and physiological stages of maturity

Quality profile	Weeks after fruitset	
	Horticultural maturity (8–10 wks)	Physiological maturity (9–11 wks)
Fruit wt (g)	718.6–1,100.5	1,200.1–12.40
Spine 5/3 cm^2	30–23	21–20
External skin colour		
'L'	38.31–36.78	36.75–36.28
'a/b'	−0.44–(−0.49)	−0.47–(−0.26)
Flesh colour		
'L'	82.67–85.23	82.93–72.34
'a/b'	−0.29–(−0.31)	−0.29–(−0.31)
External seed colour		
'L'	85.7–82.7	75.43–43.89
'a/b'	−0.03–0.02	0.18–0.44
Internal seed colour		
'L'	85.55–87.43	86.40–82.14
'a/b'	−0.16–(−0.14)	−0.14–(−0.12)
Fruit firmness	743.13–880.50	890.50–17.50
Seed firmness	225.63–429.25	646.25–787.50
Seed length (cm)	2.60–2.78	2.75–3.13
Seed width (cm)	2.25–2.20	2.35–2.50
Seed dry matter (%)	13.29–26.93	32.48–39.23
Seed germination (%)	16.75–98.0	99.50–99.75
Seed reducing sugar (%)	15.57–2.57	2.02–3.43
Seed total sugars (%)	19.12–4.32	4.50–5.92
Flesh dry matter (%)	12.68–13.85	14.10–16.37
Flesh reducing sugar (%)	2.58–3.01	12.58–12.96
Flesh total sugars (%)	3.51–4.16	13.86–14.09
Seed eating quality*	1.94–4.50	4.81–4.88
Flesh eating quality	4.00–4.80	1.0–1.0

Note: *Eating quality (1 to 5): 1 = dislike extremely, 5 = like extremely.

13.2.2 Respiration, ethylene production and ripening

Respiration and ethylene production rates in breadnut have not been determined and currently research is being conducted to confirm its respiratory pattern. Major physical and chemical changes accompany fruit ripening at the onset of physiological maturity, that is, between weeks 11 and 12 after fruit set. These ripening changes are summarized in Table 13.3. The dramatic changes during this period are shown in Fig. 13.2 (decreasing spine spacing), Table 13.3 (seed and flesh colour), Table 13.3 (internal seed colour), Figs 13.6 and 13.7 (flesh and seed dry matter, reducing sugars and total sugars), Fig. 13.8 (decreasing fruit firmness) and Fig. 13.5 (increasing seed weight and percentage seed germination).

Table 13.4 Relationship between various physiological parameters and time and/or seed dry matter in fruit

Parameter (Y)	Parameter (X)	Equation	R^2
Weight (g)	Time period	$y = 343 + 129x$	0.75***
Spines per 3 cm^2	Time period	$y = 44.0 - 3.84x$	0.73***
External firmness	Time period	$y = 916 - 57.3x$	0.16
Flesh dry matter (%)	Time period	$y = 11.4 + 0.575x$	0.53**
Flesh reducing sugar (%)	Time period	$y = 0.39 + 1.65x$	0.59**
Flesh total sugar (%)	Time period	$y = 0.67 + 1.76x$	0.62**
Seed firmness	Time period	$y = 121 + 125x$	0.91**
Seed dry matter (%)	Time period	$y = 0.59 + 5.46x$	0.84***
Seed reducing sugar (%)	Time period	$y = 21.5 - 3.15x$	0.74***
Seed total sugar (%)	Time period	$y = 24.3 - 3.21x$	0.71***
Seed total sugar (%)	Seed dry matter	$y = 21.6 - 0.482x$	0.57**
Seed external colour ('L')	Time period	$y = 99.9 - 5.54x$	0.56**
Seed external colour ('a/b')	Time period	$y = 0.234 + 0.0729x$	0.64***
Weight of 10 seeds (g)	Time period	$y = 23.0 + 9.16x$	0.74***
Germination (%)	Time period	$y = 25.4 + 20.5x$	0.85***

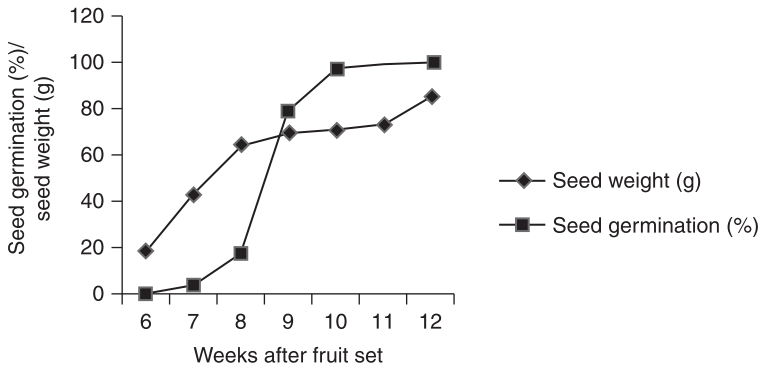

Fig. 13.5 Changes in seed weight and percentage seed germination of breadnut from weeks 6 to 12 after fruit set.

13.3 Maturity and quality components and indices

13.3.1 Changes during fruit maturation

At horticultural maturity, that is, weeks eight to ten after fruit set, fruit mass ranged from 718.6 g to 1100.5 g and this corresponded with spine spacing decreasing from 23 per 3 cm^2 to 20 per 3 cm^2 over the same period (Table 13.3). The seeds (eaten together with the flesh when cooked at this stage of maturity), ranged in size from 2.6 to 2.8 cm in length and 2.2 to 2.5 cm in width with a mass of 64.7 to 70.9 g were represented with a milky-white seed coat with a 'L' value of 82.7 to 85.7 and 'a/b' ratio of 0.02 to 0.03 (Table 13.3). Fruits at this stage of

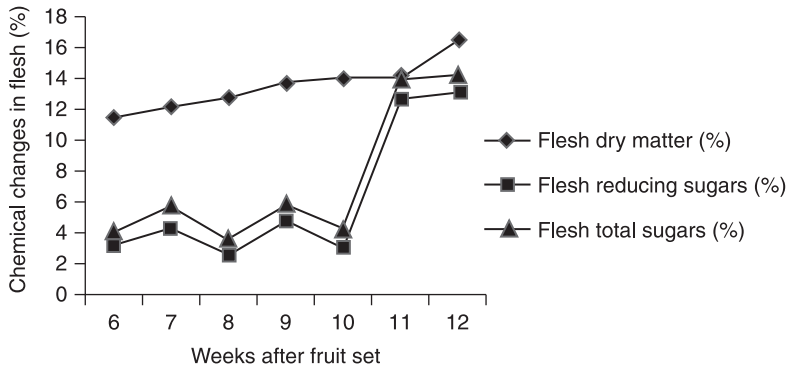

Fig. 13.6 Changes in breadnut flesh dry matter, reducing sugars, and total sugars from weeks 6 to 12 after fruit set.

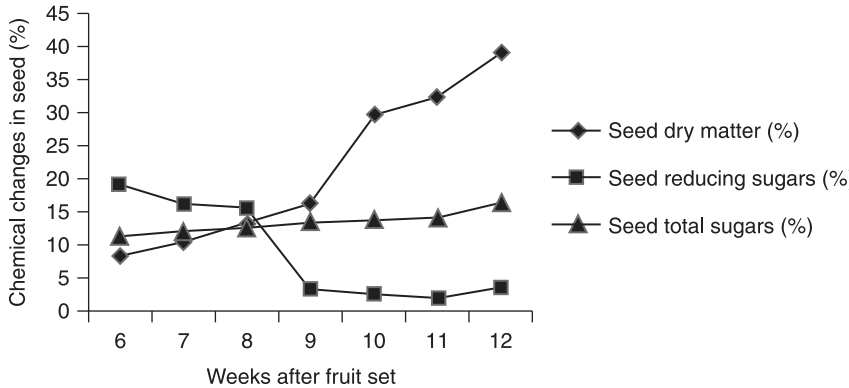

Fig. 13.7 Changes in breadnut seed dry matter, reducing sugars and seed total sugars from weeks 6 to 12 after fruit set.

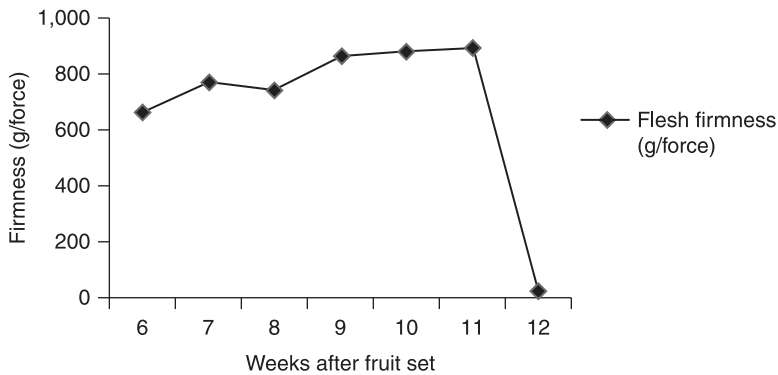

Fig. 13.8 Changes in firmness of breadnut from weeks 6 to 12 after fruit set.

maturity also had lower sugar levels for the flesh and seeds compared to earlier or later periods (Figs 13.6 and 13.7). Percentages of dry matter of flesh and seed varied between 12.7 to 13.9% and 13.3 to 29.9% respectively while percentage seed germination ranged from 16.8 to 98.8%, according to investigations conducted by Wickham and Mohammed (1996) (Table 13.3).

Breadnut fruits are physiologically mature beyond ten weeks post-anthesis and full ripening occurs at week 12 post-anthesis (Table 13.3). At this stage of maturity the brown seeds are utilized as a snack. The onset of physiological maturity is associated with major physicochemical and organoleptic changes between weeks ten and 11, which were accelerated further between weeks 11 and 12. Between weeks ten and 11 flesh reducing and total sugars increase significantly (Fig. 13.6). The reducing sugars in the breadnut flesh increased from 3.0% at week ten to 12.6% a week later, accounting for more than a four-fold difference (Fig. 13.6). Likewise, total sugars in the flesh over this same time interval increased from 4.2% to 13.9%. Panellists rating eating quality, using a hedonic scale, found the cooked flesh and seed highly acceptable at week ten, but much less acceptable at week 11 (Figs 13.3, 13.6, 13.7).

Between weeks 11 and 12 post-anthesis, the characteristics of both flesh and seed changed dramatically as the fruit ripened. Flesh firmness decreased from 890.5 g cm^2 to 17.5 g cm^2, flesh colour changed to bright light yellow with 'L' value decreasing from 82.93 to 72.34 and 'a/b' value from −0.29 to −0.31, flesh dry matter from 14.1% to 16.37%, flesh reducing sugars from 12.58% to 12.96% and flesh total sugars from 13.86% to 14.09% (Table 13.3).

Simultaneously, changes also occurred in the seeds. Seed mass increased from 73.2 g to 85.5 g; seed dry matter progressed from 32.5% to 39.2%; seed increases in reducing and total sugars changed from 2.0% to 3.4% and from 14.1% to 16.4% respectively. While the flesh at this stage of maturity is usually discarded, the cooked seeds secured an extremely high acceptable eating quality rating of 4.9 on the hedonic scale of 1 to 5 as rated by a team of trained sensory panellists (Table 13.3). Concomitant changes with the seed was the development of a brown brittle-netted seed coating with decreasing 'L' values from 75.4 to 43.9 and increasing 'a/b' values from 0.81 to 0.44. The hardened seed coating caused overall seed firmness to increase from 646.3 g cm^2 at week 11 to 787.5 g cm^2 at week 12.

The compositional changes during fruit ripening between 11 to 12 weeks post-anthesis caused almost 100% of the seeds to germinate. There are important agronomical implications of the fact that the breadnut can contain as much as 78.8% germinated seeds prior to physiological maturity, increasing to almost 100% (Table 13.3) when ripe. Breadnut fruits have the potential to produce plants by tissue culture since the fruits could be harvested with intact germinated seeds, thereby minimizing any possible risk of contamination from soil borne pathogens from abscised fruits. Other forms of artificial propagation are also possible, such as budding and grafting. Grafting on breadnut rootstock is a valuable approach to reducing breadfruit tree dieback and death and to extending production to drier areas (Roberts-Nkrumah, 2005). The breadnut therefore demonstrates early seed

maturity, if maturity is defined as the ability to germinate and give viable plants, making it possible to harvest the fruit for propagation before it appears externally to be physiologically mature.

13.3.2 Indicators of fruit maturity

Progress in fruit maturity was not associated with any significant changes in skin or flesh colour, and therefore skin and flesh colour are poor indicators of maturity (Table 13.4). However, the seed testa did undergo major changes in colour from white to brown as fruit advanced in maturity (Table 13.5). Likewise, the testa and the inner seed got firmer with time. There was an increase in percentage of seed germination as well as of percentage dry matter in the seed. Thus the colour of the seed testa, seed germination and dry matter percentages represented reliable indicators of fruit maturity (Table 13.6).

Table 13.5 Changes in skin colour and flesh colour of breadnut from weeks 6 to 12 after fruit set

Weeks after fruit set	Skin colour		Flesh colour	
	'L'	'a/b'	'L'	'a/b'
6	35.8a	−0.45bc	83.4cd	−0.31a
7	35.6a	−0.46bc	81.7bc	−0.31a
8	38.3b	−0.44b	82.bcd	−0.29a
9	36.1a	−0.44b	80.9bc	−0.29a
10	36.8a	−0.49cd	85.2d	−0.31a
11	36.8a	−0.47cd	82.9bcd	−0.29a
12	36.3a	−0.26a	72.4a	−0.31a
$LSD_{0.05}$	1.8	−0.02	2.4	−0.02

Table 13.6 Changes in external and internal colour in breadnut seed from weeks 6 to 12 after fruit set

Weeks after fruit set	External seed colour		Internal seed colour	
	'L'	'a/b'	'L'	'a/b'
6	86.2d	−0.06a	74.3a	−0.07a
7	87.8d	−0.06a	85.3c	−0.17d
8	85.7cd	−0.03a	85.6c	−0.16c
9	82.3c	−0.08b	84.7c	−0.16c
10	82.7c	−0.02a	87.4d	−0.14bc
11	75.4b	0.18c	86.4c	−0.14bc
12	43.9a	0.44d	82.16	−0.12b
$LSD_{0.05}$	3.05	0.029	1.56	0.02

13.4 Postharvest handling practices and postharvest factors affecting quality

13.4.1 Harvest operations to minimize physical damage

The heavy, dense nature of the fruit and the height of trees make harvesting operations a major problem. If the fruit abscises on its own from the tree it is usually ripe and soft. The pulp and seed then shatter upon impact on the ground, and only the seeds can be utilized. If left for prolonged periods secondary infections could dominate mainly on the soft pulp, but in any case the pulp at this stage is not utilized. The hardened seed coat protects the seed from any physical damage, as well as the soft pulp, which envelopes the seeds and therefore acts as a buffer against physical damage (Bennett and Nozzollilo, 1988). Frequently, the fallen ripe fruit pulp and embedded seed are usually allowed to remain on the ground for one to three days, and the pectolytic enzymes from the senescing pulp further degrade the pulp thereby making seed removal easier and less cumbersome.

Harvesting of breadnut fruits at the horticultural stage of maturity (that is, weeks eight to ten post-anthesis) should ideally be carried out on the day of marketing and display for sale or on the previous day, if cool storage and adequate supervision of grading and packing are available. Preferably, harvesting operations should be conducted in the early part of the morning or late in the evening to minimize build-up of field heat. Breadnut fruits must be harvested one at a time. Fruits at different stages of maturity could be located in a cluster, so care must be taken at harvest to select only fruits that are at the appropriate stage of maturity, so as to minimize breakages of spines due to abrasions. Picking poles with attached cup should be used. Fruits must be harvested with the peduncle attached at the stem end, and the attached peduncle should be at least 9 to 10 cm in length.

Breadnut fruits at harvest should be snapped from the tree at the point adjacent to the branch. When the peduncle is cut, the fruit should be allowed to fall and be caught by hand or in a net, before hitting the ground in order to reduce major physical damages such as cracks, punctures and abrasions. Physical damage could facilitate the proliferation of soil borne pathogens, moisture loss and secondary infections. Even collection of fruits with a picking pole with an attached pouch can cause adjacent fruits to rub against one another causing the spines to break at the tips and the milky exudates or latex can induce staining of the external skin (Plate XXIIIb: see colour section between pages 244 and 245). Additionally, breadnut fruits should never be allowed to be knocked from the tree, or dropped or thrown directly to the ground, as the resultant bruising and breaking of spines and skin would cause rapid softening.

The elongated peduncle from the harvested fruit should be removed with a sharp stainless steel knife in order to ensure that the peduncle is flush with the level of the fruit shoulders or slightly protruding to a maximum length of 1.5 to 2.0 cm. Peduncle trimming should be conducted in the field immediately following harvest. The fruits should then be placed downwards on a clean surface, perhaps on broad leaves such a banana leaves or a sanitized tarpaulin to permit latex drainage.

Out-grading of immature, undersized, damaged, bruised, scarred, punctured or ripe fruits can be undertaken in the field under shade or in the packinghouse. Following latex drainage, harvested fruits should be placed in a single layer in shallow, light coloured, well-ventilated field crates. Harvested breadnut fruits must never be allowed to be exposed to the sun, be it under field conditions or during transportation to the packinghouse. Marketable fruits should be immersed in a tank containing 100 ppm sodium hypochlorite for sanitizing purposes, and also to rinse any residual field materials, latex and other debris. Prior to packing, fruits should be placed in plastic crates and allowed to air dry.

13.4.2 Temperature management and chilling injury

The breadnut fruit is very chilling-sensitive if stored below 5 to 6°C and chilling injury (CI) is a major limitation during transport, distribution and display under refrigerated conditions. The symptoms of chilling injury include the skin and spines having a dull green colour (Plate XXIVa: see colour section between pages 244 and 245), water-soaked areas, browning of skin, flesh and seed (Plate XXIVb: see colour section), translucency of seed internal tissue (Plate XXIVc: see colour section), irregular brown coalesced sheet pitted lesions on seed surface, and invasive browning from seed perimeter into seed internal tissue, detrimental flavour changes, increased water loss and increased susceptibility to secondary infections (Mohammed and Wickham, 2003) (Plates XXIVa, XXIVb, XXIVc: see colour section).

Whole fruits stored in paper bags at 4 to 5°C displayed these symptoms after four days. Chilling injury became more severe when fruits were transferred to 20 to 22°C for one, two, and three days respectively. However, when fruits were individually seal-packaged in low-density polyethylene (LDPE) or high-density polyethylene (HDPE) bags, visible evidence of chilling injury symptoms were not apparent until eight days at 4 to 5°C plus two days and more upon transfer to 20 to 22°C. Thus, the modified atmosphere created within the sealed bags as well as the prevalence of high relative humidity delayed the appearance of visible chilling injury symptoms. However, despite the absence of chilling injury symptoms for fruits in sealed polyethylene bags, measurements of reduced bioelectrical resistance and increased electrolyte leakage suggested impairment to membrane integrity. The inverse relationship between decreasing bioelectrical resistance and increasing electrolyte leakage indicated that these objective measurements could provide evidence of chilling injury prior to the appearance of visible chilling symptoms, and could therefore be a useful early detection procedure for the determination of the occurrence of chilling injury (Mohammed and Wickham, 2003).

The fruit benefits from rapid removal of field heat following harvest and can be hydro-cooled, providing that the temperature of the water is not below 10 to 12°C. Iced water or air systems below this temperature should be avoided as this could result in browning of the fruit surface as well as on the spines. Room cooling is recommended but would be slow particularly if stacking and ventilation are inadequate or if the cooling capacity of the system is low.

13.4.3 Water loss

The breadnut flesh is porous, and water loss occurs if fruits are kept in storage where the relative humidity is below 85 to 90% despite the presence of spines. Studies reported by Wickham and Mohammed (1996) showed that sealing individual fruits in low-density polyethylene bags (LDPE) reduced water stress significantly compared to fruits stored as controls in paper bags. Accordingly, after two days at 28 to 30°C fruits kept in LDPE bags accounted for a percentage fresh weight loss of 2.02% compared to their counterparts stored in paper bags which had as much as 7.05%. Control fruits had a seven-fold increase in fresh weight loss after four days at ambient temperature compared to individually sealed fruits in LDPE bags. Nevertheless, in this investigation, fruits in both packages were unmarketable. In the latter package fruits succumbed to multiple pathological infections compared to the former control fruits, which were dried and withered.

13.4.4 Atmosphere

Breadnut stores well when individually packaged in low-density polyethylene films. The modified atmosphere creates a saturated microenvironment that limits water loss and also alleviates chilling if stored under refrigerated conditions. The breadnut is sensitive to ethylene, which induces rapid flesh softening and senescence.

13.4.5 Pathological disorders

Because the breadnut begins to lose firmness very rapidly if stored under ambient conditions the invasion of bacterial soft rot can be a major problem. Physical damage during harvest can also facilitate the proliferation of pathological agents. In addition, keeping the external skin under conditions where the RH is below 80% can encourage fungal growth.

If the breadnut is harvested too late or is allowed to fall on the ground during harvesting, the physical stress induced can encourage entry of fruit flies and insects into the flesh.

13.5 Packinghouse practices, storage and shipping conditions

Packinghouse operations are critical to ensure fruits of the optimum stage of maturity are selected. Due to latex exudation and subsequent brown discolourations at the cut stem end and from spine breakages, a water dip is essential. Quality checks are required prior to packing to ensure the removal of all fruits not meeting market requirements, particularly in terms of maturity and mechanical damage. Fruits should be graded according to size, external skin colour, denseness of fruits, and absence of defects arising from physical damage, as well as distorted fruit

shapes. Fruits should be individually sealed in LDPE bags and placed one layer of five to seven fruits in double-layered cardboard cartons.

Fruits should be graded in each carton according to size. Net weights should range from 12 to 16 kg. Each individual carton should be weighed, and the carton marked and labelled according to market destination. Cartons should not be overfilled during packing. The following systems of fruit sizing is recommended: large = 2.0 to 2.5 kg; small = 1.1 to 2.0 kg.

The bulk packaging should be full telescopic two-piece fibreboard cartons or one-piece self-locking waxed cartons. Fruit dividers would be desirable, as this would reduce fruit movement and rubbing. Recommended carton internal dimensions are 20 by 51 by 34 cm, or 29.5 by 44 by 29.5 cm.

It is recommended to store fruits at 8 to 9°C and 90 to 95% RH, and transport them by air. Short delays and increases in container temperatures as well as decreases in relative humidity within aircraft containers with no ventilation will encourage heat build-up and ethylene and greatly limit fruit shelf life.

Storage of seeds in excess of four to five days under ambient conditions causes the brittle-like seed coat to change from a light brown colour to a dark brown or black colour depending on the duration of storage. These dark-brown or black coloured seeds exhibit enhanced germination capabilities, and upon cooking become hard and bitter with an obvious off-flavour and off-aroma, particularly at the uppermost region closer towards germination region.

13.6 Fresh-cut processing

Enzymatic browning is initiated in the flesh and seeds from fruits harvested at the horticultural stage of maturity (weeks eight to ten after fruit set) upon exposure to air when peeled, sliced or diced within five minutes. Peeling to remove the skin and cutting of flesh into several pieces must be done at 5 to 7°C and the flesh must be dipped immediately under water or water plus vitamin C to minimize enzymatic browning. Fresh-cut slices should be stretch-wrapped in trays and stored at 7 to 8°C and 90 to 95% RH. Fresh-cut slices can be frozen, but if the flesh is stored together with the seeds the cooking quality is affected. Thus flesh and seed should be frozen separately.

13.7 Future trends

Studies to determine the breadnut's pattern of respiration are required. Work on the use of antioxidants to minimize enzymatic browning of fresh-cut slices and postharvest treatments to reduce the dramatic changes in texture are also needed. Lastly, investigations on the effects of ethylene antagonists such as 1-MCP on quality and shelf life would be useful.

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(a)

(b)

(c)

Plate XXIII Breadnut flower, immature fruit and horticulturally mature fruit (a), harvested horticulturally mature fruit showing broken spines and latex bleeding (b), edible flesh and seed (c).

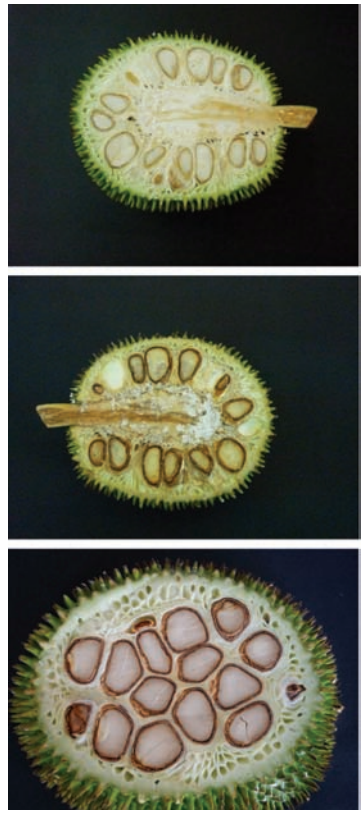

Plate XXIV Breadnut with slight chilling injury (a), with moderate chilling injury, enzymatic browning and latex staining (b), with severe chilling and translucency of seed mesocarp (c).

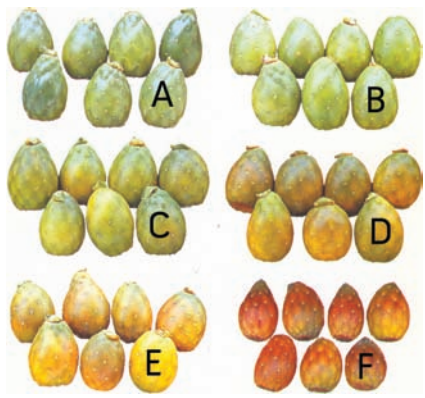

Plate XXV Cactus pear maturity stages. Image courtesy of Luz Marina Carvajal.

14

Cactus pear (*Opuntia* species)

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Abstract: *Opuntia* was originated in tropical America, but has been introduced to other regions of the world, such as Europe (particularly the Mediterranean countries) and Africa. The genus' crassulacean acid metabolism (CAM) photosynthesis allows it to adapt to areas with diverse degrees of aridity. Its fruit is currently known as cactus pear, but is also called prickly pear, tuna and fico d'India among other names, depending on the country of cultivation. Cactus pear is a berry and is mainly consumed fresh. Bioactive compounds, such as betalains, polyphenols and dietary fibre, have recently been reported in the fruit. Many processing technologies can be used to preserve the fruit. Products include dehydrated sheets, toppings and microencapsulated juices as antioxidants and colorants. This chapter discusses the postharvest physiology, technologies and processing of cactus pear.

Key words: *Opuntia*, cactus pear, prickly pear, postharvest, bioactive compounds, processing.

14.1 Introduction

The genus *Opuntia* of the Cactaceae (cactus) family contains almost 300 species. Estimates of the number of species utilized by man vary, but perhaps only ten to 12 species are commonly cultivated for production of fruit, 'nopalitos', forage or cochineal. The genus is native to North America, and its history is closely related to the ancient Mesoamerican civilizations, particularly the Aztec culture. Archaeological evidence confirms that its cultivation was initiated by natives settled in the semi-arid regions of Mesoamerica (Pimienta-Barrios, 1990; Yahia, 2011). From North America, the genus has been taken to other parts of the world including Africa and Europe (particularly the Mediterranean countries), and it is now produced and consumed in several countries (Fig. 14.1). In particular, *Opuntia* species are densely produced in the desert zones of the southern United States, north central Mexico, where the greatest genetic diversity is found, and

Fig. 14.1 Distribution of *Opuntia* spp throughout the world.

Peru. Official statistics on production levels are scarce and it is not easy to assess the size of areas planted for different purposes, i.e. fruit, vegetable, forage or cochineal production. Internationally, about 150 000 ha are devoted to the commercial cultivation of *Opuntia* for fruit, 'nopalitos' and forage (Sáenz, 2006a). In Mexico, the largest producer and consumer, around 72 000 ha are under cultivation for fruit, mainly *Opuntia ficus-indica* species, and around 10 500 ha for *nopalitos*, without considering the millions of hectares covered by wild plants (data from Flores, 1999, cited by Flores-Valdéz, 2003). In Brazil about 40 000 ha are cultivated for forage production, in Italy, 2500 ha for fruit and in Chile, around 1,100 ha (Yahia, 2011). North African countries (Morocco, Egypt, Tunisia, Algeria, Libya) are also important producers, only in Tunisia there are at least 16 000 ha devoted to fruit production (Selmi *et al.*, 2002). *Opuntia* species are also found in South Africa, Bolivia, Argentina, United States, Israel, Jordan, the Canary Islands, and Venezuela, all with smaller land areas (Sáenz, 2006a).

Opuntia species have adapted to grow and produce under low water regimes, high temperature and poor soils, adverse conditions for the production of many other crops (Nobel, 1994). They are found in a range of environments, from desert areas below sea level to high-altitude areas such as the mountains of Peru, and from tropical regions of Mexico where temperatures are always above 5°C, to areas in Canada where temperature can be as low as −40°C in the winter (Nobel, 1995; Yahia, 2011) (Fig. 14.1). The plants are xerophytes, mainly growing in arid and semi-arid zones, where the annual precipitation levels are less than 250 mm and 250 to 450 mm respectively. They are also crassulacean acid metabolism (CAM) plants (Pimienta-Barrios *et al.*, 2000) and therefore open their stomata during the night to fix CO_2 as malic acid, which is then converted into sugars during the day. As CAM plants, they are characterized by high water use efficiencies of 4 to 10 mmol CO_2 per mol H_2O, compared to C_3 and C_4 plants,

which have efficiencies of 1.0 to 1.5 mmol and 2 to 3 mmol CO_2 per mol H_2O, respectively. The cold-hardiness of *Opuntia* spp. clones used for fruit, forage or vegetable production has been reported by Le Houérou (1971), Russell and Felker (1987).

Opuntia has been described by a number of authors (Bravo, 1978; Bravo and Scheinvar, 1999; Pimienta-Barrios, 1990; Sudzuki, 1995; Scheinvar, 1995; Nobel and Bobich, 2002; Yahia, 2011). There are several species of *Opuntia* that yield edible fruit, but the most important are *O. ficus-indica, O. robusta, O. streptocantha, O. amyclaea, O. megacantha*, and *O. hiptiacantha. Opuntia ficus-indica* (L.) Mill. has gradually attained economic importance in very different areas, including Sicily (Galati *et al.*, 2002), the Mediterranean Basin (Le Houérou, 1996a), the arid highlands of western Asia (Le Houérou, 1996b), and the south-western United States (Parish and Felker, 1997; Guevara *et al.*, 2000, 1999; Gregory *et al.*, 1993; Parish and Felker, 1997). In many countries the cactus pear is considered an important re-vegetation crop to control wind and water erosion in degraded areas (Guevara and Yahia, 2005; Yahia, 2011). In North Africa, the cultivation of *Opuntia ficus-indica* cactus is also used to protect against soil erosion in arid areas, and as a forage substitute during drought.

Cactus plants serve numerous purposes, both producing fruit and vegetables, which can be eaten fresh or further processed into foods and alcoholic drinks and also acting as sources of natural colours, food supplements, pharmaceutical products, cosmetic ingredients, forage and building materials. *Opuntia* species are still only used for many of these purposes in a very few countries, but research on industrial applications of the plant is currently carried out in other regions. Research related to the development of new foods and bioactive compounds and medicinal uses of the plant has increased markedly in recent years. Food scientists and technologists are challenged to find more effective ways to preserve the fruit and the cladodes and to study the biological effects of compounds from *Opuntia* species. Due to concerns about global desertification and declining water sources, *Opuntia* spp. are gaining in importance as an effective source of food (Flores, 1995; Sáenz, 2000). Not all producing countries have an industry associated with this crop, which could be a very good source of various foods for areas where the supply of food is scarce.

14.2 *Opuntia* fruit

Opuntia fruit (Fig. 14.2a, 14.2b, 14.2c) are known at present as *cactus pear*. Some years ago FAO-CactusNet members proposed to change the name 'prickly pear' to 'cactus pear', to disassociate the fruit from the negative connotations of the word 'prickly', meaning with spines. *Opuntia* fruit are known as *higo chumbo* ('chumbo fig') in Spain, *fico d'india* in Italy, *figue de Barbarie* in France, *tuna* in Mexico, and 'prickly pear' in the United States and South Africa (however, as we mentioned before, this is evolving to 'cactus pear'). In some Arabic countries and in Israel it is known as *teen shawki* or *sabres*, which means with spiny outside, but

Fig. 14.2 Cactus pear plants.

sweet inside. In Ethiopia it is known as *beles*; in India in local dialects as *nagphani, anda torra* or *chapathi balli*, depending on the region; or simply as *higo* in Colombia. In Brazil, it is known as *palma forrageira*, since there it is cultivated mainly as a forage crop (Guevara and Yahia, 2005; Sáenz, 2006b; Yahia, 2011).

The fruit is a berry and is botanically considered as an accessory fruit formed from an inferior ovary adhering to the receptacle (Laksminarayana, 1980). The edible portion of the fruit is made up of a number of funicles intermixed with juicy papillary cells. The funicles are produced as outgrowths from the internal fruit wall and involve many black, hard seeds. The variously coloured fleshy pulp has a sweet flavour and is surrounded by a thick, fleshy skin. Fruit vary considerably in colour, size and flavour, but typically weigh 100 to 200 g. In Mexico, a sour fruit is produced by some species of *Opuntia*, which is called 'xoconostle'. This has some processing positive properties due to its higher acidity.

14.2.1 Nutritional composition, bioactive compounds and health benefits

The chemical composition of the fruit depends on several factors, such as species, cultural practices, weather conditions, plant age and fruit stage of development at harvest (Yahia, 2011). There is a large variability in the content of bioactive compounds in cactus pears and consequently in their nutraceutical potential. Generally, the nutritional and health benefits of the different cactus fruit are contributed by diverse components (Yahia and Candelario, 2011) such as pigments (Butera *et al.*, 2002; Tesoriere *et al.*, 2003), phenolic compounds (Galati *et al.*, 2003; Kuti, 2004; Pellegrini *et al.*, 2003), mucilage, fibre, and other constituents (Stintzing *et al.*, 2001; 2005; Gurrieri *et al.*, 2000; Tesoriere *et al.*, 2005; Sáenz *et al.*, 2002). A number of authors have studied cactus pear chemical composition and nutritional value (Askar and El-Samahy, 1981; Nazareno *et al.*, 2009; Sepúlveda and Sáenz, 1990; Rodríguez *et al.*, 1996; Sáenz, 2006c; Stintzing *et al.*, 2001; Pimienta-Barrios, 1990; Morales *et al.*, 2008; Yahia and Mondragon, 2011). Table 14.1 shows, as an

Table 14.1 Cactus pear pulp: chemical composition of coloured fruits (g 100 g^{-1} edible portion)

Characteristic	Green type	Purple type	Orange type
Moisture	83.8	85.98	85.1
Protein	0.82	0.38	0.82
Fat	0.09	0.02	–
Fibre	0.23	0.05	–
Ash	0.44	0.32	0.26
Total sugars	14.06	13.25	14.8
Vitamin C (mg%)	20.33	20.0	24.1
β-carotene (mg%)	0.53	–	2.28
Betanin (mg%)	–	100	–

Source: Sáenz and Sepúlveda (1999); Sáenz and Sepúlveda (2001a); Sáenz (2006c).

Fig. 14.3 Different types of *Opuntia xoconostle*.

example, the chemical composition of *Opuntia ficus-indica* coloured clones cultivated in Chile. Comprehensive information on the composition of cactus pear is not yet available due to the existence of many different species (Fig. 14.3).

The fruit is characterized by a high sugar content (12 to 17%) and low acidity (0.03 to 0.12%). The sugars are of the reducing type, with about 53% being glucose and the rest fructose (Russell and Felker, 1987; Sawaya *et al.*, 1983; Sepúlveda and Sáenz, 1990; Sáenz *et al.*, 1998). Titratable acidity is higher in the peel than in the pulp, and the pulp has a very low acid content at all stages of development (Guevara and Yahia, 2005; Yahia, 2011). The total free amino acids content is greater than that of most other fruits, and similar only to oranges and grapes. Cactus fruit is high in proline, serine, glutamine, alanine, histidine and methionine (Askar and El-Samahy, 1981). Stintzing *et al.* (2001) detected high levels of dietary taurine in fruit from *Opuntia ficus-indica*, a semi-essential amino acid considered to be a cell protective compound. Taurine has shown antioxidative effects by inhibiting the formation of reactive oxygen species (ROS). This was the amino acid found at the second highest levels after proline in three cultivars of *Opuntia ficus-indica*, cv. 'Morado', cv. 'Gymno Carpo' and cv. 'Apastillada'. In Sicilian cultivars the taurine concentration is lower than in American or South African cultivars (Tesoriere *et al.*, 2005). Storage proteins from the seeds of cactus pear (molar masses of (6,500 g mol^{-1}) have an amino acid composition similar to the 2S albumin storage protein family (Uchoa *et al.*, 1998).

Table 14.2 Mineral composition of cactus pear fruit pulps (mg $100g^{-1}$ edible portion)

Mineral	Green fruit	Purple fruit	Orange fruit
Ca	12.8	13.2	35.8
Mg	16.1	11.5	11.8
Fe	0.4	0.1	0.2
Na	0.6	0.5	0.9
K	217.0	19.6	117.7
P	32.8	4.9	8.5

Source: Sáenz and Sepúlveda (2001a); Sepúlveda and Sáenz (1990); Sáenz (2006c)

The cactus pear has a higher vitamin C content than apple, pear, grape and banana (Sáenz-Hernández, 1995). It is rich in potassium, calcium and phosphorous and low in sodium (Table 14.2). It is one of the fruits that contributes larger amounts of calcium to the diet, however, it is necessary to conduct more studies on the bioavailability of this calcium, because of the calcium oxalate crystals found in these plants (D'Aquino 1998; McConn and Nakata, 2004).

When the fruit is consumed with seeds, it contributes significantly to the fibre intake. Muñoz de Chavez *et al.* (1995) reported variable quantities of fibre, depending on the species, with a range of between 2.73 g 100 g^{-1} for *Opuntia streptacantha* and 11.38 g 100 g^{-1} for *Opuntia ficus-indica*. *O. ficus-indica* is also a potential source of pectin-like polysaccharides (Majdoub *et al.*, 2001; Sawaya *et al.*, 1983), which are hydrocolloids and also can be classified as dietary fibres. Cactus pear mucilage, which has an important role in water retention in the fruit, is a complex polysaccharide. Cactus pear peel extract is characterized by the presence of arabinose, rhamnose, xylose and galactose in the molar ratio 1.0:1.7:2.5:4.1 and a sufficiently high galacturonic acid content to make it useful as a thickener (Forni *et al.*, 1994; Matsuhiro *et al.*, 2006).

Opuntia fruit colour varies from lime green, yellow, orange, and red to purple (Inglese *et al.*, 1995; Felker and Inglese, 2003; Sáenz, 2006c; Felker *et al.*, 2008). The fruit of some types of cactus pear contain two betalain pigments, the purple-red betanin and the yellow indicaxanthin, considered some of the most interesting pigments in *Opuntia*. The betalain content of cactus pear varies. Stinzing *et al.* (2005) and Castellanos-Santiago and Yahia, (2008) identified different betaxanthins and betacyanins structures in different-coloured *Opuntia* fruits. The ratio and concentration of betalains were responsible for the yellow, orange, red and purple colours in coloured clones of *O. ficus-indica* and *O. robusta* (Stinzing *et al.*, 2005; Castellano-Santiago and Yahia, 2008). The main yellow betalain of all clones was indicaxanthin (proline adduct with betalamic acid). Castellar *et al.* (2003) studied the pigment content in three species of *Opuntias: O. stricta, O. undulata* and *O. ficus-indica*. They reported that *O. stricta* was the richest in pigments (80 mg 100 g^{-1}) and was similar in its composition to the red beet, containing betanin and isobetanin. The other species also contained

betaxantins. Sepúlveda *et al.* (2003) studied the betanin content of fourteen different types of *Opuntias* from different regions of Chile. The results indicated great betanin variability among the fruits (48.3 to 138.1 mg 100 g^{-1}). A study done on coloured cactus pear fruits from Sicily (Butera *et al.*, 2002), showed that the yellow cultivars exhibited the highest amount of betalains, found as indicaxanthins, followed by the red and white cultivars. Cactus pears also contain carotenoids. Morales *et al.* (2008) reported lower amounts of carotenoids in purple cactus pear pulp (lutein 0.15 μg g^{-1} and β-carotene 1.85 μg g^{-1}) than in the orange cactus pear (lutein 0.044 μg g^{-1}, lycopene 0.69 μg g^{-1}, and *β*-carotene 0.25 μg g^{-1}). This was the first time, to our knowledge, that lycopene was reported in cactus pear.

Betalains are soluble in water, and their stability is less affected by pH than anthocyanins, another class of natural red-purple pigments used in foods. They are relatively stable at pHs ranging from 3.0 and 7.0, which allows them to be used in low acid and pH neutral foods, such as dairy products (Sáenz, 2002; Castellar *et al.*, 2003; Azeredo, 2008; Stinzing *et al.*, 2001; 2003). Betalain stability has been studied by several authors. Viloria-Matos *et al.* (2002) evaluated the stability of betalains present in a lyophilized pulp from *Opuntia boldinghii* Br. Et R., harvested in Venezuela. The product showed maximum absorbance at 537 nm and the betacyanin content remained constant during 90 days in storage. The authors reported high water solubility of the lyophilized pigments. Coskumer *et al.* (2000) studied the effect of pH and temperature on the thermostability of yellow pigments from the peel of *Opuntia ficus-indica* growing wild in Turkey, reporting that the pH value affects the degree of thermal degradation of cactus pear pigments, being pH 5 the optimal value where the pigments show the least thermal degradation. Merin *et al.* (1987) have shown that the degradation rates of betalaines at 90°C were dependent on pigment concentration, being slower at a higher concentration. Moβhammer *et al.* (2006) studied the effect of heating at 75, 85 and 95°C for 60 min on betalain retention of yellow-orange cactus pear (*Opuntia ficus-indica*) cv. 'Gialla', after 24 h. Samples kept in the dark exhibited better pigment retentions as compared to illuminated samples. A significantly stabilizing effect was observed in samples with isoascorbic acid fortification. Indicanxanthin and betanin were predominantly degraded through hydrolytic cleavage upon both heat exposure and storage; isomerization was only marginal for betanin.

The consumption of cactus pear fruits is recommended for their beneficial and therapeutic properties associated with the bioactive components of the fruit (Livrea and Tesoriere, 2006). In the last decade, there has been a surge in interest in *Opuntia* because of its nutritional and health benefits, including, among others, improving platelet function (Wolfram *et al.*, 2003), reducing blood lipid and total cholesterol, low-density lipids, and triglycerides (Wolfram *et al.*, 2002; Wolfram *et al.*, 2003; Palumbo *et al.*, 2003), lowering isoprostane concentrations in blood indicating lower oxidative stress (Budinsky *et al.*, 2001), antiulcerogenic activity (Galati *et al.*, 2003) and liver protection from carbon tetrachloride-induced damage (Galati *et al.*, 2005).

The nutritional and health benefits of cactus fruit are currently thought to be related to their antioxidant properties, which in turn are due to their contents of ascorbic acid, phenolics including flavonoids, yellow betaxanthins and red betacyanins (Yahia, 2010; Galati *et al.*, 2003; Gurrieri *et al.*, 2000; Tesoriere *et al.*, 2003; Livrea and Tesoriere, 2006; Kuti, 2004; Chavez-Santoscoy *et al.*, 2009). The cactus pear total antioxidant activity is two-fold higher compared with pear, apple, tomato and grape and similar to that of red grape, orange and grapefruit (Yahia, 2011). Aqueous extracts of cactus pear (*O. ficus-indica*) possess a high total antioxidant capacity, expressed as Trolox equivalents, and exhibit a marked antioxidant capacity in several *in vitro* assays, including the oxidation of red blood cell membrane lipids and the oxidation of human LDLs induced by copper and 2,2'-azobis (2-amidinopropane-hydrochloride) (Butera *et al.*, 2002).

Total antioxidant activity of differently-coloured cactus fruit measured by different assays were very highly correlated among each other and also with total phenolic contents, betalains contents and ascorbic acid concentrations (Stintzing *et al.*, 2005; Corral-Aguayo *et al.*, 2008; Yahia and Mondragon, 2011). Total phenolic content had the greatest contribution to ORAC and TEAC values. Total antioxidant activity measured by six assays highly correlated with the content of vitamin C (Corral-Aguayo *et al.*, 2008). However, these correlations depend on many factors such as the different type of cactus, growing region, harvesting time, etc. Kuti (2004) isolated conjugated flavonoids (quercetin, kaempferol and isorhamnetin), ascorbic acid and carotenoids from different varieties of *Opuntia*, and found that the antioxidant activity was strongest in the purple-skinned variety. Quercetin shows the highest flavonol antioxidant activity and is one of the most predominant in coloured cactus pear. The different types of phenolics have also been associated with cactus pear colour and sensory attributes. Chavez-Santoscoy *et al.* (2009) analysed nine cactus pear juices from Mexican cultivars reporting total phenolics, flavonoids, betaxanthins, betacyanins and antioxidant capacity ranging from 22 to 226 μg gallic acid eq g^{-1}, 95 to 374 μg quercetin eq g^{-1}, 3 to 189 μg g^{-1}, 1.6 to 300 μg g^{-1} and 17 to 25 micromoles Trolox eq mL^{-1}, respectively. Morales *et al.* (2008) reported a total phenolic content of 777.43 and 371.95 mg gallic acid eq L^{-1} in purple and orange cactus pear pulp, respectively.

The antioxidant activities of vitamin C, carotenoids, polyphenols and flavonoids are well known, but betalain antioxidant activity has only been mentioned recently (Table 14.3) (Butera, 2002; Kanner *et al.*, 2001; Morales *et al.*, 2008). The purple-red betanin and the yellow indicaxanthin both have radical-scavenging and reducing properties (Forni *et al.*, 1992; Fernández-Lopez and Almela, 2001; Stintzing *et al.*, 2002; 2003; 2005; Castellar *et al.*, 2003; Odoux and Domínguez-López, 1996; Felker *et al.*, 2008; Castellanos and Yahia, 2008). Extracts from cultivars from Sicily showed antioxidant activities at 4.20 to 5.31 μmol Trolox g^{-1}, in the red and the yellow cultivar, respectively. Pure betanin exhibits a Trolox equivalent of 20.0 and indicaxanthin a Trolox equivalent of 1.76 (Butera *et al.*, 2002).

After supplementing with cactus pear (250 g twice daily) for 15 days, a remarkable increase of plasma vitamin E and C was observed, greatly improving

Table 14.3 Bioactive compounds in two coloured cactus pear pulps

Bioactive compound	Purple pulp	Orange pulp
Carotenoids (μg g^{-1} of edible pulp)	1.999 ± 0.058	0.984 ± 0.134
Total phenolics (mg GAE L^{-1})	777.43 ± 15.25	371.95 ± 12.20
Betacyanins as betanin equivalents (mg kg^{-1})	111.01 ± 0.51	29.33 ± 0.00
Betaxanthins as indicaxanthin equivalents (mg kg^{-1})	2.14 ± 0.42	89.41 ± 0.59

Source: Morales *et al.* (2008).

the oxidation stress status of healthy humans (Tesoriere *et al.*, 2004). The effects included a significant reduction in plasma markers of oxidative damage to lipids such as isoprostanes and malondialdehyde (MDA), an improvement in the oxidative status of LDL, considerably higher concentrations of major plasma antioxidants, and improvement in the redox status of erythrocytes. The inhibition of cell growth in several different immortalized and cancer cell cultures by cactus pear was also reported (Zou *et al.*, 2005). Recently, Feugang *et al.* (2009), continuing the studies done by Zou *et al.* (2005), compared Chinese and American cactus pear extracts on growth inhibition in bladder cancer cells, concluding that irrespective of cactus pear origin, the cactus pear extracts inhibit the growth of bladder cancer cells through the production of RO,S inducing apoptosis and regulating gene expression.

In order to improve the health-promoting properties of cactus pears, it is important to select cultivars with high betalain and polyphenol content and good sensory qualities. Research into the physiological effects of bioactive compounds on human health should also continue.

14.3 Fruit development and postharvest physiology

At fruit set, sugar content was very low in the fruit peel (0.1%) and fruit pulp (0.16), whereas total soluble solids are relatively high (4.5 to 5.5°Brix) (Lakshminarayana *et al.*, 1979; Alvarado, 1978). From the eleventh week onward sugars increase 100-fold, both in the peel and in the juice, but the major accumulation occurs in the final six weeks of fruit development. Glucose is generally the highest sugar, followed by fructose and sucrose. *Opuntia* fruit are non-climacteric. Their respiration rate declines during fruit development and is not different for fruit harvested at different stages of ripeness (Lakshminarayana *et al.*, 1978; 1979; Moreno-Rivera *et al.*, 1979; Yahia, 2011). The respiration rates of the fruit are temperature-dependent (Table 14.4). The fruit also produce very low amounts of ethylene (about 0.2 μL kg^{-1} h^{-1} at 20°C), and is not sensitive to ethylene exposure, but exposure at warm temperatures will enhance yellowing (Schirra *et al.*, 1997; Yahia, 2011).

Table 14.4 Respiration rates of prickly pear fruit at different temperatures

Temperature (°C)	mg CO_2 kg^{-1} h^{-1}
5	16–19
10	38–42
15	52–59
20	68–79

Source: Schirra *et al.* (1997).

14.4 Physiological disorders

Cactus pear fruit are chilling-sensitive when stored at lower than 5°C, but chilling injury (CI) may occur in some varieties even at temperatures lower than 10°C (Yahia, 2011). CI symptoms in fruit include pitting, surface bronzing and dark spots on the peel, and increased susceptibility to decay. CI occurred in a red-fruit variety after only two weeks at 6°C, but fruit from other varieties were held for a few weeks without signs of CI, and summer-harvested fruit were reported to be more chilling-sensitive than autumn-harvested fruit (Schirra *et al.*, 1999). Applications of calcium chloride, conditioning, and intermittent warming of fruit have been reported to have variable success in reducing CI (Yahia, 2011).

14.5 Diseases, rots and insect pests

Cactus plant diseases are classified as infective (biotic) or non-infective (abiotic). Infective diseases are caused by pathogens such as bacteria, fungi, phytoplasm and virus, many of which are unknown pathogens. Non-infective diseases are those associated with damage owing to the environment, the atmosphere or the soil conditions, and to genetic defects or incorrect use of pesticides (Berger *et al.*, 2006). Harvest damage to the peel and stem-end of cactus pear fruits will lead to attack by numerous pathogens and result in fruit decay (Yahia, 2011). Fungi, especially *Fusarium* spp., *Alternaria* spp. and *Penicillium* spp., are the most common postharvest pathogens on cactus fruit, but yeasts and bacteria may also be problematic. Surface decay may be minimized by dipping fruits in hot water at 53 to 55°C for five minutes and using fungicide-containing wax coatings, however these methods are ineffective when stem-ends have been damaged (Cantwell, 2002). Preharvest calcium sprays result in less postharvest decay (Schirra *et al.*, 1999).

Among the natural enemies of cactus plants are *Cactoblastis cactorum, Dactilopius opuntiae* and *Dactilopius coccus* Costa, all of which are used in Australia and South Africa to control the expansion of the plant. *Cactophagus spinolae Gyll, Chelinidea tabulata Burm, Hesperolabops gelastops Kyrkaley, Olyacella nephelepsa Dyar*, *Lanifera cyclades Druce, Dactylopies indicus Green, Seriocatrips opuntia Hood* and *Moneilema variolaris* feed on cladodes' internal tissue, decrease the production, and in some cases cause the death of the plant.

Diabrotica sp. and *Phyllophaga* spp. attack the roots of cactus and generate severe injuries (Granados and Castañeda, 1996).

14.6 Physical damage

The postharvest life of cactus pear can be significantly limited by physical damage and the fruit bruise easily during harvesting operations. Stem-end damage is considered the most serious type of physical injury, as it leads to attacks by pathogens, which result in decay (Yahia, 2011). Stem-end damage can be eliminated by careful harvesting or twisting fruit from the stem. Alternatively, fruit may be cut with a small piece of stem attached and then either packed without further treatment or cured (15 to 20°C with airflow) so that the stem dries and falls off before packaging.

14.7 Quality characteristics and criteria

Cactus pear consists of a thick fleshy skin surrounding a juicy pulp of different colours and flavours, depending on species. High-quality fruit are characterized by a high percentage of pulp, a low seed content, a peel that is easy to remove, a high sugar content (12 to 17%), low acidity (0.03 to 0.12%), and a lack of defects.

14.7.1 Maturity and harvesting indices

Opuntia plants bloom once a year in Italy, while in some other countries, such as Chile and the USA, they bloom twice per year; and cactus pear fruit take about four months from fruit set to reach harvest maturity (Alvarado, 1978; Yahia, 2011). In the variety 'Gialla' (harvested twice per year, during summer and autumn) Schirra *et al.* (1999) did not observe differences in soluble solids, acidity or pH. Ascorbic acid content was higher in summer-harvested fruit, while fruit weight was higher in autumn-harvested fruit (Berger *et al.*, 2006). The timing of the harvest is an important factor to consider as the stage of maturity or ripeness at harvest is very important for fruit quality (Plate XXV: see colour section between pages 244 and 245). Harvest times differ according to the variety, the agro–climatic conditions and whether forced blooming is used. Inglese (1995) reported that different parameters have been proposed to define the best time for harvesting the fruit, including size and fill of the fruit, changes in peel colour, fruit firmness, flower cavity depth, total soluble solids content (TSS), and fall of the glochids. Since there is no single index of harvest, various authors recommend that these be defined for each type of fruit in its area of cultivation. According to Berger *et al.* (2006), harvesting begins when soluble solids content exceeds 12°Brix and the fruit has reached its variety's target size. Peel colour is considered an important index in commercial plantations; however, soluble solids content has been reported to correlate well with colour only in some types of cactus pear fruit (Lakshminarayana *et al.*, 1979).

As an example, different 'white' cactus pear fruit maturity stages can be described as follows: 1) Mature-green fruit: well developed with a light green peel; 2) Ripening fruit: beginning to show colour change on the peel from about 25 to 75% yellow; glochids begin to fall off. Fruit usually harvested at this stage; 3) Ripe fruit: peel commonly 95 to 100% pale yellow in colour; usually soft and can be damaged easily during and after harvest; and 4) Overripe fruit: may have peel of an increasingly intense yellow colour; development of some small rusty-brown discoloured areas. The fruit has a number of prickles all over and they fall off easily when rubbed.

There are no special harvesting techniques for cactus pears, however it is important that harvesters use thick rubber or canvas-type gloves to avoid injury from prickles. It is best to begin harvesting when the temperature is as low as possible, early in the morning in order to avoid the flight of the spines in the surrounding air. Low temperatures reduce dehydration and infestation (Berger *et al*. 2006). Generally, fruit are harvested by twisting the short peduncle. The fruit are then collected in buckets or trays and then cured in the sun in order to dry out their wounds and loosen the glochids. This may be done in the field on beds of straw covered with a plastic mesh of the 'raschel' type (Fig. 14.4). Once the fruit

Fig. 14.4 Cactus pear sweep.

(a) (b)

Fig. 14.5 (a) Cactus pear arriving for packing, (b) Cactus pear fruit selection.

are dry (which will be on the day of harvest if there is sunshine), the glochids are removed using brooms made from long tender twigs. Once the fruit glochids have been removed, fruit should be packed as soon as possible and brought to a cool or refrigerated area. This is essential for prolonged storage, in order to avoid dehydration and the possibility of mould development on the fruit (Berger *et al.*, 2006) (Fig. 14.5a, 14.5b). Some harvesting aids have been tried (Lara-Lopez and Martinez-Yepez, 1985). In South Africa modified scissors are used for harvest: the fruit is cut and then caught in a metal capsule.

14.8 Postharvest treatments, cooling and storage

Storing the fruit at low temperature is very effective in reducing deterioration of visual appearance (shiny surface) due to water loss (Yahia, 2011). Cactus pear fruit are perishable and without refrigeration, they senesce rapidly and become susceptible to infections by microorganism, especially *Penicillium* spp. and *Alternaria* spp. (Berger *et al.*, 2006). They are commonly room-cooled, but may also be forced-air cooled. Cooling may be delayed if fruit undergoes a curing treatment. Fruit can be maintained for two to five weeks at 5 to 8°C and 90 to 95% RH, depending on variety, ripeness stage, and harvest season. Factors that limit fruit storage life include decay, water loss and chilling injury (CI) (Berger *et al.*, 1978; Yahia, 2011). Techniques to reduce decay and weight loss include the application of fungicides, waxes and plastic packaging, respectively (Yahia, 2011). Heat treatments, natural waxes and edible films are being considered (Berger *et al.*, 2002). High-gloss fruit waxes are especially useful when the fruit have been brushed to remove the glochids.

The fruit are susceptible to CI (Yahia, 2011). The temperatures that can be tolerated depend on the variety, harvest date and field temperatures during the

growth period. CI is manifested by reddish-brown stains on the surface; however Berger *et al.* (1978) attributed this discoloration more to damage by spines rather than to CI. Berger *et al*. (1978) claimed that the fruit could be stored under refrigeration for a period of up to two months at 0 ± 0.5°C and 85 to 90% RH. However in Italy, Chessa and Barbera (1984) reported that the temperature of storage should be between 6 and 9°C, since lower temperatures produced CI and increased decay. In cactus pear fruit cv. 'Gialla' from Italy, harvested in two seasons (summer and autumn) and stored at 6°C, CI was greater in the summer-harvested fruit than in fruit harvested in autumn. In addition, weight loss of summer-harvested fruit was 0.15 and 0.27% per day during storage and simulated marketing conditions period, respectively, while in autumn-harvested fruit it was 0.08% and 0.23%, respectively (Schirra *et al.*, 1999). Martínez-Soto *et al.* (1999) found that the optimal storage temperature for cactus pear fruit cv. 'Roja pelona' was 10°C, which allowed conservation for 60 days.

Interest has been increasing in the last decade in the use of heat treatments to control post-harvest decay (Lurie, 1998). These treatments increase the shelf life of fruit and vegetables and may replace fungicides. Water immersion treatments at 55°C for two minutes expanded the post-harvest life and maintained good fruit quality for 31 days. The effect of heat treatment and waxing, intensified fruit colour and shine, improved the fruits' external appearance, and the symptoms of weight loss were invisible (Berger *et al.*, 2002).

Post-harvest treatments of cactus pears (*Opuntia ficus-indica* Miller (L.) cv. 'Gialla') with 1,000 mg L^{-1} thiabendazole (TBZ) at room temperature did not affect the development of slight-to-moderate CI, but reduced severe CI by approximately 50% and the development of decay by 63.4% (Schirra *et al.*, 2002). The effectiveness of TBZ was much higher with treatment at 150 mg L^{-1} at 52°C, providing 91% control of severe CI and approximately 89% suppression of decay; while with no treatment, damage occurred during storage and simulated marketing period. External appearance was better in fruit treated with 150 mg L^{-1} TBZ at 52°C. Respiration rate, titratable acidity, soluble solids contents, and acetaldehyde in the flesh were not significantly influenced by treatments, but ethylene production rate and ethanol levels in the flesh were significantly higher in the TBZ-treated fruit.

14.9 Packaging, modified atmospheres (MA) and controlled atmospheres (CA)

Fruit are commonly packed according to colour and size (Piga *et al.*, 1996) in ventilated wooden or plastic crates, 4.5 kg cartons, or in single- or double-layer tray cartons (Yahia, 2011). They are also loose-packed in 4.5 to 9.0 kg cartons or boxes. Individual fruit, especially large fruit, may be separated from each other, either wrapped with tissue paper or nested on a celled tray or separated by cardboard bands to reduce scuffing and other physical injury (Yahia, 2011). Fruit may also be packaged in cartons with perforated plastic liners to reduce water loss

under dry storage conditions. Fruit packaging in plastic film limits dehydration (1.5% versus 3.7%) and CI, and improves fruit appearance (Piga *et al.*, 1996; Garcia-Vite *et al.*, 2003). However, wooden crates are commonly used for harvesting and for transport to local markets (Berger *et al.*, 2006).

Very little work has been done on the MA and CA of cactus pear fruit, but holding at 5°C in 2% O_2 + 2 to 5% CO_2 can delay ripening and senescence, and extend storage life of fruit (Yahia, 2009; 2011). Galletti *et al.* (1997) stored cactus pear fruits at 0°C under 2% of O_2 and 5% of CO_2, and found that the lowest incidence of decay was at 21 days and that fruit maintain their sensory characteristics for 42 days. In Italy under similar O_2 and CO_2 conditions during storage at 5°C, better quality characteristics were obtained in those stored under normal atmospheric conditions (Kader, 2000; Yahia, 2009; 2011). Brito *et al.* (2009) stored cactus pear fruit, harvested at two maturity stages (light green and green-yellowish) under MA and refrigeration. Fruit were maintained under MA using 12 μm PVC film and normal atmospheric conditions as control (AA) and stored at 10°C and 92% RH. CI started at 11 days of storage under AA and was higher in fruit harvested at the light green maturity stage. The use of MA for the same maturity stage delayed this disorder, maintaining general appearance above the acceptance limit (score 4 of a 1 to 9 scale) independent of the maturity stage, however, was kept higher for light green fruit under MA, up to 18 days storage reaching a yellow-orange colour by the end of storage. Weight loss was higher for fruit kept at AA and much higher for green-yellowish cactus pear fruit, reaching close to 10% losses at 18-day storage. Fruit kept under MA lost nearly 3% weight. The light green fruit kept firmer under MA compared with green-yellowish cactus pear. MA for light green cactus pear was efficient in delaying ripeness and extending post-harvest life up to 18 days storage at 10°C.

14.10 Processing

The current focus for food technologists is to produce safe and healthy foods. As mentioned above, cactus pear has many bioactive components that need to be preserved during processing. Studying the effects of traditional processing technologies on bioactive components will be a challenge for research in the coming years. Many different kinds of products made from *Opuntia* species are already on the market, mainly in Mexico. Although the main food product from *Opuntia* species is currently nopalitos (young cladodes), several cactus pear fruit products also exist (Sáenz, 2000; 2006d; Yahia, 2011). Some chemical and physical characteristics of cactus pear pulp that are significant for processing are shown in Table 14.5. Processing this fruit is a great challenge. The high pH value (5.3 to 7.1) means that it is classified as a low acid food (pH >4.5) requiring thermal treatment at 115.5°C or higher to control micro-organisms. The high content of soluble solids also makes the cactus pear's pulp a very attractive medium for the growth of micro-organisms.

Table 14.5 Some chemical and physical characteristics of purple and green cactus pear pulp

Parameters	Green pulp	Purple pulp
pH	5.3–7.1	5.9–6.2
Acidity (% citric acid)	0.01–0.18	0.03–0.04
Soluble solids (°Brix)	12–17	12.8–14.5
Pectin (g 100 g^{-1})	0.17–0.19	–
Vitamin C (mg 100 g^{-1})	4.6–41.0	20.0–31.5
Calcium (mg 100 g^{-1})	12.8–27.6	–
Colour parameters		
L* (Lightness)	18.2–26.7	22.4–33.4
a* (Red-green)	−4.2–(−5.5)	10.0–18.4
b* (Yellow)	4.0–6.5	1.1–4.3
C* (Chroma)	5.8–8.5	10.1–18.9
h° (Hue)	130.2–136.4	6.2–13.2
Viscosity (mPa s)	73.9	119.2

Source: Askar and El-Samahy (1981); Pimienta-Barrios (1990); Sawaya *et al*. (1983); Sepúlveda and Sáenz (1990); Sáenz and Sepulveda (1999); Sáenz (2000).

14.10.1 Fresh-cut (FC) processing

Fresh-cut (FC) technology could help to increase the consumption of cactus pear, as this produces a product without spines. To produce a high-quality product, the fruit to be processed must be of high quality, conditions must be hygienic, the temperature needs to be low (less than 10°C) during processing, the temperature must be constant during refrigerated storage, and the correct type of plastic film must be used for packaging, among other factors (Fig. 14.6a, 14.6b, 14.6c). Fruit at the optimal maturity stage is required, because when the fruit is overripe, peeling and slicing before packaging causes the mucilage to drip. The product then becomes less visually attractive and microbial growth is promoted.

The shelf life of FC cactus pear was extended and chemical and sensory attributes (*Opuntia ficus-indica* cv. Gialla) were maintained for eight days by placing the FC product in polystyrene trays sealed with polyolefinic film and storing it at 4°C (Piga *et al.*, 2000; 2003). It was reported that FC fruit texture was maintained by storage in ethylene-vinyl acetate (EVA) for seven days at 5°C (Sáenz *et al.*, 2001). Modified atmosphere packaging (MAP) at 4 to 8°C for up to seven days was reported to reduce microbial spoilage by mesophilic bacteria (*Staphylococcus* spp., *Enterobacter* spp., *Leuconostoc mesenteroides*), as well as yeasts (Corbo *et al.*, 2004). Oyarce (2002) evaluated whole and peeled fruit at different fruit maturity stages. Different citric acid solutions (0.25, 0.5, and 1.0%) were evaluated as preservatives, compared to a control immersed in water. The whole, peeled fruits can be stored for up to 14 days with good microbiological and quality characteristics at 5°C. The total count of mesophilic aerobic bacteria was below 5×10^4 ufc g^{-1}, and considered safe. Citric acid immersion did not affect organoleptic quality. Añorve *et al.* (2004a) studied the composition of the most

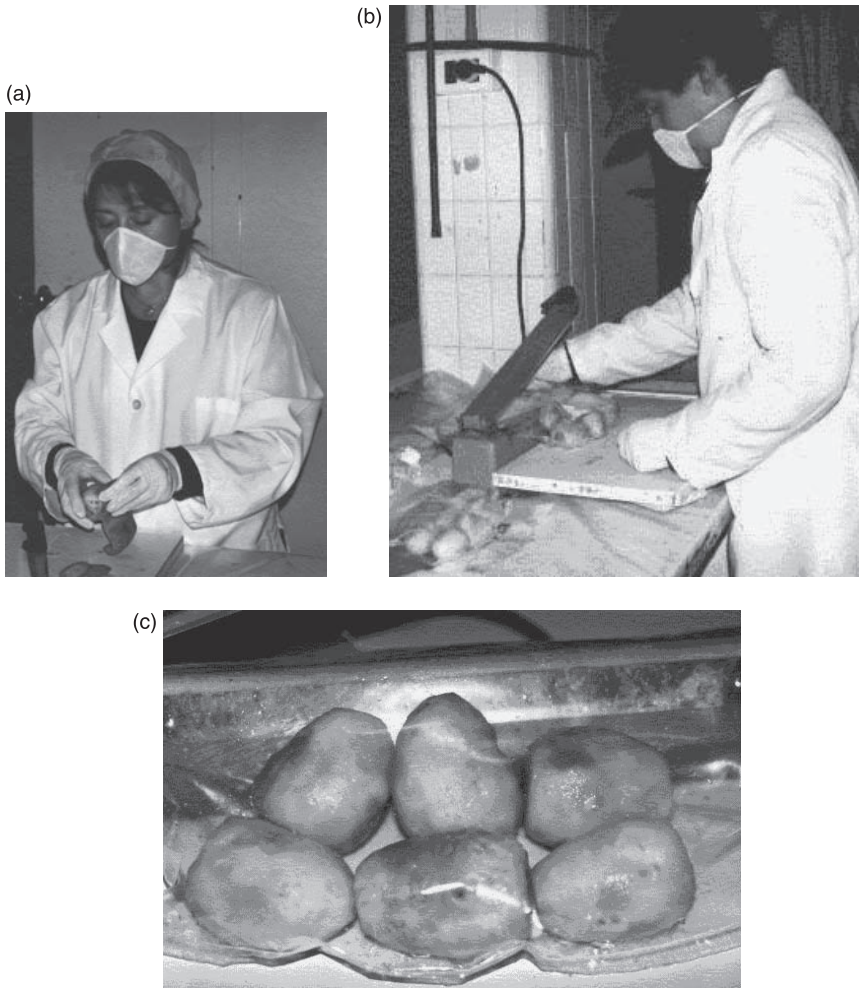

Fig. 14.6 (a) Fresh cut cactus pear manual peeling, (b) Fresh cut cactus pear bag sealing, (c) Fresh cut packed cactus pear.

appropriate CA for maintaining the quality of minimally processed cactus pears. Peeled 'Cristalina' cactus pear fruit were stored at 2°C in different CAs (air, 3% O_2, air + 10% CO_2 and 10% CO_2). After ten days of storage, the author reported that fruit stored in air retained excellent visual quality. After 15 days the fruit preserved in atmospheres containing 10% CO_2 and 3% O_2 + 10% CO_2 maintained an excellent quality. The quality of the fruit stored in 3% O_2 + 10% CO_2 decreased to very good after 20 days' storage, while the fruit stored in 3% O_2 suffered a decrease in quality in the same period. The phenolic content of fruit preserved in

air in the study by Añorve *et al.* (2004a) increased from 1.45 to 9.7 mg catechin g^{-1} in freeze-dried tissue, but the fruit under CA showed different levels of inhibition of phenolic compounds. Similar behaviour was reported by Piga *et al.* (2003), suggesting that CA storage inhibits the synthesis of phenolics and the formation of condensed polyphenols. Using the same variety, Añorve *et al.* (2004b) studied the effect of temperature (2, 6 and 10°C) on the quality of minimally processed cactus pear preserved under a constant air flow. The increase in phenolic content was directly influenced by temperature and was linked to colour changes, suggesting an association between phenolic content and colour. The best temperature for preserving fruits for up to 12 days, but avoiding darkening, was 2°C. Microbiological quality was not reported in these studies, but is an important point to be considered.

Other studies on whole or halved peeled *Opuntia amyclae* have been carried out using three film types: polyolefin, 19 micrometers thick (PO19), and co-extruded and bi-oriented polypropylene (25 and 35 μm). Whole or halved fruit could be stored at 4°C for up to 20 days without any loss in quality. Maintaining in adequate plastic film resulted in less weight loss, better fruit shine, less production of ethanol, and the highest percentage of juice drained from the pack (Corrales and Sáenz, 2006).

14.10.2 Dehydration

Russell and Felker (1987) mention dried cactus pear as another edible processed product. Peel and seeds are the waste materials of the cactus pear-processing industries, and the peel can make up 40 to 60% of the whole fruit, depending on the cultivar. Lahsani *et al.* (2004) studied the drying kinetics of cactus pear peel (1 g pieces), in a convective solar dryer. The main factor influencing the drying kinetics was the air temperature. In a slightly modified preservation procedure, Ewaidah and Hassan (1992) tested dried cactus pear sheets using the 'Taifi' cultivar, sucrose, citric acid, olive oil and sodium metabisulphite. Sodium metabisulphite improved the colour, and citric acid produced an acid taste similar to that of traditional apricot sheets. Sepúlveda *et al.* (2000) developed fruit leather made with cactus pear and quince pulp, without preservatives. The authors tested different proportions of pulp and found the best blend to be 75:25 cactus pears: quince pulp. The blend was dehydrated in a forced air tunnel in thin layers until the moisture level was close to 15 to 16%. The product had a pleasant texture, and the components of the fruit gave it moistness, allowing direct consumption. This kind of product is well liked by children and can be considered an energy food, with caloric values of about 319 to 327 cal 100 g^{-1}. El-Samahy *et al.* (2007) prepared yellow-orange sheets by adding different ratios of sucrose (0, 1, 2, 3, 4, 5 and 10%). The prepared pulp was dehydrated in an air oven at different thicknesses (5, 10 and 15 mm) and temperatures (60 and 70°C), reaching the best scores of total acceptability with sheets containing 2 and 3% sugar, and there were no significant differences between the control and the sheets containing 1, 2 and 3% sugar in aroma, colour and texture. Drying rates decreased by

increasing the thickness of cactus pear layer, and were faster at 70°C than at 60°C. Recently, Lisham (2009) prepared attractive coloured cactus pear bars with apple pulp, sucralose and flax seeds to increase fibre content (Fig. 14.7 and 14.8). The total phenolic content was 151.6 to 166.2 mg GAE 100 g^{-1} for orange and purple cactus pear bars, respectively (Table 14.6). These kinds of products have good perspectives as healthy foods, and could be prepared by blending with other fruit

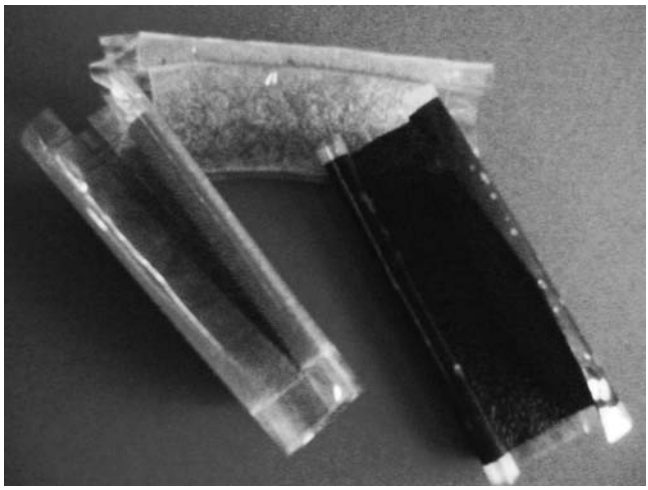

Fig. 14.7 Cactus pear sheets ready for consumption.

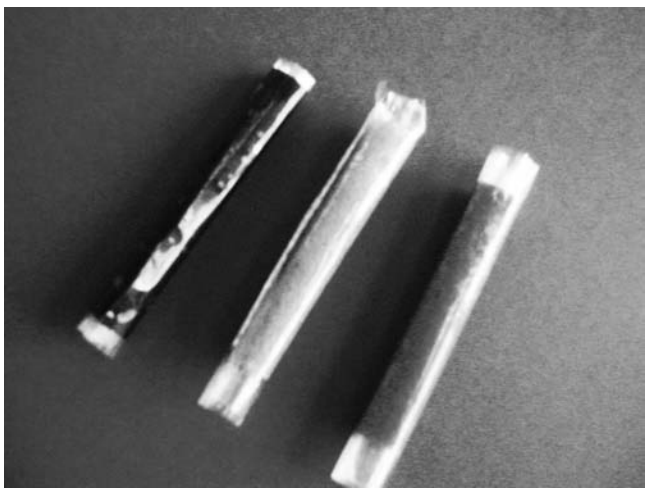

Fig. 14.8 Cactus pear sheets.

Table 14.6 Bioactive compounds in cactus pear bars from coloured fruit pulp

Bioactive compounds	Orange pulp	Purple pulp
Polyphenols (mg GAE 100 g^{-1})	151.6 ± 2.9	166.2 ± 1.2
Soluble dietary fibre (g 100 g^{-1})	5.6 ± 1.8	7.5 ± 0.9
Insoluble dietary fibre (g 100 g^{-1})	32.2 ± 1.9	36.4 ± 2.5
Total dietary fibre (g 100 $^{g-1}$)	38.8 ± 2.6	43.9 ± 2.2

Source: Lisham (2009).

pulps. For small-scale production they are easy to prepare and involve low-cost technologies. Solar energy could be used, especially in rural areas.

14.10.3 Juices and pulps

Two of the most common domestic uses of cactus pear, besides fresh consumption, are as juices and pulps. The technology for the production of cactus pear fruit juice is more complex than that for acidic fruits and those that have less delicate flavours and aromas. Special control of pH and the durations and temperatures of heat treatments is required, since these are critical not only for preservation but also for final product quality. Treatments for pasteurization of green pulp also need to be different from treatments for cactus pear juices or pulp of other colours, since betalains are more stable under heat treatment than chlorophylls (Plate XXVI: see colour section between pages 244 and 245). The first trials to design processing procedures to produce pasteurized cactus pear fruit juice were carried out in Mexico more than 30 years ago, but the results were inconclusive. Some authors described the character of the flavour and aroma of the juices produced as pleasant, while others indicated how difficult it was to achieve appropriate levels of microbiological safety and slow down acetic fermentation of the juice, even after reducing its pH by the addition of lemon juice. Some studies on juice production are summarized below.

Cactus pear (*Opuntia ficus-indica* cv. Cardona) juice was processed with added citric acid to reduce pH value to 4.3 and sodium benzoate (500 ppm), treating it thermally for five mins at 90°C of (Paredes and Rojo, 1973). The juice was then vacuum canned in enamelled tins, and the product was reported to have a pleasant flavour and taste, but not microbiologically stable. Espinosa *et al.* (1973) studied *Opuntia ficus-indica* juice, and found several difficulties with its preservation. In spite of reducing the pH value to 4.0 with lemon juice and carrying out a mild thermal treatment (20 mins at 80°C), the acetic fermentation continued and the juice could not be preserved. Later, Carrandi (1995) evaluated the microbiological behaviour and the chemical and sensorial characteristics of the juice of green pulp cactus pear fruit. The treatments applied to the juice included two types of additives, a natural extract of grapefruit seeds (Kilol®) and potassium sorbate, which is normally accepted in the food regulations of many countries. The juice was pasteurized in a HTST system (98 to 100°C, 20 to 22 s), and packed

immediately in glass bottles, which were sealed in a room with UV light. After cooling, the bottles were stored at 0 to 5°C for 15 days. It was concluded that additives tested were not effective in ensuring microbiological stability, since, no matter which preservative was used, lactic acid fermentation (produced by *Lactobacillus*) was observed within two to three days. After this failed trial, the same author, using a more drastic thermal treatment such as bottle juice treatment (100°C during 20 mins), produced a product that was safe and stable, but did not resemble fresh cactus pear juice, owing to the changes that occurred to the colour, flavour and aroma.

In countries where consumers are accustomed to consume fresh cactus pear juice, preservation technologies need to be able to produce juices as similar as possible to fresh juice. El-Samahy *et al.* (2007) in Egypt, using orange-yellow cactus pear, prepared juices in several different ways. Pulp was mixed with sugar solution (1:1), and adjusted before thermal treatment at 15°Brix and pH 5. This prepared juice was divided into three parts. The first part was filled into 100 mL glass bottles after heating to 80°C and then pasteurized in boiling water for 25 min (the temperature inside the bottle was 95°C). Sodium benzoate at 100 ppm was added to the second part and then it was pasteurized under similar conditions to the first one. Lastly, the third part, once filled into glass bottles after heating to 80°C, was sterilized directly at 121°C for 10 mins. The juice bottles were stored at room temperature (28°C) or refrigerated (8°C). The total bacterial count following all treatments was low, with absence of yeasts, moulds and coliform groups during 6 months' storage, but the sensory characteristics were better in the pasteurized juice than in the sterilized ones. The deterioration of colour, taste and odour in the sterilized juices had been severe, probably due to the effect of the thermal treatment on pigments and aroma; in spite of using yellow-orange cactus pear, in which betalains are more heat-stable, high temperatures caused deterioration. Moβhammer *et al.* (2005) developed a process for the production of clarified juice from *Opuntia ficus-indica* cv. 'Gialla' and 'Rossa'. The authors screened enzymes to choose the best preparation, selecting Pectinex Ultra Sp-L for 'Gialla-2002' and Fructozym MA-X-Press for 'Rossa-2002'. Typical unit operations for fruit juices were applied after peeling. The juices, despite high amounts of amino acids and reducing sugars, did not show Maillard browning, and a cactus pear juice with an attractive appearance was obtained.

Another possibility is to produce concentrated juices. The lower a_w of the concentrates compared with natural juices provides clear protection against microbial growth and can extend the shelf life of the juice. Concentrated juices up to 63 to 67°Brix can be obtained in an α-Laval centrifuge vacuum evaporator or similar equipment, working close to 40°C (Sáenz, 2000). The stability of the juice against the growth of micro-organisms was good, but the sensory analyses indicated that their acceptability was relatively low. This was due to colour (chlorophyll damage) and herbaceous aroma resulting from the concentration process (Sáenz and Sepúlveda, 2001b).

As already mentioned, treatments have different effects on green pulps and juices compared to those of different colours. The changes in colour that occurred

in green pulp cactus pear juices were studied by Sáenz *et al.* (1993). Heat treatment caused a deterioration of chlorophyll and a loss in green colour compared with the fresh juice, which was milky-white and more opaque. The same was observed with concentrated juices (68.8°Brix) stored at different temperatures (2, 10, 20, 27 and 37°C); the juices stored at room temperature became darker with time, showing an increase in the colour parameter a* (from −2.84 to −0.57) which according to the CIELab notation indicates the contribution of green or red, depending on whether the value is negative or positive, respectively. These results indicate that the colour characteristics of green cactus pear fruit juices, concentrated as well as unconcentrated, are clearly affected by storage time and temperature, which means that it is necessary to take this into account in the design of industrial processing and in storage recommendations for these products. The colour stability of juices from purple, red or orange cactus pear fruit is quite different. The absence of chlorophylls is an advantage in this type of fruit. Colour contributes to fruit appearance and consumer preference. Barbagallo *et al.* (1998) produced a slightly concentrated purée (37%) from cactus pear fruit cv. 'Gialla', compared the product to natural pulp and found that the colour, as well as the aroma and flavour of the concentrate were similar to the natural product. The acidity was modified with citric acid to pH 4.0. The authors concluded that the slightly concentrated purée could be a useful ingredient for the confectionery industry and for the semi-processed sector. Cassano *et al.* (2007) studied the potential of a membrane-based process for the clarification and concentration of cactus pear fruit juice from *O. ficus-indica* cv. 'Gialla', to overcome some of the problems associated with thermal evaporation. The juice was concentrated up to 61°Brix and the results represent a valid approach to preserve the nutritional and sensorial characteristics of the juice, using low temperatures.

Juice technologies appear as promising alternatives mainly for purple or red cactus pear. Both natural (pasteurized) or concentrated juices and pulps are possible (Fig. 14.9).

These concentrates could be consumed directly after dilution and also could be used as colorant in other foods, increasing antioxidants intake. According to Sáenz *et al.* (2002), yoghurt containing low doses of concentrated purple cactus pear and high in betanin (100 mg 100 g^{-1}) was preferred by panelists to raspberry yoghurt (Sáenz *et al.*, 2002). Moreno-Alvarez *et al.* (2003) used fresh cactus pear pulp from *Opuntia boldinghii*, a species without commercial uses in Venezuela, to colour citrus beverage. The beverage was 15% orange juice + 15% rape-fruit juice + 65% water + 5% cactus pear pulp, formulated with 0, 0.01, 0.1 and 0.5 ascorbic acid. The products were pasteurized and stored at 7°C using amber bottles. A higher betalain retention was observed in the formulation with higher ascorbic acid content. As pigments are also present in the peel of some cactus pear cultivars, the whole fruit could be used to increase the juice yield. The concentrated purée could be a good ingredient for the candy and beverages industry as a semi-processed product.

Freezing is perhaps one of the most promising technologies for production of high quality pulp, for use (when diluted) in the preparation of refreshing drinks,

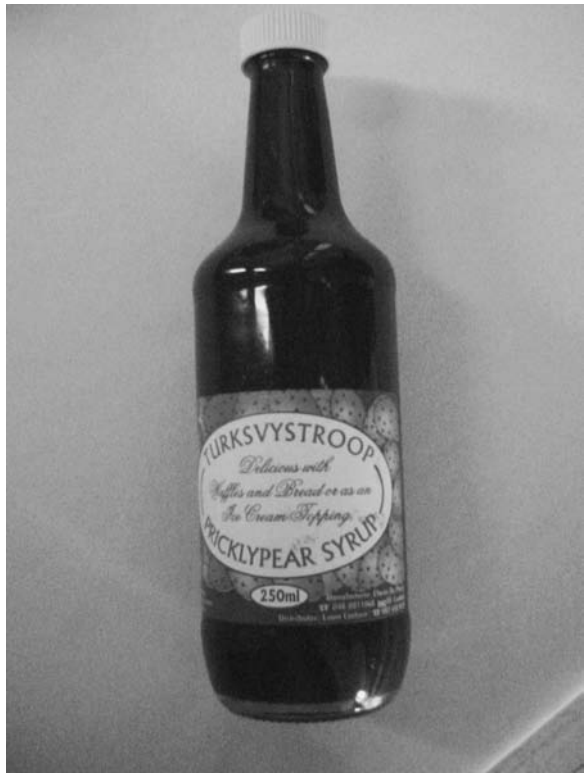

Fig. 14.9 Cactus pear syrup from South Africa.

as well as in the preparation of other foods such as pastries, ice creams, liquors, and jams. This product is not marketed on a large scale globally, except in California (USA) where a red cactus pear pulp, sweetened to 22 to 24°Brix, is made. Nevertheless these products represent an interesting option. Freezing processes have been applied to other fruits and vegetables for many years, and if cactus pear chemical characteristics are taken into account, they can also successfully be applied to cactus pear fruits. Bunch (1996) reported the production of a versatile and stable product frozen purée made from purple cactus pear and some percentage of pineapple juice, which could be used in a number of beverages and food dishes.

From the juice, it is also possible to produce other types of products such as syrups, toppings, nectars and vinegars. Chutney type foods are another alternative not developed yet for the cactus pear. Sáenz *et al.* (1998) developed a process to obtain a natural liquid sweetener from cactus pear juice. The high sugar content of the sweetener and its composition, mainly fructose and glucose, make this product very attractive, but one of the difficulties is the juice clarification stage. The fruit's mucilage makes the juice cloud very stable and many enzymes were tested to

hydrolyze it. The best result was achieved using an enzyme preparation made up of a mixture of pectinolytic enzymes with a high arabanase activity (Pectinex AR). The process to obtain this syrup or natural sweetener begins with cactus pear juice extraction. Afterwards, the juice (16.5 °Brix) is enzimatically clarified (as described above), carbon decolorized, filtered and vacuum concentrated to 60°Brix. The product had 60°Brix (56% of glucose, 44% of fructose), a density of 1.2900 gmL^{-1}, water activity (a_w) of 0.83 similar to that of honey or marmalade, and a light golden-yellow colour with a viscosity of 27.1 mPa. The sweetness was 67 compared with sucrose. These characteristics are similar to those of other liquid sweeteners currently marketed. The high enzyme doses used in this process compared with the traditional juice treatments (apple, pear and others) makes it necessary to investigate other types of enzymatic treatment.

Ruiz-Cabrera *et al*. (2004) carried out tests to produce dehydrated juice powder, by spray drying *Opuntia streptacantha* juice. Although no details were provided of the storage life or the rehydration properties of the product, they did indicate a significant loss of vitamin C, from 23.65 mg 100 mL^{-1} in fresh juice to 10.28 mg 100 mL^{-1} in dehydrated juice. The role of the mucilage in this process could be studied. These macromolecules, as has been mentioned before, retain a great amount of water, making juice preservation by liophylization difficult. The product maintains a very attractive colour but its high hygroscopicity make it difficult to re-hydrate and dilute.

Sauces or toppings are currently very popular in international gastronomy. They are used to dish up desserts, are added to fruits and are diluted with water to make beverages. Coloured *Opuntias* have a great potential to prepare this kind of products with functional properties. Morales *et al.* (2008) studied several topping formulations from purple and orange cactus pear. The highest level of betanin was identified in the purple cactus pear pulp (111.0 $mgKg^{-1}$), whereas the orange pulp showed the highest amount of betaxanthins (89.4 $mgKg^{-1}$). Total phenolics were 777.4 and 371.9 mgL^{-1} for purple and orange pulp, respectively. Lower amount of carotenoids such as lutein, lycopene and β-carotene were found in both pulps (Table 14.7). The bioactive compounds, carotenoids, polyphenols and betalains, showed degradation close to 90, 50 and 30%, respectively, due to the thermal processing used to prepare the toppings, betalains being the most stable.

Table 14.7 Bioactive compounds in two coloured cactus pear toppings

Bioactive compounds	Purple topping	Orange topping
Carotenoids (μg g^{-1} of edible pulp)	0.186 ± 0.001	0.021 ± 0.001
Total phenolics (mg GAE L^{-1})	350.50 ± 15.25	131.48 ± 5.72
Betalains	81.06 ± 1.83	63.80 ± 1.86
Betacyanins (mg betanin kg^{-1})	66.09 ± 1.03	0.92 ± 0.00
Betaxanthins (mg indicaxanthin kg^{-1})	14.97 ± 1.53	62.88 ± 1.86

Source: Morales *et al*. (2008).

The sugar content of fruit juices has been exploited for many years for the production of fruit vinegars. Pérez *et al.* (1999) prepared vinegar from orange-coloured cactus pear fruit, using for the acetic fermentation a must with a previous alcoholic fermentation (A), a cactus pear juice with sugar added (22°Brix) and different *Acetobacter*. The resulting product had excellent yellow colour and fresh aroma, as the fermentation of the juice with added sugar was rapid (Table 14.8). Prieto *et al.* (2009) produced balsamic type vinegar from cactus pear fruit. The process begin with the fermentation of a concentrated cactus pear juice (30°Brix) with wine yeast (*Saccharomyces cerevisiae*), until it reaches 4 to 5° GL. Afterwards, the 'must', was acetified until a level of 35 to 43 gL^{-1} acetic acid degrees was reached in the vinegar. The residual sugar was between 21 and 25 gL^{-1}. The vinegar from the orange and purple cactus pear juice was more acceptable than that from the green cactus (Fig. 14.10). Vinegar from purple cactus pear appears to be a new and attractive processed product, even for rural areas, as the technologies involved are relatively simple and inexpensive.

14.10.4 Other traditional products

Jam is one of the most well known and widely accepted products consumed on a large scale worldwide. It is easy to make, available in different types and can be made from a wide variety of fruits. Jam is obtained through concentration by boiling fruit pulp with sugar, pectin and citric acid, to ensure adequate gelling. The preservation process, like dehydration, is based on the reduction of a_w. Generally, preservatives (sodium sorbate and/or potassium benzoate) are added in order to conserve quality once the pack has been opened. Corrales and Flores (2003) summarized the general process for the production of jam from 'Cardona' cactus pear fruit (*Opuntia streptacantha*). The fruit, without peel, is screened to

Table 14.8 Physical and chemical analysis of two types of vinegar produced from cactus pear fruit

Parameter	Vinegar (substrate A)	Vinegar (substrate B)
Density ($g\ L^{-1}$)	1.013	1.0127
Volatile acids (%)	6.71	9.8
Non-volatile acidity (%)	0.0132	0.0181
Dry matter (%)	5.33	4.27
Ash (%)	0.982	0.832
Alkalinity of ash (%)	0.374	0.567
Chloride (%)	0.768	0.27
Oxidation index (%)	1112	1204
Total aldehydes (%)	0.625	0.0006
Final acetic acid level (%)	6.7	9.8
Fermentation time (days)	183	40

Source: Pérez *et al.* (1999).

Fig. 14.10 Balsamic-type cactus pear vinegar.

separate the seeds; the resulting thick juice is mixed with sugar, pectin, citric acid, preservatives (sodium benzoate); the mixture is concentrated in an evaporator (or in an open pot) until it reaches 65 to 67°Brix; it is packed hot into glass jars and after cooling labels are applied. Aguirre *et al.* (1995) tested different species of *Opuntia* and different formulations of jams packed in glass jars, using whole cactus pear fruit with or without peel, or only the pulp, with the addition of sugar, citric acid and pectin. Jam produced from whole fruit with peel achieved the highest rating, and also had a processing advantage, as there is no need for a manual peeling operation. Since the pulp contains seeds, it is necessary to employ a stone mill to obtain adequate and acceptable texture in the jam, which means that jam production using pulp and seeds must be carried out on at least a semi-industrial scale. Earlier, Vignoni *et al.* (1997) tested two formulations, one which included 55% sugar, lemon juice and lemon peel and one which had only 55% sugar added. No sensory difference was found between the two formulations. Jam from the acid variety *Opuntia xoconostle* is marketed in Mexico and it is known for its attractive colour (Fig. 14.11a, 14.11b).

Heat treating to obtain products such as canned cactus pear fruit, generally does not give good results, since the fruit texture and colour change and the sensory quality of the canned fruit is low. Both of these characteristics need to be studied further, since good colour and texture are difficult to attain (Sáenz-Hernández, 1995). In South Africa, Joubert (1993) studied the changes in texture of the fruit of various cultivars and colours when they were canned. The process consisted basically of peeling the fruit and placing it in cans with syrup at 20°Brix, acidified

(a)

(b)

Fig. 14.11 Food products from (a) *Opuntia xoconostle* and (b) *Opuntia xoconostle* juice.

Fig. 14.12 Canned xoconostles in syrup.

with citric acid (to reduce pH to 4.2) and then thermally treating it at 100°C for 15 min. The product's texture, flavour and colour deteriorated. The deterioration of texture was reduced when 0.25% $CaCl_2$ was added to the syrup. The trials using syrup without citric acid resulted in the formation of gas inside the cans within a few days, which confirmed the importance of the control of pH in this type of product, and in particular for this fruit. Fruits of *Opuntia xoconostle*, canned in syrup are currently marketed in Mexico. Since this is an acid fruit, less drastic heat treatment is required in the canning process (Fig. 14.12).

In Latin America it is very common to consume gelled candies or sweets made from fruit pulps and sugar. Several products are marketed based on various fruits such as quince, Malabar squash (*Cucurbita ficifolia*), a range of berries, apple, etc. Sáenz *et al.* (1997) studied the development of gels from pulps of cactus pear, using green pulp from fruits of *Opuntia ficus-indica*. Sugar, and a gelling agent, carrageenan were added to the pulp (35 to 40%). Two levels of pH were tested: 3.5 to prevent microbial growth and 6.1 (original pH of the pulp). A strong colour change was observed when the pH was reduced, due to the transformation of chlorophylls to pheophytins, but the product retained its chemical, physical and sensorial characteristics for more than 14 days under refrigeration (4 to 6°C). If the sugar concentration were increased, refrigeration storage could be avoided, similar to commercial products.

Liquors and other fermented products are obtained from cactus pear. *Colonche* is one of the best-known products in Mexico. It is a low-alcohol drink, produced from the juice of *Opuntia streptacantha*. Wine and *aguardiente* (distilled liquor) from cactus pear fruit juice are other products that have been available in Mexico for many years. An artisanal food industry close to Mexico City produces liquors

Fig. 14.13 Xoconostle juice and liquor.

from *Opuntia xoconostle*, obtained by macerating the fruit pulp in high-degree alcohol. Years ago a Sicilian industry introduced liquors from red *Opuntia* to the Italian market (Fig. 14.13).

One of the needs within the cactus pear industry is the development of new processed cactus pear products to utilize the waste (peel and seeds). Cactus pear fruit contains a variable amount of seeds, generally in high proportions (10 to 15 g 100 g^{-1}). Sawaya and Khan (1982) and Sepúlveda and Sáenz (1988) analysed the yield and composition of oil extracted from the seeds of cactus pear fruit grown in Saudi Arabia and Chile, respectively. They found a high proportion of unsaturated fatty acids, an important content of linoleic acid, and a low level of linolenic acid, which could affect its stability. This suggests that the seeds are a potential source of edible oil. El Kossori *et al.* (1998) analysed the seeds of fruit grown in Morocco, highlighting not only the oil, but also the content of fibre (54.2 g 100 g^{-1}), which was mainly cellulose. Using the seed would only be of interest in the context of integrated cactus pear utilization due to the low oil yield obtained (6 to 17%) when compared with other commonly used oilseeds. With the same aim Ramadan and Mörsel (2003) studied the peel oil, which El Kossori *et al.* (1998) reported to be 2.43% (dry weight), and reported a value of 3.68 g 100 g^{-1}. Linoleic, oleic and palmitic acids were the major fatty acids, comprising more than 75%. The fatty acid profile of peel shows it as a good source of the nutritionally essential oleic acid, as well as polyunsaturated fatty acids such as γ-linolenic acid. However, oil yield from seeds and peel is low, and could only be a reasonably good source of lipid production from a massive cactus pear industry.

14.10.5 Encapsulation technologies

The stability of betalains and polyphenols is an important aspect to consider for their use as antioxidants and colourants in foods, and could be improved using microencapsulation technologies, such as spray drying. Microencapsulation is a technique whereby a bioactive compound is encapsulated by a biopolymer, thereby protecting it from oxygen, water, or other conditions so as to improve its stability (Desai and Park, 2005). This method is also used to change liquid solutions to powders, which are easier to handle. Rodríguez-Hernández *et al.* (2005) studied spray drying as a technique for stabilizing cactus pear pulp from *Opuntia streptacantha*, and recently Sáenz *et al.* (2009) tested inulin and maltodextrin as an encapsulating agent for cactus pear pulp (*Opuntia ficus-indica*) (Fig. 14.14). The recovery of polyphenols was over 100%, which could be a consequence of the hydrolysis of the cactus pear polyphenol conjugates during the preparation of the samples or during the drying process (Table 14.9). An increase in phenolic compounds was observed in all systems during storage at 60°C. Indicaxanthins in all systems showed a slow degradation during storage at 60°C and better stability than betacyanins. The microcapsules (Fig. 14.15a, 14.15b) are interesting food additives for incorporation into functional foods, as the substances they contain are both antioxidants and red colourants.

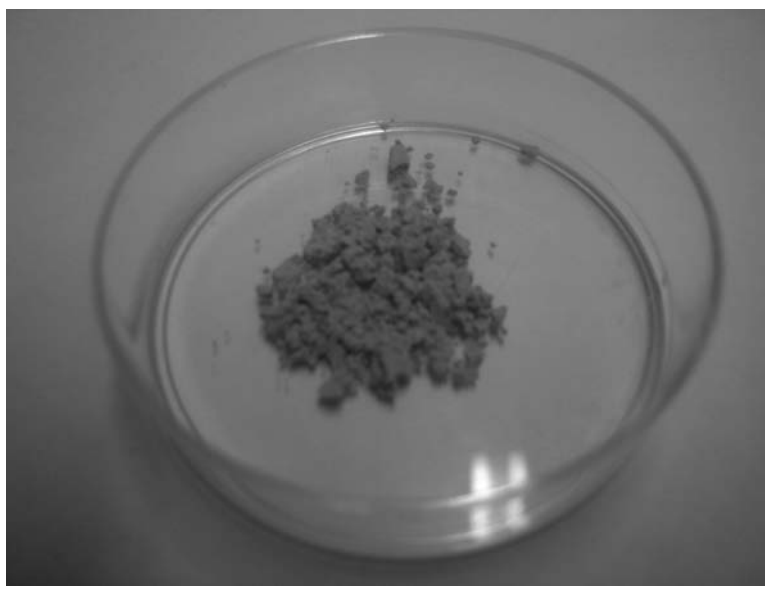

Fig. 14.14 Microcapsules of purple cactus pear pulp.

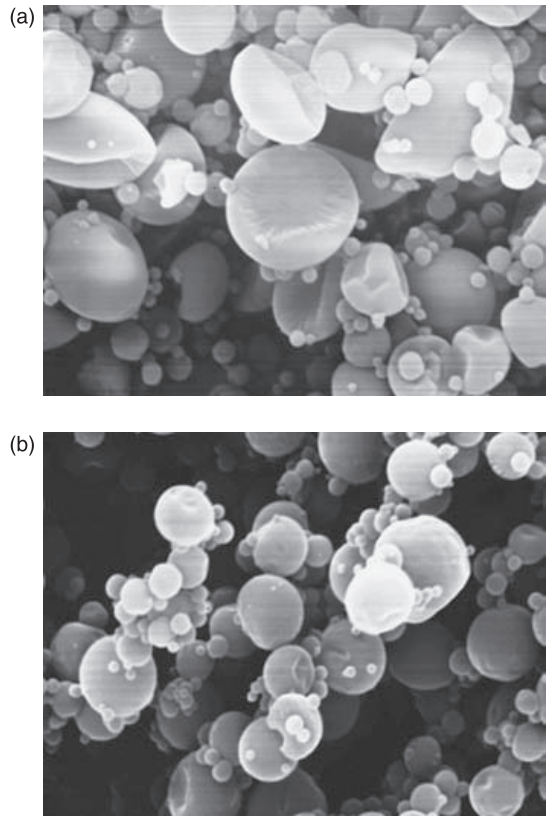

Fig. 14.15 Scanning electron microscopic photographs of microcapsules for (a) the cactus pear pulp-matodextrin and (b) the cactus pear pulp-inulin.

Table 14.9 Bioactive compounds content of cactus pear pulp before and after encapsulation

System		Betacyanins (mg BE g^{-1}powder)	Indicaxanthins (mg IE g^{-1}powder)	Polyphenols (mg GAE/g^{-1} powder)
CP-MD	Before spray-drying*	0.58	0.21	1794
	After spray-drying	$0.6 \pm 6 \times 10^{-3}$	$0.22 \pm 1 \times 10^{-3}$	2135 ± 0.0
	Recovery (%)	100	100	119
CP-I	Before spray-drying*	0.58	0.22	1802
	After spray-drying	$0.64 \pm 9 \times 10^{-3}$	$0.24 \pm 2 \times 10^{-3}$	2028 ± 4.5
	Recovery (%)	100	100	112

Notes
CP: cactus pulp, BE: betanin equivalent, IE: indicaxanthin equivalent, GAE: Gallic acid equivalent, MD: Maltodextrin, I: Inulin.
* Calculated according to polyphenols' pulp content.
Source: Sáenz *et al*. (2009).

14.11 Conclusions

Cactus pear fruit (*Opuntia*) is extensively cultivated in several parts of the world, because it adapts to a wide range of soils and environmental conditions, and can grow in arid regions. The fruit is popular in different countries and contains important nutritional and health components such betalains, polyphenols and dietary fibre, among others. Despite increasing interest in the fruit, research that has been carried out during recent decades, knowledge about its bioactive components and functional properties that has been generated and new processing technologies developed, great challenges still remain and it is important to continue research into this 'treasure under the thorns'.

14.12 References

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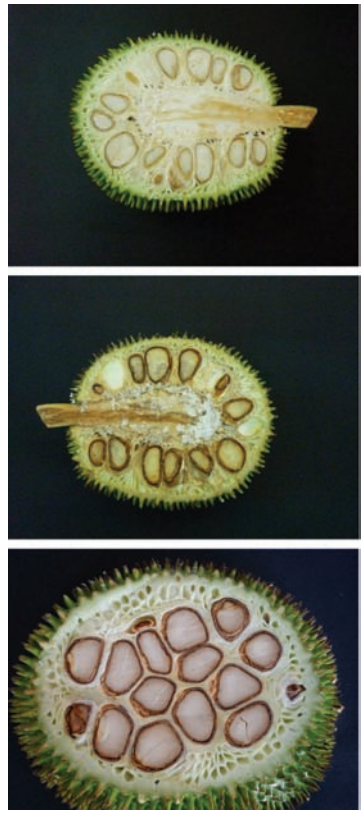

Plate XXIV Breadnut with slight chilling injury (a), with moderate chilling injury, enzymatic browning and latex staining (b), with severe chilling and translucency of seed mesocarp (c).

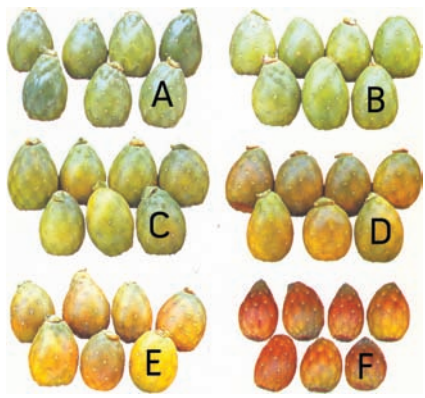

Plate XXV Cactus pear maturity stages. Image courtesy of Luz Marina Carvajal.

Plate XXVI Coloured cactus pear juices.

Plate XXVII Cajá fruits and pulp.
Photo: Rafaella Mattietto.

15

Cajá (*Spondias mombin* L.)

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Abstract: Cajá (*Spondias mombin* L.) is a small fruit, native to the tropical Americas, that grows abundantly in Brazil. This chapter focuses on the botanical and physiological aspects of cajá, followed by its importance and uses, postharvest physiology and composition, pests, storage recommendations, and finally, some processing possibilities. The fruits have a thin layer of pulp, which is extracted for commercial uses. Even though it is still obtained from an extractive production system, cajá has attracted commercial interest due to its flavor and aroma characteristics and its nutritional quality.

Key words: *Spondias mombin*, postharvest, yellow mombin, extractive culture, functionality, pro-vitamin A, processing.

15.1 Introduction

15.1.1 Origin, botany and morphology

The cajá tree is found widely throughout the tropical Americas. In Brazil, it is abundant, especially in the North and Northeast regions (Western Amazon and Atlantic Forest), where it occurs naturally in groups or in isolation. These are probably zones of species dispersion (Prance and Silva, 1975; Mitchell and Daly, 1995). It is reported that cajá is present from South Mexico to Peru, and Asia and Africa are also cited in the literature as continents where the cajá tree may be found. There has been some discussion about the origin of this species. According to some authors, its origin is in the American continent, as it can be found throughout tropical Americas. However Duvall (2006) has evaluated the evidence of an African origin based on bio-geographical, ecological and historical aspects and considers that the natural dispersion of plants at large distances is usual. This is not always accepted, though, and most authors still support the idea that *Spondias mombin* was introduced to Africa, rather than originating there.

Spondias mombin belongs to the *Spondias* genus, which is part of the *Anacardiaceae* family that includes 73 genera and about 850 species. Its fruits are

known as *cajá miúdo* or *cajá pequeno* (Southeast and Southern Brazil), *taperebá* (Amazon), *prunier mombin* (French Guiana), ciriguela del monte and jacote (Guatemala), *azucaró* and *cedrinho* (Bolivia), *ciruella amarilla* (Mexico and Ecuador), *jobo* (Central America), *hogplum* or *yellow mombin* (North America), *ambaló* (Goa) and *munguengue* (Angola) (Sacramento and Souza, 2000).

The tree is tall and can be 30 m high. Its trunk, which is straight and cylindrical and coated by a thick and rough bark, is 40 to 60 cm in diameter and branches in its terminal part. The leaves are composed and alternated, with five to eleven pairs of leaflets that are petiolate and have short (5 cm long) petiolules. Leaflet blades are oblong (5 to 11 cm long by 2 to 5 cm wide) with a full margin and an acute apex. Rachis are 20 to 30 cm in length (Prance and Silva, 1975).

This species has small flowers, which are hermaphrodite, staminate, pistillate and protandrous, which favors cross-pollination and genetic variability in orchards. The inflorescence is composed of pedunculate flower bunches. Each flower has five sepals, five petals, ten stamens, a gynoecium with an ovary formed by five carpels coinciding with the number of loculi and five free styles with linear and dorsal stigmas. The number of flowers per panicle may reach more than 2000; however, in spite of this, only about 30 fruits are formed per inflorescence. The flowers appear after the vegetative lag phase that occurs at the same time the branches emerge (Lozano, 1986; Silva and Silva, 1995; Sacramento and Souza, 2000).

Cajá fruits (Plate XXVII: see colour section between pages 244 and 245) are characterized as drupes with an oval or oblong shape, flattened at the base. The peel that coats the fruit is smooth and thin, with colors varying from yellow to orange (Vieira Neto, 2002). The edible part, a thin layer of pulp, varies similarly in color, which is related to its carotenoid composition. It is a very juicy and aromatic pulp, with a sweet–sour taste.

The seeds are large, white, lignified and rough. They are claviform or reniform in shape, in varied amounts. They are situated in the endocarp, a tuberculate structure in pentagonal form. The endocarp is the most characteristic part of the fruit due to its consistent mass that contains the loculus and the parenchyma, a spongy tissue that covers the botanical seed (Lozano, 1986; Villachica *et al.*, 1996; Azevedo *et al.*, 2004). The endosperm is thin, starchy and adheres to the internal tegument surface. The embryo is axial, with a similar seed form and light cream color, possessing flat and flesh cotyledons (Cardoso, 1992). While studying the morphology of the cajá tree, Souza *et al.* (2000) have confirmed the existence of variation in the number of loculi (two to five) and seeds (zero to five) contained by the fruit. The prevailing morphology contains four loculi (52.8%) and one seed (44.8%) in the endocarp, with no seed formation (15.2%) also considered normal.

15.1.2 Phenology and reproduction

The cajá tree may be considered a perennial or semi-deciduous plant, depending on the region's climate. It is heliophytic, a selective hygrophyte and is fast growing (Lorenzi, 1992; Justiniano *et al.*, 2001; Pinto *et al.*, 2003a). It may be found in upland and lowland forests, commonly in inhabited places, bordering channels of

natural drainage and in other humid areas, as well as in the savanna. The plant is also found in secondary formations, where it spontaneously regenerates. Usually, the cajá tree develops well in humid, sub-humid and hot weather. It may also be found in temperate-hot weather and it is reported to be tolerant to dry periods, although it cannot be considered xerophytic (Sacramento and Souza, 2000). It prefers growing in alluvial soil, which has neutral to slightly alkaline pH and is rich in nutrients. Deep and well-drained soils are recommended for the satisfactory development of its roots, whereas plantations in areas with a slope greater than 20% are not recommended (Justiniano *et al.*, 2001, Fraife Filho *et al.*, 2008).

The harvest period varies strongly between the production areas, depending on climatic factors, which include the typical rainfall, and non-climatic environmental factors, such as soil type and the intrinsic constitution of the plant, in other words its genetic variability. According to some studies, the genetic diversity levels for *Spondias mombin* L. are higher than those related to other tropical tree species (Silva, 2009; Gois *et al.*, 2009). In Brazilian states, the harvest period in the two main production regions usually occurs from December to February in the Amazon and from March to May in the Northeast region (Sacramento and Souza, 2000; Bosco *et al.*, 2000). However, fruit production is reported all year round in some regions.

In Brazil, the cajá is obtained on the whole from extractive production systems. It is cultivated domestically, but there are few commercial plantations. There is increasing demand for cajá fruits, which is not met, even in Brazil's internal market, due to seasonality of production and a lack of commercial plantations. Expanding cajá tree cultivation is therefore necessary and for this to be possible, cajá tree breeding and propagation and production methods must be studied. The tree may be propagated by seed or in a vegetative way by cuttings, grafts, plantations of shoots, roots, or by micropropagation (Carvalho *et al.*, 2002). However, there are reports that vegetative propagation of Spondias by cuttings using existing technology has significant limitations and the technology for commercial production of seedlings is non-existent (Souza, 1998). Among the methods of asexual propagation, grafting has been successfully used in cajá fruit culture. However, the best grafting method is still the subject of debate among the scientists. Some authors recommend cleft grafting while others indicate that splice and side-veneer grafting are better methods. Such divergence is explained by researchers as being a consequence of the great genetic variability of fruit trees.

Some studies on the nutritional demands of the cajá tree show that it responds to organic fertilization and rotation of production although this has not yet been reported in the n without literature reports. Alves (2009) has observed that the maximum production of cajá fruits (22.8 kg per plant) was as a result of a dose of 30 g of triple superphosphate, 45% of P_2O_5 per plant.

In the area of genetics, some of the recent research has investigated the genetic diversity of the cajá tree, using molecular and isoenzymatic markers, and aimed to characterize genotypes to estimate the repeatability coefficients of morphological and agronomical characters. These studies indicate that large genetic diversity exists, even within the accessions of a unique germplasm bank. The observed variability in almost all of the characteristics studied permits the identification of

superior genotypes, which may assist in the selection of plants for the establishment of commercial orchards (Gois *et al.*, 2009; Silva, 2009; Soares *et al.*, 2008; Da Silva *et al.*, 2009). The results of studies of some populations suggest that *Spondias mombin* has high potential for the *in situ* conservation and for seed production (Gois *et al.*, 2009).

15.1.3 Importance, culinary and medicinal uses, nutritional value and health benefits

In the production regions, cajá fruit is valued for its exotic flavor, intense aroma and easy acceptance by consumers. Despite the fact that cajá is still not entirely domesticated and its trade is reliant on extractive production, its productive potential is high, generating jobs and income during harvest period in all the areas where it naturally occurs.

It is often eaten fresh, however, due to its high acidity and perishability, the processed fruit is more frequently consumed. Cajá frozen pulp is the most common processed product, as it does not require advanced technology or great investment. The lack of these is a constraint of the main Brazilian production regions. Various other products are also derived from the frozen pulp, including juices, nectars, jams, ice-creams, candy bars, fillings, fermented drinks, liqueurs, and many others.

Like most tropical fruits, cajá has good nutritional value, including good levels of minerals and vitamins. The physico-chemical characteristics and proximal composition of fresh cajá pulp are shown in Table 15.1. As usually observed in fruit pulps, cajá contains high levels of moisture and low levels of lipids. The fruit is characterized by its high acid content (low pH) and contains low amounts of mostly reducing sugars. Moreover, it contains low amounts of protein and fiber, although these values are still appreciable when compared to other fruits. Cajá fruit is very rich in potassium, which is its major micronutrient. Because of that, it should be consumed in moderation by people with high risk of hyperkalemia (Albino *et al.*, 1999). The amounts of micronutrients such as iron, manganese and copper are significant (Mattietto, 2005). As shown in Table 15.1, cajá pulp contains about 11 to 28 mg.100 g^{-1} ascorbic acid.

The yellow color of cajá pulp indicates the presence of carotenoids, which contribute to the attractive appearance of the fruit and products derived from its pulp. The following carotenoids have been found in cajá pulp: lutein, zeinoxanthin, β-cryptoxanthin, cis-β-cryptoxanthin, α-carotene, β-carotene, and phytoene. β-cryptoxanthin, lutein and zeinoxanthin were the main carotenoids present (Hamano and Mercadante, 2001; Tiburski, 2009). Mendonça (2004) analysed the total carotenoids content of 19 plants from the Brazilian Northeast region (Teresina, Piauí) and observed that it varied from 8.9 to 16.0 $\mu g.g^{-1}$, with an average value of 12.3 $\mu g.g^{-1}$. Some of the carotenoids in cajá pulp are some vitaman A precursors, mainly β-cryptoxanthin and β-carotene and some have been shown to be antioxidants. According to Rodriguez-Amaya and Kimura (1989), β-cryptoxanthin was the major pro-vitamin A source in cajá.

Table 15.1 Characterization and nutritional composition of fresh mature cajá pulp, according to different authors

	Barbosa *et al*. (1981)	Bora *et al*. (1991)	MS (2002)	Mattietto (2005)	Tiburski (2009)	Silva *et al*. (2009)
pH	2.1	3.38	–	2.77	2.83	2.28
Total acidity (% citric acid)	1.65	1.71	–	1.28	1.46	1.62
Total soluble solids (°Brix)	10.2	11.73	–	8.58	14.9	9.35
Total sugars (%)	–	–	–	4.54	–	7.61
Reducing sugars (%)	6.74	5.35	–	4.25	–	7.49
Moisture (%)	–	–	–	89.42	83.66	89.23
Total proteins (%)	–	0.25	0.80	0.82	1.06	0.67
Total lipids (%)	–	0.66	2.10	0.26	0.62	0.34
Fibers (%)	–	1.10	1.00	1.18	1.87	1.48
Ascorbic acid (mg.100 g^{-1})	11.06	20.80	28.00	23.72	–	20.18
Ash (%)	–	–	–	0.58	0.76	0.41
Calcium (mg.100 g^{-1})	–	28.60	26.00	21.76	11.03	–
Phosphorus (mg.100 g^{-1})	40.00	26.35	31.00	23.05	32.84	–
Iron (mg.100 g^{-1})	–	1.20	2.20	1.08	0.32	–
Sodium (mg.100 g^{-1})	–	–	–	–	5.55	–
Magnesium (mg.100 g^{-1})	–	–	–	22.87	15.09	–
Potassium (mg.100 g^{-1})	–	–	–	177.14	288.27	–
Manganese (mg.100 g^{-1})	–	–	–	0.35	0.025	–
Zinc (mg.100 g^{-1})	–	–	–	0.19	–	–
Copper (mg.100 g^{-1})	–	–	–	0.20	–	–
Boron (mg.100 g^{-1})	–	–	–	0.15	–	–
Sulphur (mg.100 g^{-1})	–	–	–	10.46	–	–

The phenolic compounds present in the cajá pulp have also been largely studied in terms of their antioxidant effects and their possible benefit implications to human health. Table 15.2 shows the carotenoids and phenolic compounds content of fresh cajá pulp, as reported by different authors.

Jacinto *et al.* (2004) have studied the antioxidant activity of the cajá extract in a homogenate of mouse brains. They used α-tocopherol as a standard and verified that the cajá extract had good antioxidant activity only at the highest concentration tested (10 mg.mL^{-1}).

Table 15.2 Bioactive compounds in cajá pulp

	Kimura (1989)	Rodriguez-Amaya and Kimura (1989)	Mattietto (2005)	Rufino (2008)	Tiburski (2009)
Total phenolics (mg.100 g^{-1})	–	–	–	579.2 ± 4.4	260.21 ± 11.89
Tannins (mg.100 g^{-1})	–	–	314.78 ± 0.37	–	–
Antioxidant activity (μmolTrolox.g^{-1})	–	–	–	40.7 ± 0.2	17.47 ± 3.27
Total carotenoids (μg.g^{-1})	17.3 ± 2.0	22.86 ± 3.76	38.56 ± 0.13	–	48.69 ± 1.57
Vitamin A (RE.100 g^{-1})*	135.00	120.9	47.3	–	223.0

Note: *Calculated as 6 μg of β-carotene = 1 μg RE and 12 μg of β-cryptoxanthin + cis-β-cryptoxanthin + α- carotene + (9-cis- + 13cis-β-carotene) = 1 μg RE.

Araújo *et al.* (2004) concentrated cajá pulp proteins to 90% saturation and evaluated their inhibitor effect against mammalian digestive enzymes (bovine trypsin, human salivary α-amylase and porcine pancreatic α-amylase). Inhibitory activity of the pancreatic α-amylase was higher in cajá (0.0345 mg of inhibitor per gram of pulp) than in other tropical fruits. Even though the importance of α-amylase inhibitors in human nutrition is not yet very clear, some studies suggest that the medical use of these inhibitors causes reduction in the starch absorption in the intestinal lumen that could, theoretically, influence the digestion of carbohydrates in diabetic or obese patients (Layer *et al.*, 1985).

Spondias mombin species also have medicinal uses. Biological effects of parts of the tree other than the fruit, such as the leaves, bunch and bark have been reported in the literature. Scientific studies confirm that cajá has natural anti-fungal and antiviral properties. Corthout *et al.* (1991) isolated two ellagitannins (geranin and galloilgeranin) from the leaf extracts and observed pronounced antiviral activity against *Herpes* (type 1) virus and *Coxsackie* virus. Other studies cited abortifacient activity (Offiah and Anyanwu, 1989), beta lactamase inhibitory activity (Coates *et al.*, 1994), anti-inflammatory activity (Villegas *et al.*, 1997), antimicrobial and astringent effect (Abo *et al.*, 1999), antipsychotic effect with potential use in psychiatric disorders (Ayoka *et al.*, 2005), and anti-diabetic activity using α-amylase inhibitory activity of the 3β-olean-12-en-3-yl (9Z)-hexadec-9-enoate from *S. mombin* leaf (Fred-Jaiyesimi *et al.*, 2009).

15.2 Fruit development and postharvest physiology

In Brazil, the cajá fruit development cycle, from the flower to complete maturity on the tree, takes about 125 days. This is dependent on environmental conditions, which may vary depending on the production region. According to Moura *et al.*

(2003), who studied plants from the Northeast of Brazil, maturation of the fruit begins around 97 days and ends 117 days after anthesis. Bosco *et al.* (2000) studied cajá trees from the Northeast region and observed that the period time from fecundation to fruit maturity was 85 to 88 days.

Studies on cajá postharvest physiology, including studies on cajá fruit respiration, are still scarce. Recently, a study by Sampaio *et al.* (2007) determined degrees of fruit ripeness according to respiration and physico-chemical data. The data obtained indicated the initial stages of ripening, pre-climacteric, minimum climacteric, maximum climacteric and post-climacteric (Sampaio *et al.*, 2007). In this study an adapted method was used for measuring CO_2 and O_2 concentrations of the modified and controlled atmospheres. The maximum CO_2 production was 54.2 $mL.kg^{-1}.h^{-1}$, maximum O_2 consumption was 49.0 $mL.kg^{-1}.h^{-1}$ and the average respiratory quotient (which represents the carbohydrate oxidation) was 1.11. According to the authors, the climacteric rise commenced after about 108 hours of storage, reaching a maximum after 186 hours and was followed by the start of the senescence process. This gives the fruit a shelf life of about 8 days, which is an appropriate period of time to transport the green-mature fruit to the commercial centers.

Changes in fruit composition are associated with alterations in cajá respiratory behavior postharvest. Filgueiras (2001) reported a significant increase in total soluble solids from 8.36°Brix in the initial stage of ripening to 11.56°Brix in the mature stage. Sampaio *et al.* (2007) have also reported an increase of this parameter from 9.1°Brix (initial) to 13.7°Brix (climacteric maximum) during maturation, while acidity decreased from 1.55% to 1.40% in pre-climacteric, 1.0% at climacteric maximum, and 0.8% in the post-climacteric stage. A similar phenomenon was observed in the ascorbic acid content, where the initial value of 13.1 $mg.100\ g^{-1}$ decreased to 11.6 in pre-climacteric, 8.0 at climacteric maximum, and 7.4 $mg.100\ g^{-1}$ in the post-climacteric stage (Sampaio *et al.*, 2007).

Sampaio *et al.* (2007) have also observed that the degradation of chlorophyll, as well as the increase in carotenoids, occurs simultaneously with different climacteric phases. The fruit exocarp color changes from dark green in the pre-climacteric to light green in the minimum climacteric and orange-yellow at the climacteric peak. The orange-yellow color is maintained in the post-climacteric. The color change from green to yellow orange in the fruits of cajá tree may be considered an important sign of physiological maturation.

Tables 15.3 and 15.4 show the physico-chemical parameters variation during respiration of the cajá during postharvest, based on the previously published data.

15.3 Maturity and quality components and indices

Mature cajá fruit has a pleasant yellow color and attractive flavor. It is a small oval fruit, with a diameter varying from 13.3 to 33.0 cm and length from 15.0 to 48.5 cm. Its weight varies from 1.4 to 20 g (Moura, 2009; Mattietto, 2005).

Table 15.3 Changes in the physical and chemical parameters during postharvest respiration of cajá fruit

Ripening stage	Time (hour)	Relative humidity (%)	Temperature (°C)	Total soluble solids (°Brix)	Titratable acidity (%)	Brix-acid (ratio)	Ascorbic acid (mg%)
Initial	48	86.0 ± 4.2	27.8 ± 1.9	9.1 ± 0.6	1.35 ± 0.39	6.7	13.1 ± 1.0
Pre-climacteric	54	89.8 ± 1.9	28.5 ± 1.1	9.6 ± 1.2	1.31 ± 0.56	7.3	11.6 ± 1.3
Climacteric min.	102	88.1 ± 3.7	28.5 ± 0.8	10.9 ± 0.9	1.20 ± 0.07	9.1	10.2 ± 1.0
Climacteric max.	168	91.7 ± 2.3	29.2 ± 0.8	13.7 ± 1.0	1.0 ± 0.04	13.7	8.0 ± 0.8
Post-climacteric	192	88.6 ± 2.1	28.9 ± 1.1	13.1 ± 1.2	0.8 ± 0.1	16.4	7.4 ± 1.1

Source: Sampaio *et al.* (2007).

Table 15.4 Cajá characterization in four degrees of ripeness

Parameter	Degree of ripeness*			
	1	2	3	4
Weight (g)	13.62	14.05	15.91	19.93
Length (mm)	3.72	3.79	3.97	4.31
Diameter (mm)	2.65	2.67	2.81	3.22
pH	2.86	3.04	3.10	3.17
TSS (°Brix)	8.37	9.27	10.30	11.57
TTA (% citric acid)	1.25	1.12	1.08	1.03
TSS/TTA (ratio)	6.93	8.31	9.57	11.24
Total sugars (%)	4.95	6.04	7.23	8.41
Reducing sugars (%)	4.19	5.15	6.29	7.66
Starch (%)	3.55	2.59	1.93	0.52
Total chlorophyll (mg.100 g^{-1})	9.71	5.60	2.89	2.36
Total carotenoids (mg.100 g^{-1})	0.54	0.71	0.78	0.91
Total phenolics (%)				
Water soluble	0.12	0.11	0.11	0.12
50% methanol soluble	0.13	0.14	0.13	0.15
Pure methanol soluble	0.11	0.11	0.11	0.12
Total pectin (%)	0.28	0.18	0.14	0.28
Soluble pectin (%)	0.07	0.09	0.10	0.08
Fractionated pectin (%)				
High metoxilation	2.96	3.45	9.75	10.31
Low metoxilation	0.63	0.83	0.88	2.12
Protopectin	0.77	1.30	1.09	2.21
Poligalacturonase ($U.g^{-1}.min^{-1}$)	19.22	20.77	19.78	18.32
Pectinmetilesterase ($U.g^{-1}.min^{-1}$)	350.31	281.38	305.22	362.32
Vitamin C (mg.100 g^{-1})	43.01	39.80	36.89	36.86

Notes: * Degrees: 1 – green, 2 – mostly green, 3 – mostly yellow, 4 – mature yellow; TSS: total soluble solids; TTA: total titrable acidity.
Source: Filgueiras (2001).

Soares *et al.* (2006), studying 15 genotypes of the cajá from Northeast of Brazil (Teresina, Piauí), suggested that the fruit weight ranged from 5.7 to 16.5 g, with an average value of 9.9 g. The pulp average yield was about 72.6%. Bosco *et al.* (2000) have proposed a cajá fruit classification scheme based on weight. The fruit is considered small if its weight is lower than 12 g, medium between 12 and 15 g, and big, when greater than 15 g. In a study with 19 plants from Northeast Brazil, Mendonça (2004) concluded that 84% of the fruits were small as their weight was lower than 12 g, 5% were medium and 11% big. Mendonça has also observed that the weight of the fruit did not influence the pulp yield, with the smaller fruits offering higher yields, with an average value being 69.77%. Pinto *et al.* (2003b) evaluated 30 genotypes of the cajá tree from the Bahia state, also in the Northeast region, and obtained an average weight of 12.12 g (range: 6.20 to 18.00 g), showing the species' genetic diversity.

The average pulp yield was 70.7% and the seed weight was 4.34 g. Pulp yield may vary according to the region and equipment used for extraction, though. For example, Filgueiras (2001) have obtained 81.65% yield when working with the cajá fruits in the Northeast region, while Mattietto (2005) obtained only 33.25% yield with cajá fruits from the Northern region. The chemical composition of the mature fruits has already been presented in Tables 15.1, 15.2 and 15.4 (stage 4) according to the previously published data.

The mature cajá fruit is very aromatic. Augusto *et al.* (2000) reported a comparative study of aromatic compounds in Brazilian fruits, including cajá. They detected 34 volatile compounds in the fruit, when using solid-phase microextraction-gas chromatography–mass spectrometry. The main groups they have identified were the alcohols, aldehydes, esters, ketones and terpenic compounds. The study by Ceva-Antunes *et al.* (2003) included the identification of volatile compounds of cajá from two different regions in Brazil, the North (Pará state) and Northeast (Ceará state). There were similarities in their composition with 30 compounds being identical. The main groups were hydrocarbons and esters while the main compounds were (*E*)-caryophyllene (18.7%), ethyl butyrate (10.0%) and ethyl hexanoate (7.0%) in cajá from the North region while myrcene (41.1%) ethyl hexanoate (4.9%) and butyl butyrate (3.9%) were the most abundant cajá compounds from the Northeast. Narain *et al.* (2004) also evaluated the aroma of tropical fruits and classified cajá as one of the most aromatic. They detected 33 volatile compounds and the main classes were similar to those determined by Augusto *et al.* (2000). They detected and quantified esters (48.76%), alcohols (21.69%), aldehydes (11.61%) and ketones (4.19%) and also observed that other aromatic compounds, like γ–octalactone, butyric and hexanoic acid, contribute to the characteristic fruit aroma.

15.4 Preharvest factors affecting fruit quality

Cajá trees grow very tall, which makes it difficult to harvest the fruit. The fruit can only be harvested once it has fallen from the tree. When mature, the fruits are collected from the ground by manual harvesting. Falling from the tree may damage the fruits because their peel is thin and does not protect the pulp. The damaged fruits may be susceptible to the attack of microorganisms and it is common to observe fermentation in fallen fruit. Furthermore, on the ground the fruits may suffer from damage due to ants and other insects, as well as other animals.

According to Sacramento and Souza (2000) and Bosco *et al.* (2000), fruit harvesting, even by picking up from the ground, must be done at least twice a day, to preserve fruit quality. In the year 2000, the authors estimated that less than 30% of cajá production was available for consumption due to harvest problems, accessibility and transport conditions. Recent data on cajá losses are not available.

To obtain better quality fruits, practices such as sailcloth use and ground protection have been adopted in some places. However, no harvest technique has yet been developed that could collect the fruit from the tree at an adequate maturity stage. This could considerably improve its sensory and chemical characteristics for industrial processing.

15.5 Insect pests and their control

Even though no rational harvesting methods exist, some studies have identified the occurrence of pests and diseases that prevent the development and fruit production of the cajá tree. A frequent pest observed in Brazil that also affects the fruits of the cajá tree is the fruit fly (*Ceratitis capitata* (Wied)). It is a common pest in fruits and causes large losses to Brazilian fruit growing. It has also been reported in many other countries, being considered one of the pests of higher importance to the world economy, both because of direct damage to the fruit, and indirectly due to the embargo on fruits exports (Brito, 2007). *C. capitata* can be found throughout the African continent, Mediterranean, Atlantic islands, South, Central and North America, East Asia, Australia, Europe, as well as the Indian and Pacific Ocean islands (White and Elson-Harris, 1992). Its presence has already been verified in almost all the Brazilian states (Uramoto, 2002). It attacks the reproductive organs of the plants, pulp fruits and flowers (White, 1996). Carvalho *et al.* (2004) have observed a correlation between the physico-chemical characteristics of the cajá fruits and the bioecological characteristics of the fruit flies. They presented a positive correlation between the pupae number per fruit mass and the average length of the fruit. The percentage of natural parasitism presented a positive correlation with the pulp yield, which confirms that cajá tree is a natural tephritid repository.

Silva (2007) has studied the population dynamics of the fruit fly species that use cajá as a host, verifying that there are two dominant and frequent species, *Anastrepha antunesi* and *A. oblique*. The infestation index was 56.75 pupae per kilogram of fruit, and the level of parasitism was 37.64%. The observed parasitoids were from the Braconidae family, with three species: *Asobara anastrephae* (14%), *Utetes anastrephae* (32%) and *Doryctobracon areolatus* (54%). The latter, which was the most frequent and present in a higher number of samples, was associated with *A. obliqua* and *A. antunesi.* Two additional species of the fruit fly have been reported in the literature as being associated with the cajá damage incidence: *A. fraterculus* and *A. sororcula* (Malavasi *et al.*, 1980; Carvalho *et al.*, 2004). Fruit fly attack on cajá fruits begins at the green-mature ripeness stage, which is characterized by a light green color at one end of the fruit and a light yellow color in the rest of the peel. The fruit fly eggs are deposited into the fruits and after hatching the larvae consume the pulp and facilitate the penetration of molds and bacteria, causing putridity and the fruit to fall (Vieira Neto, 2002; Costa, 1998). Fraife Filho *et al.* (2008) suggest that the fallen fruits that have deteriorated and show fruit fly larvae should be buried deeper than 5 cm, to avoid the insects coming to the surface, therefore stopping its cycle.

To combat the fruit flies, it is common to do control checks of the field by physical or biological methods (Vieira Neto, 2002). The most common method of control is to use toxic baits, insecticides (in powder or liquid form) and post-harvest fumigation (Brito, 2007). Alternative methods have also been developed for some fruit fly species, which minimize the use of agrochemicals, using water, steam and hot air instead, as described by Brito *et al.* (2009). They have observed that steam and hot water were effective in causing mortality of *Ceratitis capitata* with better effects when the exposure time and temperature were increased. Hot water was more efficient than steam for destruction of the fly eggs. Also analysing the physico-chemical quality of the cajá fruits, the authors have concluded that at 46°C the fruits must be exposed to steam for 27 minutes and at 50°C for 20 minutes to control *C. capitata* larvae without affecting such fruit characteristics as total soluble solids, acidity and pH.

There are also other pests that affect the cajá tree leaves, bunch and fruits: thrips, mealybugs, caterpillars, borers, ants, larvae of terminal buds, whitefly, leafhopper, yellow mites and flowers' mites (Fraife Filho *et al.*, 2008).

The main diseases that affect this species are: anthracnose (*Glomerella cingulata* (Ston), wart (*Sphaceloma spondiadis* Bitancourt and Jenkins), resinose (*Botryosphaeria rhodina* (Cooke) Ark), cercosporiose (*Mycosphaerella mombin* Petr. et Cif), algae defect (*Cephaleuros virescens* Kunze) and phytonematodes (Sacramento and Souza, 2000). Feitosa *et al.* (2008) have studied pathogen control post-harvest in cajá fruits using natural pesticide and resistance inductors. The pathogens detected in the fruits were *Colletotrichum* sp., *Aspergillus* sp. and *Clostridium* sp. The authors concluded that the treatments (*bion, agromos, ecolife*, basil leaf extract, melon, cashew apple peel and angico) had a significant effect on the occurrence of the phytopathogens and that their biological control is possible depending on the product used and on the initial degree of contamination.

15.6 Postharvest handling practices

After harvesting, some of the fruits intended for sale as fresh fruit are placed in straw baskets coated at the base with banana leaves (Plate XXVIII: see colour section between pages 244 and 245), or in conventional plastic bags.

The baskets protect the fruits and are the package preferred by consumers in *feiras* (free markets) and street corners (informal market) in Pará state, North of Brazil. Plastic bags are not adequate packaging for the fruit as they promote conditions that contribute to fermentation, reducing even further the already short shelf life of the fruits.

Cajá fruits, even when well packaged at the natural environmental temperature in the production regions (around 28 to 30°C), must be consumed within 24 hours maximum, due to their high perishability. The high moisture and sugar content of the fruit, the thin peel that does not offer protection, manual harvesting and contact with the ground are some of the factors that also contribute to the short shelf life of cajá fruit.

The rest of the cajá production is directed to agro-industries, mainly in the Northeast region, where the fruit is processed. There the fruit is transformed into pulp, as will be further discussed in section 15.7.

15.6.1 Harvest operations

Commercial harvest operations are not practiced in most of the production regions, as has already been described. Fruits are collected from the ground, after they have fallen from the trees naturally. Some studies of the cajá harvesting stage have shown that when the mature (yellow) fruits were collected, they could be stored at room temperature for only one day, even when they were carefully manipulated to avoid mechanical damage and exposure to adverse conditions. On the other hand, fruits harvested at the initial stages of color change (mostly green) could be maintained for four days and would still attain a similar quality to fruit harvested at maturity (Filgueiras *et al.*, 1998).

15.6.2 Recommended storage and shipping conditions

Costa (1998) studied cajá storage conditions at room temperature and refrigeration, with or without the use of modified atmosphere with a 15 micron PVC film. According to the author, at room temperature, the weight loss (55.0%) of non-packaged fruits was more than three times higher than at the modified atmosphere (15.5%). When stored refrigerated (8°C), without packaging, the fruits were preserved in good condition for processing for five days, and in good condition for fresh consumption for two days. The modified atmosphere and refrigeration allowed fruit quality to be maintained for ten days if the fruits were meant for processing, and eight days if they were meant for fresh consumption. After that the fruits started to show signs of chilling injuries.

Freezing of the cajá fruit was evaluated by Mata *et al.* (2003). They suggest that this process may be effective to avoid the fruit perishing and to control seasonality. They observed that it takes 75 minutes to freeze the fruit (phase II) at −30°C, 44 minutes at −60°C, and 40 minutes at −90°C. The thermal diffusivity data during freezing varied from $2.8 \times 10^{-7} m^2.s^{-1}$ to $3.4 \times 10^{-7} m^2.s^{-1}$, in phase I (cooling) and from $3.1 \times 10^{-7} m^2.s^{-1}$ to $3.2 \times 10^{-7} m^2.s^{-1}$ in phase III (post-freezing).

15.7 Processing

15.7.1 Fresh-cut processing

Cajá is a small fruit that with a relatively large seed and soft and thin edible part and peel. Therefore it is not possible to obtain fresh-cut products from it.

15.7.2 Pulp production and other processing practices

As previously mentioned, the main industrial product of cajá fruit in Brazil is the frozen pulp.

Table 15.5 Identity and quality standard (PIQ) of cajá pulp

Characteristic	Descriptor	
Color	Yellow	
Taste	Sour	
Aroma	Characteristic	
Parameter	**Minimum**	**Maximum**
Soluble solids (°Brix at 20°C)	9.0	–
pH	2.2	–
Acidity in citric acid equivalent (g.100 g^{-1})	0.90	–
Total sugars natural from cajá (g.100 g^{-1})	–	12.0
Total soluble solids (g.100 g^{-1})	9.5	–

Source: Brasil, (2000).

According to the Brazilian legislation, cajá pulp or purée is the non-fermented and non-diluted product, obtained from the edible part of the fruit, using adequate technological processes and presenting a minimum value of total solids, as defined by the Identity and quality standard (PIQ) shown in Table 15.5 (Brasil, 2000).

The production process of the cajá frozen pulp follows the conventional steps used in the fruit pulp industry. Initially, when the fruit gets to the factory, it is weighed, selected, cleaned and sanitized (Fig. 15.1). It is then fed to a brush

Fig. 15.1 Cleaning of cajá fruits. Photo: Rafaella Mattietto.

depulper (Fig. 15.2), where the pulp is separated from the seeds (Figs 15.3 and 15.4), followed by the refining depulper consisting of smaller mesh sieves. In small businesses, the refined pulp is directly packaged in polyethylene plastic bags, with capacities varying from 100 g to 1 kg, and immediately frozen in

Fig. 15.2 Fruit depulping. Photo: Rafaella Mattietto.

Fig. 15.3 Fruit pulp. Photo: Rafaella Mattietto.

Fig. 15.4 Cajá seeds after pulp extraction. Photo: Rafaella Mattietto.

freezing chambers. In the large businesses, the refined pulp is pasteurized before packaging and freezing (Matta *et al.*, 2003).

In the Northeast region of Brazil other types of industrial cajá products can be found, such as ice cream, fruit juice and candy bars.

Many studies have focused on products and processes, which can increase cajá fruit consumption and use. Some of them concentrate on the quality and characteristics of the commercially available products; others aim to evaluate and optimize the conditions of the processes. There are also studies on the development of new cajá products.

Quality and characteristics of established products

Carotenoid content has been evaluated in two different types of cajá commercial products: pasteurized juice and frozen pulp. The frozen pulp had a higher total carotenoid content (20.6 $\mu g.g^{-1}$) than the juice (16.7 $\mu g.g^{-1}$), although the profiles of both products were very similar in terms of the β-cryptoxanthin content, contributing to 34.0 and 33.0% of the total in pulp and juice, respectively. Besides β-cryptoxanthin, the higher contributions were of lutein, zeinoxanthin and β-carotene, with average concentrations in the frozen pulp of 5.5, 3.8 and

2.0 μg.g^{-1}, respectively, representing 26.7, 18.4 and 9.7% of total carotenoids. In the juice the contents of these three carotenoids were 3.5, 3.5 and 1.4 μg.g^{-1}, corresponding to 21.0, 21.0 and 8.4% (Hamano and Mercadante, 2001).

A study on the pasteurization conditions of the cajá pulp (Bastos *et al.*, 2008) showed that in the evaluated conditions the pulp parameters were not significantly affected by the process. Furthermore, microbiological safety was attained and peroxidase was inactivated. The selected pasteurization condition for preserving the pulp for four months was 85°C for three minutes. A sensory evaluation was also conducted and there was no significant difference between the non-pasteurized and pasteurized pulps.

Tiburski (2009) has studied the high-pressure process applied to cajá pulp. The study evaluated the effect of time (2.9 to 17 minutes) and pressure (157 to 441 MPa) on the characteristics of the cajá pulp using a central composite design. The results showed that the pressurized pulp, under all evaluated conditions, satisfied the Brazilian standards for microbiological quality (Brasil, 2001). The variance analysis did not show a significant effect (at 95% probability) of the evaluated factors on the bioactive compounds of the cajá pulp, although there was a tendency for higher contents of bioactive compounds at intermediate conditions, like 300 MPa/10 min for the phenolic compounds and 300 MPa/5 min for the carotenoids.

New product development

The development of blends containing cajá pulp has been studied by different authors. Bonomo *et al.* (2006) formulated three juice blends based on cajá and graviola (*Annona muricata* L.) pulp in different proportions. The sensory properties of the blends were analysed by 37 consumers. There were no significant differences among the formulations, at 95% probability, with an average score of 6.5 on a 0 to 9 hedonic scale. The blends were well accepted by 76.6% of the consumers.

Mattietto *et al.* (2007) have studied the stability of a blend of cajá and umbu (*Spondias tuberosa*). After formulation and pasteurization, the blend was stored for three months at room temperature. The results indicated good overall sensory acceptance of the blend (84.76%) and intention to buy (90.62%). The product presented an energy value of 68.2 kcal. 100 g^{-1}, and was rich in tannins and vitamin C. The heat treatment employed has been proved to enable a storage period of up to 60 days, after which the product browned and fungal growth was observed.

Microfiltration and ultrafiltration processes have been performed by the present authors. The aim for cajá pulp processing by filtration is to obtain two products: the pulp, rich in carotenoids and phenolic compounds and a clarified juice, rich in sugar, organic acids and flavors that can be used as raw material for blends, jams, and soft drinks, among others. Preliminary results showed that it is possible to obtain pulpy fractions containing carotenoid contents of about 4000 to 5000 μg.100g^{-1}.

A new product that consisted of mixed restructured fruit constituted of guava and cajá pulps was evaluated. Three formulations were evaluated and their physico-chemical parameters were determined. In the three products significant

levels of carotenoid and vitamin C were observed. The sensory analysis has showed that all of them were well accepted and variance analysis verified that there was no significant difference among them (Silva *et al.*, 2009).

Silva (2005) has studied the process of obtaining cajá powder by spray-drying, using maltodextrin and modified starch as encapsulants, single or combined, evaluating different formulations. The study found that the powder containing 15% maltodextrin had the highest hygroscopicity among the evaluated formulations. Moreover, the cajá powder required adequate package conditions to avoid it rehydrating. On the other hand, when the sensory acceptability of the juices, reconstituted from the powders, was evaluated, it was verified that the formulation using single maltodextrin was the only one that did not show a significant difference in sensory acceptability to the original pulp.

The development of other products like jam, conventional clarified juice and fermented beverage have also been studied, with good results (Silva *et al.*, 1999; Dias *et al.*, 2003).

15.8 Conclusions

Cajá may be considered one of the most promising tropical fruits and is easily appreciated because of its intense flavor. Besides its natural content of vitamins and minerals, which is similar to other fruits, it also contains other important components that are largely studied today because of their additional physiological effects on the human body, like carotenoids and phenolics compounds. This could add to its market appeal.

Brazilian production is based on the extractive system. Therefore there are scientific studies on genetics, breeding, species propagation and post-harvest biology and technology, which aim to make rational harvesting and plantations possible.

The cajá production season is short (three months maximum in some regions). The fruit also has another constraint: it is highly perishable, with just a 1-day shelf life under natural commercialization conditions. This emphasizes the importance of adding value to the species by further processing. Frozen pulp is still the most common processing method in the production regions.

Today, cajá pulp from the Brazilian Northeast has already been exported and it is possible to find cajá products like mixed juices in foreign countries. However, it is important to continue to improve cajá products and processes and to develop new ones that aim to add value to the fruit and contribute to its agri-chain development.

15.9 References

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Plate XXVI Coloured cactus pear juices.

Plate XXVII Cajá fruits and pulp.
Photo: Rafaella Mattietto.

Plate XXVIII Cajá fruits as usually commercialized at Brazilian free markets in the Northern region. Photo: Rafaella Mattietto.

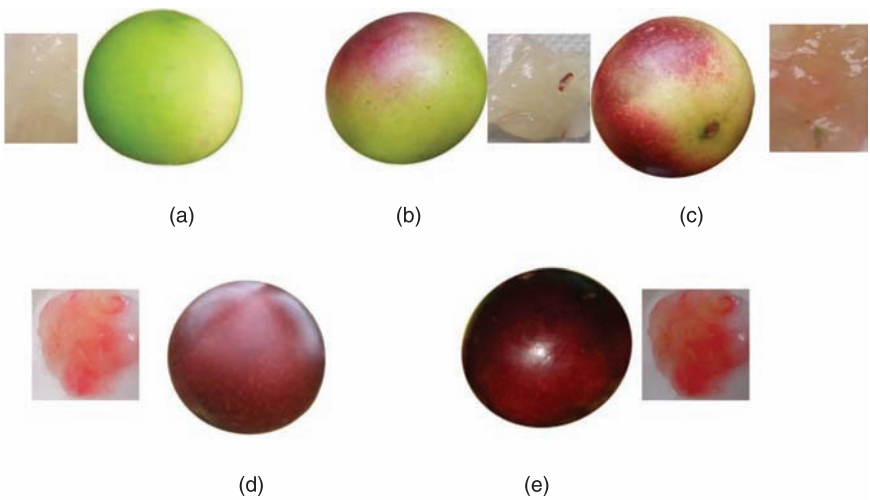

Plate XXIX Camu-camu colour chart during ripening. Stages of maturity classified according to external skin colour and in some cases pulp colour (blending skin with different colours and white flesh). (a) Mature green; (b) Turning; (c) Half-mature; (d) Mature; (e) Fully mature.

16

Camu-camu (*Myrciaria dubia* Kunth McVaugh)

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Abstract: Camu-camu is a small wild berry from the Amazon river region which shows sigmoid growth and has an acid and astringent taste and the highest L-ascorbic acid content known in the fruit world. The development of a red skin is the most widely used harvest index. Camu-camu has an apparent climacteric behaviour without a detectable peak of ethylene production. Camu-camu is susceptible to shrivelling, loss of ascorbic acid and, at low temperatures, to chilling injury. For this reason, it is recommended that fruit at the turning or red colour stage be stored at temperatures around 10°C in modified atmosphere packaging (MAP). The local fresh fruit market uses MAP with low-density polyethylene bags for short storage periods. The fruit is consumed fresh or in the form of juice, while the pulp is also processed for beverages and lyophilized capsules, or to extract health-promoting compounds.

Key words: Amazonic fruit, *Myrtaceae*, Camu-camu, climacteric behaviour, ascorbic acid, shrivelling.

16.1 Introduction

16.1.1 Origin, botany, morphology and structure

The camu-camu (*Myrciaria dubia* Kunth McVaugh) is a native shrub from the Amazonian rain forest belonging to the *Myrtaceae* family. It is known as 'camo-camo' (in Peru), 'caçari' or 'araçá d'água' (in Brazil), 'guayabo' and camu-camu (in Colombia), and 'guayabato' or 'guaiabito' (in Venezuela). Camu-camu grows wild in floodable areas of streams and on the banks of rivers, lakes or swamps of the Amazon region (Peru, Brazil, Colombia, Ecuador and Venezuela). In its native environment, the tree can reach 4 to 8 m in height, and may remain up to six months submerged in water, and it grows naturally in the floodplain area. Besides the Amazon region, the species is found in Pará and Rondônia States (Brazil) (Luduvig, 1997; Justi *et al.*, 2000). Typically, the camu-camu shrub achieves a height of 1 to 3 m. The fruits are

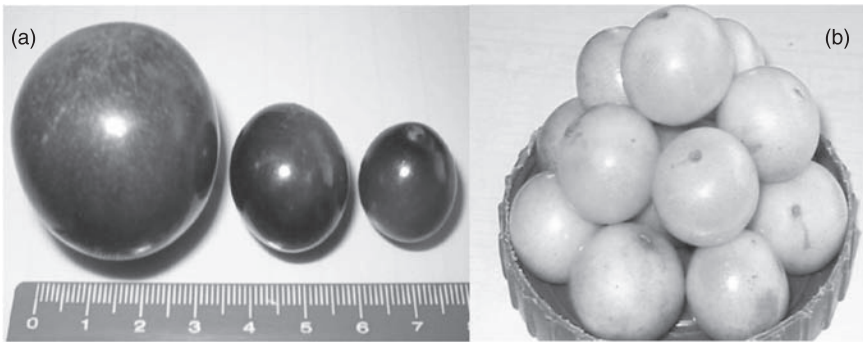

Fig. 16.1 Camu-camu mature fruit of Peru. (a) Red skinned. (b) A yellow-skin mutant. Both pictures courtesy of Mario Pinedo Panduro PhD, Instituto de Investigaciones de la Amazonia Peruana (IAAP), Iquitos, Loreto, Peru.

globular, measure from 1.0 to 3.2 cm in diameter, weigh 2 to 20 g, have one to four seeds per fruit and 50 to 55% white pulp with a thin shiny skin, which ranges from pink to deep red or even dark purple when fully mature (Rodrigues and Marx, 2006; Rodrigues *et al.*, 2001; Fig. 16.1). A probable mutant, whose fully mature fruit has a dark yellow skin, has been identified in Peru (Pinedo, 2009; Fig. 16.2), resembling the arazá fruit in shape and colour. Camu-camu is sometimes confused with the guavaberry or rumberry, the arboreal camu-camu [*Myrciaria floribunda* (H. West. ex Willd) O. Berg], a fruit with similar red skin colour but lower ascorbic acid content and globe shape with a typical long apex and turning dark brown colour when fully mature (Pinedo, 2009; Villachica, 1996a, 1996b).

16.1.2 Worldwide importance

Camu-camu is produced in floodable areas (rivers with 'white' waters, pH >6.5 and low sodium content) in the western Amazon countries mentioned above and is also cultivated in Bolivia. The world production and economic value of this fruit have not yet been quantified. However, its properties and uses make it a very valuable crop. Most of the production comes from Peru (480, 305, and 95 t in 2007, 2008 and 2009, respectively, earning 1.8, 0.98, and 0.35 (January to July 2009) million US dollar revenues, respectively; IIAP, 2009). In Cochabamba (Bolivia), almost 1000 hectares have been planted in recent years and in 2009 production is estimated to be 30 t frozen pulp. Camu-camu is consumed fresh or processed (pulp, juices, jams or as a source of antioxidants). The fruit is also transformed into nutraceutic or energetic products that are being exported to Japan (around 160 t in 2004/2005 from Peru with a value of $132 million US) (Peters and Hammond, 1990; Saguino *et al.*, 2003).

Private investment in camu-camu destined for the Japanese market started in 1994. Since 1996, the government of Peru has been promoting the cultivation of the tree in support of the export industry and to increase rural income (Penn,

2006). The Peruvian government-funded 'reforestation' projects have been implemented by state and private institutions under a national programme to produce camu-camu for export to Japan. In fact, more than 90% of the camu-camu trade from Peru is intended for Japan, USA or the Netherlands, followed by different European countries and, to a lesser extent, Canada. The price is very variable and is associated with fluctuations in the price of acerola (*Malpighia glabra* L.) or sweetbriar rose (*Rosa eglanteria* L.) in Japan and other international markets (Pinedo, 2009; Pinedo *et al.*, 2001). Obviously, such fluctuations do not satisfy the business interests of the companies involved (Pinedo *et al.*, 2001). Camu-camu production and postharvest activities are a great boost to local economies in the areas of production. There is no customs code yet for camu-camu because it is not considered as a commodity (Hughes, 2007).

Because camu-camu was not present in the European Union (EU) markets before 1997, food safety-inspired EU legislation has discouraged investment in export-oriented supply chains [Regulation (EC) No 258/97], which represents a market access barrier for camu-camu and other under-utilized plant species (GFU, 2009; Jaenicke *et al.*, 2009). Different strategies are being developed to overcome the barriers to market entry to Europe. For example, at the international level, barriers to market entry can be removed by the development of niche markets (all according to EU regulations) such as those promoted by Denomination of Origin certification, Protected Designation of Origin (PDO), Protected Geographical Indication (PGI), Traditional Speciality Guaranteed (TSG), eco-labelling, fair trade and/or organic (Jaenicke *et al.*, 2009).

16.1.3 Culinary uses and health effects

Camu-camu can be blended into desserts, drinks and 'smoothies', and is also used in savoury recipes such as sauces and raw soups. When used in small quantities, its sour taste enhances dishes much in the same way as lemon juice does. Some people take half to one teaspoon of camu-camu in a glass of water to add flavour. Camu-camu fruit is also used as fisherman's bait and as colouring to dye 'chambira' (*Astrocarium chambira*) textile tissues.

The nutraceutical value of camu-camu is well known since it has the highest vitamin C content (410 to 3,250 mg.100^{-1} g pulp; Table 16.1) of all known fruits (Bradfield and Roca, 1964), though other authors indicate up to 6,100 mg.100^{-1} g (Yuyama *et al.*, 2002). Vitamin C is used by different industries and its lyophilized form is used as a functional food.

Compared with other fruit, camu-camu presents outstanding antioxidant features against peroxyl radicals and peroxynitrite (Lichtenthäler and Marx, 2005). In addition to ascorbic acid and anthocyanins, at least 30 flavonol glycosides (polyphenols at around 739 mg.100^{-1} g fw) seem to contribute to the overall antioxidant capacity of camu-camu fruit pulp (Chirinos *et al.*, 2010; Pérez and Augusto, 2009; Reynertson *et al.*, 2008; Rodrigues and Marx, 2006; Rodrigues *et al.*, 2006). Major biologically active phenolic compounds identified by Reynertson *et al.* (2008) in lyophilized pulp are, in order of content, ellagic acid,

Table 16.1 Camu-camu fruit composition on a fresh weight basis at harvest (half-mature fruit, according to different authors

	Reference				
Component per 100 g	Villachica (1996b)	Rodrigues (2002)	Justi *et al.* (2000)	Zapata and Dufour (1993)	Institute Sinchi (2008)
Water (g)	94.4	93.28	94 g		
Protein (g)	0.5	0.49	0.4 g		0.01
Total carbohydrate (g)	4.7	5.65	3.5		0.015
Fibre (g)	0.6	1.18	0.1		0.024
Ash (g)	0.2	0.24	0.3		
Lipids (g)	0.2	0.34	0.2		
Citric acid (g)				1.9	
Fructose (g)				0.951	
Glucose (g)				0.816	
pH		2.89		2.56	
Soluble solids (°Brix)		6.9		6.8	
Acidity (g citric acid)		1.8		3.8	
Thiamine (mg)	0.01				
Riboflavin (mg)	0.04				
Niacin (mg)	0.062				
Vitamin C (mg)[1]	2994	1355	1410	960	2996
Total amino acids (mg)				63.7	
Serine (mg)				31.6	
Valine (mg)				28.9	
Leucine (mg)				19.9	
K (mg)			83.88	71.1	
Ca (mg)	27		15.73	6.5	0.03
Mg (mg)			12.38	5.1	
Na (mg)			11.13	2.7	0.003
Fe (mg)	0,5		0.53	0.18	0.22

Note: [1]Levels of 3253 mg per 100 g pulp have been reported by Villachica (1996b).

Source: Modified from Rodrigues and Marx (2006). With permission of the journal editor of Ernährung/Nutrition.

quercetin, rutin, quercitrin, cyaniding-3 glucoside and traces of delphinidin-3-glucoside, while myricetin was not detectable. Chirinos *et al.* (2010) have confirmed these compounds in other stages of maturity at harvest, along with some additional phenolics (flavan-3-ol, flavonol, flavanone and ellagic acid derivatives), while others remain unidentified. All these compounds are natural antioxidants and anti-inflammatories considered important in chemoprevention.

Camu-camu pulp also has pro-oxidant activity because it increases free radical generation in the presence of Fe(III) and ethylendiaminetetracetic acid (EDTA), while the presence of thiourea or mannitol, components with a known antioxidant action, inhibit free radical generation (Guija *et al.*, 2005).

Brack (1999), Duke (2009), Pinedo (2009) and Pinedo and Armas (2007) mentioned the use of camu-camu for constipation, influenza, rheumatism, diabetes mellitus, arthritis rheumatoid and several diseases, especially when taken as a

fresh juice, based on fruit composition and evidence of the active principles, including vitamins (ascorbic acid, niacin, beta-carotene, riboflavin), amino acids (thiamine), calcium and fibber. Jovel (1996) reported that the fruit are pounded and strained, and water is added to make a drink given to children and adult as a tonic, but also used to treat 'pulsario' (a type of colic).

Camu-camu is also currently used therapeutically to improve asthma, bleeding gums, colds, fatigue, flu, cold sores, depression, Epstein Barr virus, herpes, immunity and liver function, and even to enhance weight loss (Brack, 1999; Duke, 2009; Null, 1998). Capsules of around 0.5 g dry camu-camu powder are sold in pharmacies due to the wide range of claimed health benefits derived from the antioxidant and nutrient content, although few of these benefits have been scientifically tested (Null, 1998). Camu-camu-derived products are sold as nutrients for healthy skin, hair and nails: the fruit is used in hair products such as conditioners to strengthen and untangle the hair, as well as to promote vitality and shine and it is also included in nourishing facial masks (Daugherty, 2008).

Inoue *et al.* (2008) tested camu-camu's properties in smoking volunteers. Although the mechanisms are not clear, the authors concluded that camu-camu juice has more powerful anti-oxidative and anti-inflammatory properties than vitamin C tablets containing equivalent vitamin C contents, and thus, as a dietary supplement, may be expected to prevent atherosclerosis. Carotenoids (Azevedo-Meleiro and Rodriguez-Amaya, 2004; Zanatta *et al.* 2007) and anthocyanins (Chirinos *et al.*, 2010; Zanatta *et al.*, 2005) are the main candidates to support these properties.

Scientific evidence concerning toxicity, potential allergenic hazards, and, to a lesser extent, nutritional composition of camu-camu is currently not available. More research is needed to confirm its true benefits.

16.2 Fruit development and postharvest physiology

16.2.1 Fruit growth, development and maturation

The phenology of camu-camu flower and fruit development has been characterized in Peru (Inga *et al.*, 2001; Peters and Vaszuez, 1987; Pinedo *et al.*, 2001). Camu-camu growth follows a sigmoid curve according to longitudinal, equatorial diameters and fresh weight. In Colombia, the fruit exhibits three growth stages: the slow growth stage, which lasts around 26 days from fruit set (S1), an exponential growth stage (S2), which lasts up to around 56 days and a third stage (S3), during which the fruit attains its final size at around 66 days (Bardales *et al.*, 2008) (Fig. 16.2).

16.2.2 Respiration, ethylene production and ripening

The fruit has a moderate respiration rate during the exponential growth stage (1,000 $nmol \cdot kg^{-1} \cdot s^{-1}$ CO_2), which decreases during the maximum growth phase (S3) to 400 $nmol \cdot kg^{-1} \cdot s^{-1}$ CO_2. Fruit respiration during ripening remains low (less than 400 $nmol \cdot kg^{-1} \cdot s^{-1}$ CO_2) (Fig. 16.2d). During ripening, the fruit

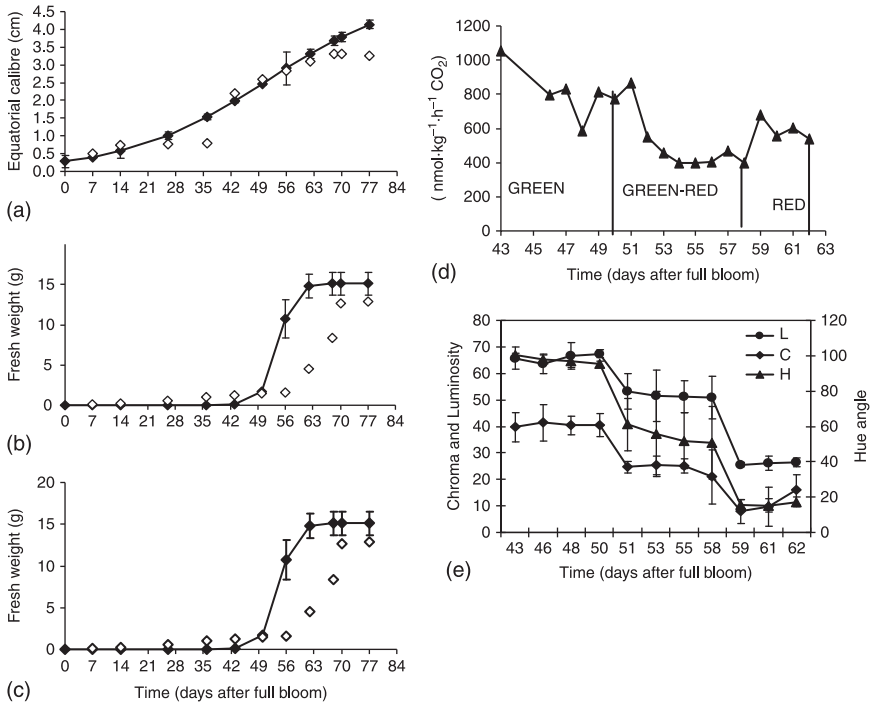

Fig. 16.2 Sigmoidal growth of camu-camu fruit. (a) Fruit weight. (b) Longitudinal diameter. (c) Equatorial diameter. (d) Respiration rate. (e) Skin colour changes (lightness, chroma and hue angle or L*C*h*, respectively). Source: Redrawn from Bardales *et al*. (2008).

harvested in half-mature and mature stage shows a climacteric behaviour within two to three days after harvest (Fig. 16.3), accompanied by levels of ethylene production that range from 0.1 $\mu L \cdot kg^{-1} \cdot h^{-1}$ to undetectable. However, the high respiration rates after harvest without a climacteric peak of respiration rate (Fig. 16.3a and 16.3b), and absence of peak of ethylene, can be somehow affected by preharvest (i.e. flooding) or postharvest conditions (transportation), and requires further studies.

The skin colour changes as the fruit ripens on the tree (Plate XXIX: see colour section between pages 244 and 245) and Fig. 16.2e, although the flesh is always white. However, to obtain pulp, the skin and mesocarp are blended so that the pulp extracted changes according to the stage of fruit ripening. These changes range from white to creamy in mature-green fruit to pink in half-mature, dark pink/fuchsia in mature fruit, and finally red in over-mature fruit (Rodrigues *et al.*, 2001; Plate XXIX: see colour section). However, skin hue angle in turning or half-mature fruit do not change much during ripening at 12 or 20°C (Jiménez *et al.*, 2008).

In camu-camu the ascorbic acid concentration increases in tree ripening fruit from mature-green (2.1 $g.100^{-1}g$) to the half-mature stage of maturity (2.9 $g.100^{-1}g$),

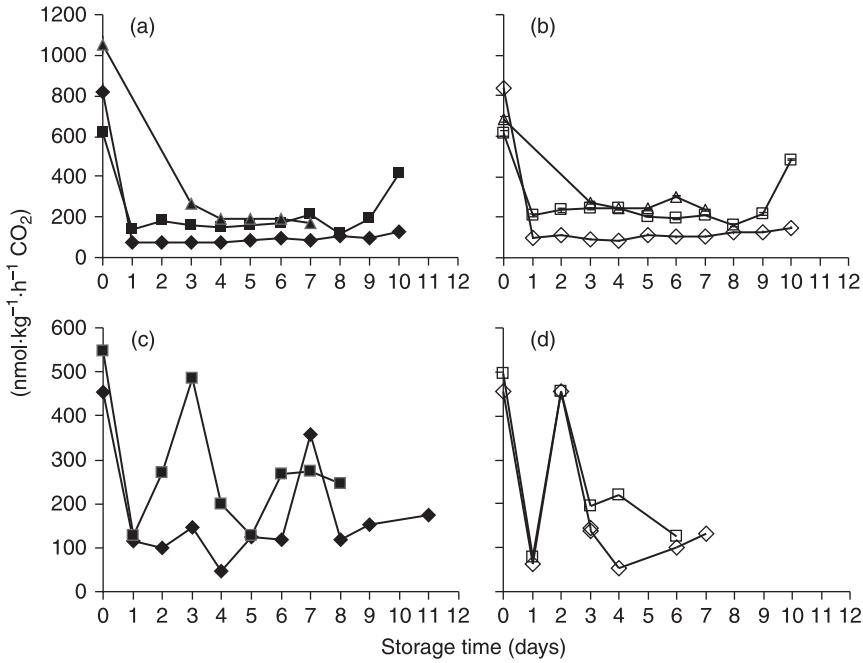

Fig. 16.3 Respiration rate of half-mature and mature camu-camu fruit stored at 6°C (▲, Δ), 12°C (♦, ◊, or 20°C(■, □ and 90% RH in two stages of maturity. (a) (c) half-mature, (b) (d) mature. Bars (SD, n = 5) are not shown if smaller than the size of the symbol.

though some authors have reported maximum values in less mature stages (Rodrigues and Marx, 2006). Dehydroascorbic acid levels are low: less than 0.03 g.100^{-1} g, which is around 30 times lower than the levels of ascorbic acid reported by Zapata and Dufour (1993). Ascorbic acid and dehydroascorbic acid usually decrease from mature-green to fully mature fruit at harvest, although a relative maximum may be found in turning or half-mature stages at harvest, concomitant with a relative maximum in total phenolics and 2,2-diphenyl-1-picrylhydrazyl (DPPH) antioxidant activity (Alves *et al.*, 2002; Chirinos *et al.*, 2010). Other authors have found a maximum in ascorbic acid, total polyphenols and total antioxidant activity [evaluated by using 2,2'-azino-bis(3-ethylbenzthiazoline-6-sulphonic acid) (ABTS^{+}) or 2,2-diphenyl-1-picrylhydrazyl (DPPH^{+}) radicals] in tree ripened mature fruit (Pérez and Augusto, 2009).

Differences in ascorbic acid can be attributed to environmental and/or geographical production conditions or a possible genetic variation, similarly to the differences in volatile composition observed by Franco and Janzantti (2005). For example, maximum concentrations of ascorbic acid are recorded in fruit harvested at noon or, at least, after morning exposure to the sun (Pinedo, 2009). Also, analysis of the peel indicated about 5% of ascorbic acid content, much higher than that found in the pulp (Villachica, 1996a).

Ascorbic acid also increases during postharvest ripening with continuous increases at 12°C and a relative peak after three days at 20°C, in both cases irrespective of the degree of maturity considered (pink or half-mature) (Jiménez *et al.*, 2008). Postharvest fruit ripening at 20°C and 85% RH for one week results in a 50% lower ascorbic acid content compared with harvest levels (2.99 $g.100^{-1}g$), while mature fruit reach 1.77 $g.100^{-1}g$ after five days at 20°C.

Research concerning the genetic basis of ascorbic acid biosynthesis is under way in acerola (Badejo *et al.*, 2009) and these results can be of interest for camu-camu fruit. In fact, molecular markers have been developed from simple sequence repeat (SSR) loci obtained from publicly available expressed sequence tags (ESTs) in camu-camu fruit (Rojas *et al.*, 2008; Lima da Silva, 2006). EST-SSRs will boost gene expression studies during fruit ripening and different postharvest treatments.

Titratable acidity, phenols (total, water soluble or methanol soluble), total pectin and consistency decrease during ripening, with slight sugar and aroma biosynthesis in fully mature fruit (Alves *et al.*, 2002; Ramos *et al.*, 2002). The flavan-3-ols and ellagic acid groups are the most representative phenolic compounds in this fruit from mature-green to mature stages (Chirinos *et al.*, 2010).

Citric acid also decreases in tree-ripened fruit (2 to 3%). On the other hand, reducing sugars (glucose, fructose), total nitrogen and potassium, and free amino acids (serine, valine and leucine) increase during ripening. As fruit mature from predominantly green to predominantly purple, soluble solids, pH, starch, total sugars, soluble pectin, and total soluble solids:acidity ratio change little (Alves *et al.*, 2002). Zapata and Dafour, (1993) indicated slight increases in total soluble solids in mature fruit, in agreement with Chirinos *et al.* (2010), who reported a decrease in the soluble solids:acidity ratio for the three ripening stages from mature-green to mature (4.28, 3.44 and 2.57, respectively). During storage at 20°C and 68% RH, total soluble solids decrease in mature and in half-mature fruits, although this decrease is more pronounced in fruit harvested in the half-mature stage (Silva *et al.*, 1997).

16.3 Maturity and quality components and indices

The fruit used to obtain pulp weighs around 20 g and the diameter is 20 to 30 ± 5 mm, similar to cherry (*Prunus avium* L.). Dry matter is below 6.5%. (Rodrigues *et al.*, 2006). Firmness decreases from 35 N in mature-green stage to 11 N in mature fruit, as measured using a penetrometer with a 1.6 mm diameter plunger. The mature fruit is easy to detach from the tree, after which the area quickly develops a scar, although fruit micro cracks heal quickly.

The development of a red skin is the common harvest index. Camu-camu skin is a dull green during S1 and S2, turning to pink-red by the middle of S3. This colouration is rapidly replaced by a characteristic red purple colour, due to the presence of anthocyanins. By the end of S3, the fruit is dark red as senescence progresses. The hue angle (h*) colour parameter decreases during ripening from

110° (dull green; at harvest time) to 26° (red wine, mature fruit). Fruit lightness and chroma colour parameters also decrease during ripening, which reflects the slight opacity, dull and less vivid colour of the fruit (Bardales *et al.*, 2008; Zanatta *et al.*, 2005). Fruit colouration is not usually homogeneous in the intermediate stages of maturity, with ground colour changing from green to light orange and finally dark red (Plate XXIX: see colour section between pages 244 and 245).

Skin colour in camu-camu is governed by the total anthocyanin concentration (around 54 mg.100^{-1} g) and carotenoids. Cyanidin-3-glucoside is the major anthocyanin in camu-camu fruits, when it represents 89.5% of the total, followed by delphinidin-3-glucoside (4.6%) and other minor anthocyanins, which represent about 6.5% (Rodrigues and Marx, 2006).

The major carotenoids vary widely, depending on many factors associated with the fruit environment (temperature and solar radiation, which depend on the location) or fruit × environment interactions (maturity, area of production, etc.) and perhaps the method of identification (Rodriguez-Amaya *et al.*, 2008). The total carotenoid content ranges from 350 to 1100 μg.g^{-1} fw peel (higher in the warmest regions) and 16 peaks have been identified by different HPLC methods. The major carotenoid identified in camu-camu peel is trans-lutein (161 to 602 ± 100), followed by β-carotene (73 to 142 μg.100^{-1} g fw), violaxanthin (12 to 116 μg.100^{-1} g fw), luteoxanthin or cis isomer of lutein (22 to 60 μg.100^{-1} g fw) and zeaxanthin (23 to 38 μg.100^{-1} g fw). Neoxanthin, cis-neoxanthin, flavoxanthin, 5,6-Epoxy-lutein, 5,8-Epoxy-zeaxanthin, 5,6-Epoxy-zeaxanthin, β-cryptoxanthin, 5,8-Epoxy-β-carotene, 5,6-Epoxy-β-carotene, a (Z)-isomer of β-carotene and at least two unidentified carotenoids have been found at concentrations, ranging from one to 20 μg.g^{-1} fw peel (Azevedo-Melero and Rodriguez-Amaya, 2004; Zanatta and Mercadante, 2007). Other carotenoids identified, such as sintaxanthin or citranaxanthin, seem to be artefacts of the extraction method with acetone (Zanatta and Mercadante, 2007).

Camu-camu fruit has the highest recorded amount of vitamin C extracted from fresh fruit known, three times higher than in acerola (Aragao *et al.*, 1996; Zapata and Dafour, 1993), and consequently vitamin C is one of the key attributes to evaluate camu-camu fruit quality.

Camu-camu fruit possess a low sugar concentration compared to other fruits. Fructose shows higher levels than glucose in fully mature fruits, while sucrose levels show low to trace levels (Zapata and Dufour, 1993). Fructose and glucose levels double during fruit maturation (Zapata and Dufour, 1993). Citric acid is the predominant organic acid, while malic and succinic are secondary organic acids.

The terpenes, alpha-pinene and delta-limonene, are the predominant fruit volatiles in samples from northwest Brazil (Franco and Shibamoto, 2000), while alpha-pinene and delta-limonene predominate in samples from the Amazon basin (Franco and Janzantti, 2005).

Camu-camu is a good source of potassium (71 mg.100^{-1} g), minerals (iron, calcium and phosphorum), vitamins (B1 and B2), flavonoids (flavonolglicosides) and amino acids. Serine is the predominant amino acid. Leucine and valine increase during ripening (Zapata and Dufour, 1993). The pH of the mature fruit is

around 2.5 to 3.2 units and soluble solids range from 5.8 to 7.4°Brix, depending on the area of production, and vary among fruit (Rufino *et al.*, 2009). GABA (γ-aminobutyric acid) is detected in the range of 0.5 to 3.25 $mg.100^{-1}$ g, and higher concentrations (up to 8.2 $mg.100^{-1}$ g) are probably a response to flooding (Rodrigues and Marx, 2006). This is one of the reasons why camu-camu could be used as a model fruit crop system to study the mechanism of fruit resistance to anoxia within the plant and the GABA shunt, as has been observed in other species (Menegus *et al.*, 1989).

The flavour of the camu-camu is sweet, with plum, apricot and particularly peach notes, and the taste has a very strong front note of nutmeg, cherry and plum (Bauer, 2000). Phenolic compounds are associated with astringent tastes, particularly in less mature fruit (Alves *et al.*, 2002).

The variability in the nutrient composition is probably due to differences in harvest-time during the day, stage of maturity, mixture of fruits of slight differences in maturity for analysis, possible negative interaction between juice components (Albertino *et al.*, 2009; Pinedo, 2009) or the well-known susceptibility of camu-camu to vitamin C losses (particularly if frozen, because, in many cases, analysis is performed on frozen pulp) (Rodrigues and Marx, 2006). Some producers in Bolivia maintain that the fruit may lose up to a quarter of its vitamin C content in less than a month.

16.4 Preharvest factors affecting fruit quality

Although camu-camu shrub physiology is not well known, it is clear that floodable conditions are necessary for plants to bloom fully, and for optimum overall quality (Pinedo, 2009). The average temperature in production areas is about 25 to 27°C and precipitation varies between 2500 and 4000 mm per year. The nutritional requirements of plants have not been studied, but soils are rich in river basins. The plant has been cultivated in alluvial floodable soils, in non-floodable soils with deficient drainage and in well-drained soils; its adaptation to all these conditions is satisfactory (Rodrigues *et al.*, 2001).

The productivity of plantations increases with time. In fact some plantations in Peru are over 47 years old. Some transient reduction in productivity may be associated with agronomical practices, as in any other natural resource (Pinedo, 2009). Two species of bee (*Melipona fuscopilara* and *Trigona italica)* are the main insects responsible for flower pollination (Inga *et al.*, 2001; Peters and Vasquez, 1987). The higher the basal diameter of the tree, the higher the fruit yield (Peters and Vasquez, 1987).

Fruit dehiscence is an important problem which increases exponentially after fruit set, affecting around 60 to 73% of the fruit 36 days after fruit set (immature stage), depending on the year of study and sampling method (Inga *et al.*, 2001; Peters and Vasquez, 1987; Pinedo *et al.*, 2001). The effect of the plant material origin, area of production, rain abundance, soil quality and sunshine hours may contribute to dehiscence and other critical quality traits, such as the

ascorbic acid content. Differences may also arise from variations in quantification methods (Table 16.1; Rodrigues and Marx, 2006; Rodrigues *et al.*, 2001). The effect on camu-camu fruit quality of different crop management techniques such as the association of camu-camu tree plantation with other vegetables or fruit crops suitable for flooding conditions (Pinedo *et al.*, 2001) has not yet been evaluated.

The germplasm available for commercial plantations in Peruvian public institutions consists of 43 accessions from eight river basins of the region: Loreto: Nanay, Itaya, Ucayali, Napo, Amazonas, Tigre, Curaray and Putumayo (IIAP, 2009). Differences in fruit quality of the accessions have not yet been fully characterized.

16.5 Postharvest handling factors affecting quality

16.5.1 Temperature

Storage temperature at 12°C is advised to avoid chilling injury (CI), and to reduce the severe shrivelling that occurs at 18 to 20°C, particularly in fully mature fruit.

16.5.2 Harvest operations

Mechanical damage during the handling chain is the most important issue for camu-camu quality. Specific recommendations to reduce this problem are harvesting in the turning and half-mature stages (Plate XXIX: see colour section between pages 244 and 245) and having only one layer of fruit per tray, particularly when the fruit is intended for transportation to distant markets.

16.5.3 Water loss

Weight loss after harvest is dependent on the stage of maturity, with lower losses occurring at 12 or 20°C and 85% RH in mature-green stages compared with mature ones (6% and 14% after ten days of storage) (Jimenez *et al.*, 2008). In half-mature fruit, a storage temperature of 12°C is advised because weight loss is obviously reduced compared with fruit kept at 20°C. In mature fruit, an upsurge of weight loss after one week of storage is concomitant with the development of moderate to severe shrivelling, while at 12°C this increase occurs after nine days. At 20°C, the maximum shelf life is six days for both stages of maturity, weight losses remaining below 5%. At 12°C, maximum shelf life is estimated at nine days for half-mature and seven days for mature fruit. However, when the criteria to establish shelf life are based on fungi and yeast growth, shelf life is estimated at 12 days for half-mature and nine days for mature fruit.

16.5.4 Atmosphere

Levels of 8 ± 2% CO_2 and 10 ± 2% O_2 at 12°C are considered advisable to prevent the adverse effects of softening and the development of off-flavours and a sour

aroma due to fermentation (Ortiz *et al.*, 2007). Such an atmosphere slightly delays the loss of ascorbic acid in mature-green and ripe fruit. Carbon dioxide levels above 10% and O_2 levels below 5% induce fermentation. Polymers such as polyvinyl chloride (PVC) film do not help in retaining ascorbic acid or anthocyanins in half-mature fruit stored at 20°C and 68% RH (Silva *et al.*, 1997). Ozone is not advisable due to the risk of oxidation of ascorbic acid and anthocyanins.

16.6 Physiological disorders

16.6.1 Chilling injury

Camu-camu is very sensitive to chilling injury (CI), and symptoms in the form of pitting are noticed if temperatures remain between 6 and 10°C for one week or more (Table 16.2). The CI symptoms that developed in camu-camu stored at 6°C were uneven ripening, slight flesh acidification, pitting and watery breakdown of external tissues (Carrillo *et al.*, unpublished data; Plate XXX: see colour section between pages 244 and 245; Table 16.2). CI increases during the subsequent shelf-life period (Fig. 16.3) and may be associated with decay. Half-mature fruits exhibit higher sensitivity than fully mature ones. A decrease in ascorbic acid is associated with CI, as in other *Myrtaceae* such as arazá (Hernández *et al.*, 2009).

Table 16.2 Storage losses (disorders and decay) of fruit harvested in half-mature and mature camu-camu fruit subjected to different storage duration at different temperatures (per cent fruit)

Storage losses	Harvest	Half-mature						Mature					
		6°C		12°C		20°C		6°C		12°C		20°C	
		3d	10d	3d	10d	3d	10d	3d	10d	3d	10d	3d	10d
Watery breakdown	0	3	8.3	4	5	7	11	4	7.7	8	15	10	20
Fruit softness	0	7	14	3	10	13	18	14	16	7	12	15	25
Decay	0	4	8	2	5	3	6	4	8	3	7	5	10

16.7 Pathological disorders

The main rot affecting camu-camu fruit is anthracnose, which is caused by *Colletotrichum* sp. and detected by sunken brown circular spots of 1 to 2 cm diameter (Verde and Sánchez, 2005). Necrotic spots caused by *Erwinia* sp. are identified by watery breakdown and off-odours but affected fruit are difficult to observe after harvest. The rot is strongly associated with insect proliferation

(Pinedo *et al.*, 2001), but can be associated with other causes. After processing, the remains of pulp on the seeds can be affected by different fungi (such as *Aspergillus* sp. and *Penicillum* sp.), causing secondary fruit infection or *Erwinia* sp. rotting (Pinedo *et al.*, 2001). Seeds are disinfected with 0.1% benomyl solution.

16.8 Insect pests and their control

In Iquitos (Peru) fruits may be damaged by *Edessa aff. aulacosterna* Stal, 1872 (Heteroptera: Pentatomidae), producing slight to severe fruit loss (Iannaconne *et al.*, 2007; Pinedo *et al.*, 2001). Another important fruit pest is *Conotrachelus dubiae* O'Brien, 1995 (Coleoptera: Curculionidae), whose adults feed on fruit of different diameters and states of ripeness (Nascimento *et al.*, 2003, Pérez and Iannacone, 2008). The fruit attacked by *Conotrachelus dubiae* show a pale pink colour, and larvae develop beside the seed, provoking massive fruit rot, strongly associated with the bacteria *Erwinia* sp. (Pinedo *et al.*, 2001). Tropical flies such as *Anastrepha* sp. (Diptera: Tephritidae) or *Neosilba zadolicha* (Diptera: Lonchaeidae) have been reported as secondary pests in plantations of Peru (Couturier *et al.*, 1992; Pinedo *et al.*, 2001).

The bee *Trigona branneri* Cockerell 1912 (Hymenoptera, Aphidae) can feed on the skin, pulp and/or even the seeds of the fruit, particularly in the case of large beehives. Measurements to control these pests include the removal of rotten or infested fruit, the removal of dropped fruit, the use of plastic boxes for harvesting to avoid larvae, the use of selective traps for flies, the manual removal of beehives if necessary, and harvesting fruit in the half-mature stage (Couturier *et al.*, 1994).

16.9 Postharvest handling practices

16.9.1 Harvest operations

As the shrubs are flooded for most of the year, harvesting is carried out in small boats that transport the fruit packaged in plastic baskets of 25 kg. Camu-camu is harvested between half-mature and fully mature stages (Plate XXIX: see colour section between pages 244 and 245). Mature fruit drop easily, while half-mature fruit remain still strongly attached to the plant. Fruit are harvested in the peripheral stand area once or twice a week, and are transported by boat to the packinghouse or processing plant. Half-mature fruits resist handling better than fully mature fruit, but harvesting fruit of different stages of maturity is common due to harvesting difficulties. Sometimes the trees are shaken in commercial plantations instead of manual harvesting, causing fruit impact damage. Different soil covers such as polyethylene nets have been proposed to deaden the impact and facilitate fruit transfer to the boxes (Pinedo *et al.*, 2001).

16.9.2 Packinghouse practices

Fruit are graded according to the maturity stage into mature green (stage 1), turning and half-mature (stage 2 and 3) and mature and fully mature fruits (stages 4 and 5) (Plate XXIX: see colour section between pages 244 and 245). Other authors have proposed only four stages of maturity (Pinedo *et al.*, 2001). At least two different calibres have been specified for processing purposes (around 20 and around 30 mm diameter). Fruit are usually subjected to air-cooling at 5 to 10°C after harvest and boxes of 23 to 24 kg are piled up to 2 m high with adequate space between piles. Other boxes of lower capacity (7 or 10 kg fruit) are also suitable for storage but only if they have the right surface to avoid mechanical damage due to fruit compression. For this reason, boxes should not measure more than 20 cm in height and no more than ten boxes per pile are recommended. Fruit subjected to pulp processing are usually disinfected.

16.9.3 Control of ripening and senescence

Ripening and senescence are controlled by temperatures between 6 and 13°C and 90% RH, the lower temperatures of 6 and 11°C being suitable for short periods only (<8 days) due to the possible risk of CI. Storage of half-mature fruit at 10°C for eight days or mature fruit at 10°C for four days reduces the respiration rate, delays skin colour changes and reduces weight and nutrient losses (sugars and ascorbic acid) (Carrillo *et al.*, unpublished data). Modified atmosphere packaging (MAP) (in the conditions reported in the following section) delays ripening and senescence, but the polymer should be chosen carefully, bearing in mind carbon dioxide and oxygen permeability, as mentioned in the next section (Ortiz *et al.*, 2007). Edible coatings have not been tested yet for fresh fruit, but would probably contribute to reducing weight loss.

16.9.4 Recommended storage and shipping conditions

The best storage conditions are 12°C and 90% RH. In Peru, Pinedo *et al.* (2001) recommended storing the fruit intended for pulp processing at 5°C for ten to 15 days. Under passive modified atmospheres involving low density polypropylene films (38 or 74 μm) with a medium barrier to O_2 (permeability to O_2 of 2330 to 4000 or 7800 $mL \cdot m^{-2} \cdot day^{-1}$ atm^{-1} calculated at 25°C) and a permeability to CO_2 of 42 000 $mL \cdot m^{-2} \cdot day^{-1}$ atm^{-1} calculated at 25°C), the atmospheres reach equilibrium ($8 \pm 2\%$ CO_2 and $10 \pm 2\%$ O_2) after around five to seven days at 12°C and 90% RH. Such conditions have proved adequate for maintaining fruit quality, particularly in fruit of smaller calibre (20 mm diameter). The above MAP reduces ascorbic acid and anthocyanin degradation and also weight loss (Ortiz *et al.*, 2007).

16.10 Processing

Camu-camu has not been used or studied for fresh-cut processing. Camu-camu processing operations to obtain pulp have been reported by Villachica (1996b).

The fruit is subjected to a double-rinsing process, the first rinsing with tap water to remove soil remains, dust and other objects; then disinfection with a solution such as 0.2% Tecto or 0.5% (w/v) sodium metabisulphite, followed by a second rinsing with pressurized water sprinklers to remove fungicide residues. After drying, fruit without the right quality attributes are removed. Finally, a second manual or automatic selection procedure according to calibre and/or colour is feasible.

Pulp yield is around 44 to 51%, with no significant differences between half-mature and fully mature fruit, but it is lower in large fruit (Pinedo *et al.*, 2001).

To preserve fresh pulp, ultrasounds have been successfully applied for 5 min to keep and even increase ascorbic acid and total polyphenol levels compared with levels at harvest (Pérez and Augusto, 2009), probably because the techniques improve the extractability of these compounds.

Pulp or juice pretreatments before freezing usually reduce the vitamin C content compared with freezing the fruit directly before processing (Ramos *et al.*, 2002). The organoleptic, physico-chemical and microbiological properties of this pulp have been officially defined for export in Peru (Ramos *et al.*, 2002). One type of maltodextrin with dextrose equivalents of 20 in a 1 to 100 scale (DE20) added to camu-camu pulp increases the freezing stabilization potential (and pulp quality) by increasing the glass transition temperatures of the maximally freeze-concentrated phase (*T'g*) from −58.2°C (natural pulp) to −39.6°C when 30% (*w*/*w*). Sucrose has a negligible effect on *T'g* but considerably enhances freezing point depression and less ice is formed (Da Silva *et al.*, 2008).

The refined pulp is sold frozen and packed in high-density polyethylene bags as a raw material for the fabrication of products derived from camu-camu such as jams, nectars, ice cream, liquor, yoghurt and sweets (Velazco and Vega, 2003). Camu-camu is made into a popular ice cream in Peru (Lee *et al.*, 1998). Recently, chefs from Peru have started to use camu-camu pulp, together with other exotic fruit from the Amazon basin, to prepare new recipes that have been presented in gastronomy congresses and exhibitions.

Camu-camu fruit can be squeezed to make drinks (also for fruit blends) or used to flavour other food items. Camu-camu can be used as a soft drink. In Japan, salad dressing, tea with camu-camu and other drinks enriched with camu-camu are available in different types of packaging. The juice has been processed by microfiltration (Barreto *et al.*, 2008) and is also used to enrich other fruit juices, such as orange juice (Pinedo *et al.*, 2001).

Anthocyanin degradation is responsible for the loss in red colour of other processed products. Combining camu-camu juice with other tropical fruits may involve the same problem of the low stability of some anthocyanins in the presence of high concentrations of ascorbic acid. This process occurs mainly due to the direct condensation of the ascorbic acid on the carbon 4 of the anthocyanin, resulting in losses of both components (De Rosso and Mercadante, 2007).

To avoid camu-camu juice adulteration, site-specific natural isotopic fractionation nuclear magnetic resonance (SNIF-NMR) and 13C isotopic ratio mass spectroscopy

(IRMS) can be used to discriminate between ascorbic acid samples obtained from industrial suppliers and those extracted from fresh camu-camu fruit (Albertino *et al.*, 2009).

Organic nutritional beverages made from organically grown fruit are certified by USDA and contain pure 'Sangre de Drago' as a preservative instead of potassium sorbate and/or sodium benzoate. Camu-camu is suitable for the production of fermented alcoholic beverages and the addition of the peel to the pulp contributes positively to its acceptability (Maeda and Andrade, 2003).

Japanese patents have been registered for camu-camu to be used as skin antioxidant, human body lotion, cosmetic and moistener, skin lotion to improve skin elasticity, an agent to suppress the effect of melanin, bleaching agent, and as a component of energetic drinks (Hughes, 2007; WIPO, 2006). Extracts of maca (*Lepidium Meyenii* Walp) and camu-camu are part of a patent for a carbonated energy drink that also contains extract of guarana, caffeine, glucose, fructose, and water (Walter *et al.*, 2006).

Camu-camu can be dried in slices using hot air at 50°C. This retains 78% of the ascorbic acid content, while the moisture of the product falls by 90% on a fresh weight basis (Da Silva *et al.*, 2005). However, the most profitable camu-camu product is lyophilized or dry powder, a treatment that concentrates ascorbic acid 16 times (Da Silva *et al.*, 2006; Ramos *et al.*, 2002). This powder is sold in multi-vitamin tablets, pills or microencapsulated with other tropical fruit powders or extracts. A tapioca root starch base can be mixed with fresh camu-camu juice and lyophilized. The residual water content is critical to extend the lyophilized shelf life for long-term storage.

The process of juice microencapsulation by spray drying after blanching at a temperature of 95°C for 2 min has been optimized (Dib Taxi *et al.*, 2003). The best conditions include subsequent extraction using a brush-type depulper and drying with Arabic gum or malt dextrin in a mini spray dryer using an air entry temperature of 95°C and concentration of 15% wall material. Other extracts and concentrates are also available on the market. These last about 18 months without preservatives and include aseptically packed juice, SO_2 preserved or frozen juice as foods, and whitening essences for cosmetics and beauty care (particular cosmetics derived from camu-camu seeds). Camu-camu can be concentrated by reverse osmosis and osmotic evaporation at low temperature (20 to 35°C). Osmotic evaporation provides a concentrate with less than 3% ascorbic acid losses and more than 10% ascorbic acid content (Rodrigues *et al.*, 2004).

16.11 Conclusions

Little is known about postharvest physiology and technology of camu-camu and the postharvest physiology of this fruit with an apparent climacteric behaviour should be studied in detail. Vitamin C losses after harvest or in fully mature fruit on the tree are serious constraints to extending the fruit's shelf life without

compromising nutrient value and flavour. The physiological meaning of the high ascorbate concentration and its fast postharvest degradation, together with camu-camu nutrient biochemistry and genetics, need to be studied, because these are very relevant factors for increasing camu-camu consumption. Harvesting indices, apart from the colour of individual fruit (particularly those based on non-destructive methods), are needed. Studies on postharvest behaviour, together with breeding programmes as well as germplasm and biodiversity maintenance are required, because different ecotypes of *Myrciaria* sp. have been identified with thicker skin, harvesting dates from January to May, fibrous texture and lower ascorbic acid content (Anguiz, 2002; Pinedo, 2009).

Fruit shrivelling and mechanical damage are the main obstacles to maintaining fresh fruit quality. Quarantine procedures and new postharvest technologies, such as edible coatings to reduce nutrient losses (ascorbic acid and pigment oxidation) and dehydration, should be developed in order to expand the market for fresh fruit. New processing techniques must be applied on a commercial scale in order to improve the storability of fruit nutrients and insure juice safety requirements. Potential uses as a new acidic flavour or to develop functional foods remain to be exploited, particularly because of the fruit's potential as an organic product (Hughes, 2007). However, toxicity and potential allergenic hazards need to be studied, accompanied by a detailed fruit composition analysis and the characterization of fruit metabolites if legal regulations are to be satisfied and, if feasible, to obtain the category of GRAS food. Adulteration must be avoided to extend the use of camu-camu derivatives in the cosmetic market (Hughes, 2007). Socioeconomically speaking, aspects such as local development, the strength of consumption in the producing countries, micro credits for local production and postharvest facilities need to be improved, while the return of benefits to local growers is also critical for developing this crop, which is restricted to reduced and isolated plantations in tropical floodable areas.

New protocols of good manufacture practices for fresh and processed fruit are being developed, particularly in Peru, in order to improve food safety, but they must be applied in other countries. Potential risks derived from the use of contaminated water containing residues dumped by new oil extraction activities should be strictly controlled.

16.12 References

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Plate XXVIII Cajá fruits as usually commercialized at Brazilian free markets in the Northern region. Photo: Rafaella Mattietto.

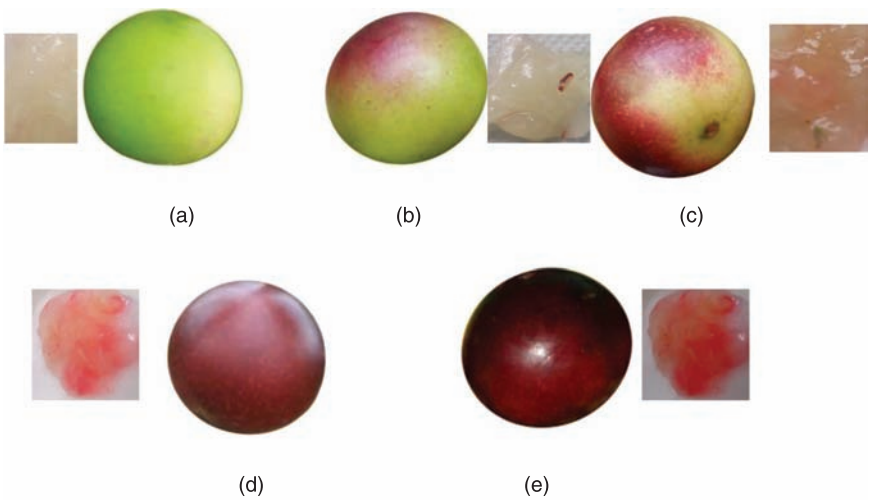

Plate XXIX Camu-camu colour chart during ripening. Stages of maturity classified according to external skin colour and in some cases pulp colour (blending skin with different colours and white flesh). (a) Mature green; (b) Turning; (c) Half-mature; (d) Mature; (e) Fully mature.

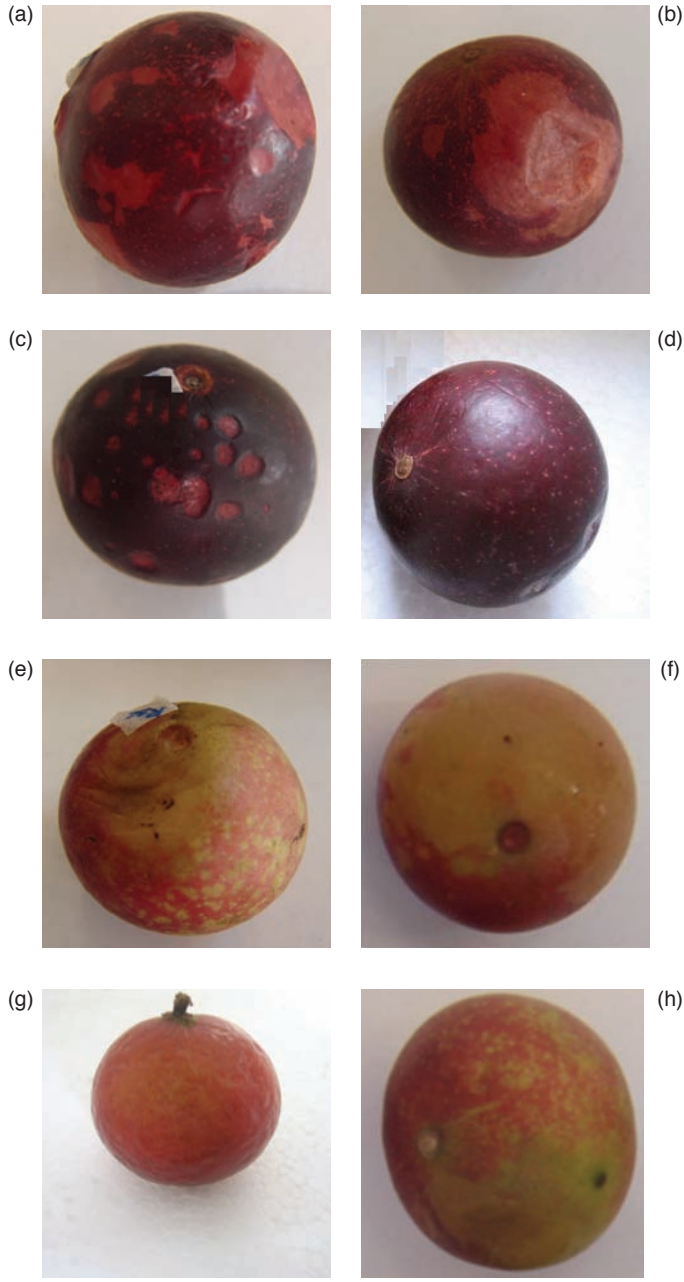

Plate XXX Chilling injury symptoms in camu-camu fruit after storage at 6°C and 90% RH for four days (mature fruit, top) or eight days (turning fruit, bottom). (a) Scald; (b) Scald plus dehydration; (c) Pitting; (d) Sound fruit (mature); (e) Uneven ripening; (f) Skin scald; (g) Watery breakdown (soft yellow area); (h) Sound fruit (turning).

17

Cape gooseberry (*Physalis peruviana* L.)

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Abstract: The Solanaceae species cape gooseberry (*Physalis peruviana* L.) is native to Peru, and forms its fruit in an inflated calyx (husk). Both calyx and skin color are synchronous and can be used to indicate maturity. Being a climacteric fruit, storing it with the husk prevents early breakdown. Most current exports include the husk, which has to be dried thoroughly to control fungi attacks. The fruits withstand temperatures as low as 1 to 2°C, which favors long-term storage. A minor crop for a long time, Colombia has become one of the most important exporters of the cape gooseberry worldwide, mainly to European countries.

Key words: *Physalis peruviana*, Andean fruit, postharvest, synchronous fruit and calyx coloring, husk drying.

17.1 Introduction

17.1.1 Origin, botany, morphology and structure

Like various solanceaous plants, the cape gooseberry (*Physalis peruviana* L.) originates from the Andean highlands of South America. It is found in markets from Venezuela to Chile and has long been a minor fruit of the Andes (FAO, 1982). The cape gooseberry was known by the Incas, but its origins are not clear (National Research Council, 1989). Only Legge (1974) mentioned that it is native to Peru, in the same areas where the tomato originated, whilst Bartholomäus *et al*. (1990) reported that it comes from Ecuador and Peru. There are indications that the fruit came from Brazil and was acclimated to the highlands of Peru and Chile (CRFG, 1997). In South Africa, it was introduced more than 200 years ago as an anti-scurvy fruit (Brücher, 1989). Soon after its adoption by the early settlers at the Cape of Good Hope, it was carried to Australia and then to New Zealand (Morton, 1987). In China, India and Malaysia, the cape gooseberry is grown on a lesser scale, and often interplanted with vegetables (Morton, 1987).

The cape gooseberry belongs to the plant family Solanaceae. Legge (1974) reported that the genus *Physalis* includes about 100 species, which form their fruits in an inflated calyx: however Whitson and Manos (2005) limited the genus to 75 to 90 species. According to Brücher (1989), the genus only has a few representatives in the Old World; most species (probably 90 taxa) are American, principally concentrated in Mexico (70) with a dozen in South America. CRFG (1997) pointed out that there exists considerable confusion in the literature concerning the various species, which include the clammy ground cherry (*Physalis heterophylla*), the tomatillo (*P. ixocarpa*), the purple ground cherry (*P. philadelphica*), the strawberry tomato (*P. pubescens*), and the sticky ground cherry (*P. viscosa*). Hybrids between these species are also known.

Some of the vernacular names for the cape gooseberry in English are Goldenberry, Peruvian ground cherry, Poha yam or Poha berry; in Spanish *Uchuva, Uvilla, Capulí, Aguaymanto* and *Topo*; in French *Coqueret du Pérou* or *Groseillier du Cap*; in German *Kapstachelbeere*; in Portuguese *Groselha do Perú*; in Italian *Fisalis* and in Dutch *Lampion*.

Plants grow wild and half-wild in many parts of the Andes, e.g. in Colombian forests 2200 m above sea level (a.s.l.) (Fischer, 1995), and also in many areas of the Hawaiian Islands at medium and somewhat higher elevations (Morton, 1987), where it is known as 'Poha' (Carman, 1980–1981). This perennial shrubby herb is a soft-wooded, somewhat vining plant, normally growing to a height of about 1.0 to 1.5 m, with sympodial branch ramification (Plate XXXI: see colour section between pages 244 and 245). The vegetative growing basal stem, somewhat woody toward its base, after forming eight to twelve nodes, branches twice dichasially, so that four generative stems (or leaders) are formed (Fischer, 2000). If staked and pruned, plant height may reach 2 m. Cape gooseberry plants have an indeterminate growth habit, i.e. the development of new shoots, leaves, flowers and fruits are simultaneous.

The softly hairy heart-shaped leaves are peciolated, inserted alternately or sometimes seemingly opposite (Everett, 1981). Bell-shaped, nodding hermaphrodite flowers form in the leaf axils. Flowers are yellow with dark purple-brown spots in the throat, and cupped by a purplish-green, hairy calyx (CRFG, 1997). The anthers are purplish-red (FAO, 1982).

The calyx (or husk), which is small at the beginning of fruit development, grows to a bladder-like organ, which completely encloses the ripening fruit (Fig. 17.1).

The calyx measures about 5 cm and its form can be round or elongated (Fischer *et al.*, 1997a). When fecundation occurs, the ovary has a length of 2.0 to 2.5 mm: at this moment the corolla abscises and the fruit begins to grow, simultaneously with the calyx (Valencia, 1985). At the final stage of fruit development the calyx becomes papery and bladder-like. The calyx has been found to play a dominant role in both build-up and translocation of carbohydrates, mainly sucrose, for the fruit during the first 20 days of its development (Fischer and Lüdders, 1997). The husk protects the fruit from extreme climatic conditions (sun, cold, hail), mechanical damage, aerial distributed diseases, insects and birds. Valencia (1985) found a glandular tissue, located in the inner base of the calyx that produces a 'terpenic resin' when the fruit has a diameter of 10 to 11 mm, which covers the

Fig. 17.1 Cape gooseberry plant with flower buds, flowers and developing fruits in calyx. Photo: G. Fischer.

fruit up to its mature stage. She suggested that the 'resin' could be a repellent against insects. Baumann and Meier (1993) identified this substance as withanolide E and 4β-hydroxywithanolide E, whose level increases in the surrounding calyx (in contrast to the fruit) during fruit maturation and to concentrations having anti-feeding effects.

The nearly round fruits are glossy yellow berries with many flat seeds (150 to 300 corns/fruit), which take 60 to 80 days to mature. Fruits measure 1.25 to 2.50 cm in diameter and weigh about 4 to 10 g (Fischer, 1995). Valencia (1985) describes the inner structure of the fruit as appearing like a mini-tomato, although the pulp is formed by a tissue from both the pericarp and the placenta, in contrast to the tomato where the pulp originates principally from the placenta.

Cape gooseberry plants grow and produce well in the Andean regions between 800 and 3000 m a.s.l. (FAO, 1982). In Colombia, plants grow well in daily/night medium temperature regions of 18/13°C (Fischer, 2000), whereas in Baton Rouge (USA) daily temperatures of 30°C impeded flowering (Wolff, 1991). The cape gooseberry produces well in monoculture, and Verheij (1991) reported its culture was also successful in an open forest culture system. In greenhouses, the minor light (UV) incidence favors exuberant internode and leaf growth. Depending on the region's microclimate, the annual rainfall should be between 1000 and 2000 mm and well distributed, and irrigation is recommended during the dry periods. Plant growth and development do well with relative humidity of 70 to 80% (Fischer, 2000).

The plant's productivity in poor soils, ease of cultivation, and low requirement for water and fertilizer have made it an attractive potential crop (McCain, 1993). The plant is fairly adaptable to a wide variety of soils; a fertile, well-drained, sandy soil (National Research Council, 1989), and a pH range between 5.5 and 6.8 are preferred (Almanza and Fischer, 1993). Vegetative growth can overwhelm fruit production if soils are too rich (Klinac, 1986). Special attention has to be made to an appropriate nitrogen supply during plant structure formation taking into account that fruits are formed in each node (starting from the first natural bifurcation) and thus node insertion is essential for fruit production (Fischer, 2000). Martínez *et al.* (2008) found a 90% lower fruit number in cape gooseberry plants that did not receive any boron or potassium and only 15% nitrogen fertilization in the nutrient solution, whereas plants without phosphorous nutrition decreased fruit numbers by 50% compared to control plants.

17.1.2 Worldwide importance and economic value

The main distribution of cape gooseberry production lies in tropical America and Africa, the Antilles, Australia and India. Its environmental requirements are adapted to the Andean regions where *P. peruviana* grows well between 800 and 3000 m a.s.l. (FAO, 1982), but it is also found at sea level in New Zealand.

Although the National Research Council (1989) reported that in most places where they are grown, cape gooseberries are considered fruits only for backyard gardens, nowadays, this fruit has achieved economic importance for the growers and the exporters in some countries. Colombia is probably the country with the largest production area (800 to 1000 ha) in the last decade, with yields between 15 and 28 t ha^{-1} (Agronet, 2010). Production volume and quality are oscillating due to prolonged dry periods (caused by the Pacific phenomenon 'El Nino') and rainy periods, the latter causing fruit cracking and fruit and calyx disease. In 2009, the main buyers of Colombian cape gooseberries were the European countries: The Netherlands (3225.4 tons), Germany (1610.0 tons), Belgium and Luxemburg (966.1 tons), Sweden (214.1 tons) and France (130.4 tons). In the Americas, in 2009, Colombia exported 144.6 tons to Canada, but only 18.4 tons to the USA (Agronet, 2010), which could be a result of the demanding quarantine cold treatment (see Section 17.4.3) of APHIS-USDA, especially for the Colombian exporters. The medium Fob price for all Colombian cape gooseberry exports in 2009 was US$ 3805 per ton. In general, tropical countries have the advantage of producing and supplying the international markets with fresh fruits year-round.

Exports to Europe and Canada are done with the calyx while US consumers prefer fresh fruits without husks. Due to the fact that the conditions and requirements for export to Europe and the USA are different, special conditions in harvest, postharvest handling and commercialization are required for each of these two important world markets (García *et al.*, 2008).

Other considerable commercial production areas in the Americas exist in Ecuador and Chile. In Africa, countries like Zimbabwe, Kenya and South Africa

have produced cape gooseberries for export, mainly to European countries. Further production of this crop has been reported from Costa Rica (CCI, 2000), India, Australia and New Zealand, among others.

17.1.3 Cultivars and genetic variability

Ligarreto *et al.* (2005) named various countries in Latin America and the Caribbean (Brazil, Chile, Colombia, Costa Rica, Ecuador, Guadalupe, Guatemala, Mexico and Peru), where collections of *Physalis* germplasm exist, mostly in universities and/or research stations. For example, in Colombia, 222 holdings of *Physalis* are located in the National University (Palmira) and 98 accessions in the Corpoica research stations: Rionegro and Tibaitata. The genetic variability of this genus in Latin America and the Caribbean is represented by traditional varieties, mostly wild ones, except in Brazil and Mexico, where the improved varieties of *P. peruviana* and *P. philadelhica* exist (Ligarreto *et al.*, 2005).

The National Research Council (1989) suggests selecting cape gooseberry plants with superior and sweet fruit types and with a uniform growth habit along the Andean cordillera where the greatest variation is likely to be found. The Council also recommends selecting plants whose shapes are amenable to mechanical harvesting which would also be a major advantage, provided that the fruit mature uniformly, all at once.

Verhoeven (1991) reported that in Australia the cape gooseberry is commercialized under the names of the cultivars such as 'Golden Nugget' or 'New Sugar Giant', that develop large fruits but with an incipient flavor. But Australian fruits with a smaller size present a better flavor and are preferred for elaboration of marmalades and other processed foods. Wolff (1991) reported three commercially important varieties from Baton Rouge (USA), 'Peace', 'Giant Groundcherry' and 'Goldenberry'. Five varieties were described by CRFG (1997), 'Giallo Grosso', 'Giant', 'Giant Poha Berry', 'Golden Berry' and 'Long Ashton Golden Berry', all with fruits approximately 1 inch in diameter. At Calcutta University in India, cv. Rashbori is used in testing programs (Majumdar and Mazumdar, 2002).

From Germany, G. Fischer introduced two ecotypes 'Kenya' and 'South Africa' to Colombia. These African cape gooseberries bear larger fruits. Fischer (1995) found Kenyan and South African cultivars with an average fresh weight of 6.2 g and 6.7 g, respectively, compared to the Colombian provenience with 4.2 g. The African ecotypes possessed a higher provitamin A content (Fischer *et al.*, 2000), but a more intense yellowish-orange color and higher total soluble solids (TSS) content favored the Colombian fruits (Fischer, 1995). Different cape gooseberry ecotypes can present wide variations in chromosome number. Rodriguez (2004) found $2n = 24$ in wild ecotypes, but $2\ n = 32$ in 'Colombia' and $2\ n = 48$ in 'Kenya' provenience.

The National Research Council (1989) indicated that this interesting botanical relative of tomatoes and potatoes has commercial promise for many regions, and recommended this species to tomato breeders seeking a challenge.

17.1.4 Culinary uses, nutritional value and health benefits

The cape gooseberry fruit, which is acid-sweet in taste and with a pleasant flavor, is typically consumed fresh, whole or sliced, without the calyx, but with the skin. The juice is consumed in a pure form or in the preparation of cocktails. The fruit is also used for fruit salads, mousse, desserts, ice cream, puddings, chutneys, yoghurt, a topping or dipped in chocolate (Camacho, 2000).

Due to its high content of pectin and acidity, the fruits are also used in making excellent jam, jellies and sweet pickle (Mazumdar, 1979). Cooking the juice with sugar makes a thick cape gooseberry-flavored syrup. Also cape gooseberries serve in the preparation of sauces, which are then used in deserts as a flavoring for cakes. But also, ripe berries are used in enriched preparations of meat and curries (Mazumdar, 1979).

Ripe good-quality fruits can be used as a dried food, similar to raisins and exported as such. Vitamin E-impregnated cape gooseberry fruits (using an isotonic dissolution of sucrose in the aqueous phase of the emulsion), were juicier, sweeter and less acidic than natural samples (Restrepo *et al.*, 2008). Due to their 'exotic touch', it is common to use cape gooseberry fruits, half opened or without the husk, for decoration purposes on cold buffets in restaurants and hotels.

There is much interest in cape gooseberry fruit consumption due to its nutritional values, especially in provitamin A, vitamin C, and minerals such as phosphorous and iron, and fiber (Rehm and Espig, 1991), which make it ideal for diets (Table 17.1). Due to its high β-carotene content, some Andean people apply

Table 17.1 Nutritional characteristics of cape gooseberry fruit. Ranges are presented

Parameter	Minimum	Maximum
Energy (kJ)	290	290
Water (%)	78.9	85.9
Proteins (%)	0.5	2.3
Fat (%)	0.4	1.3
Carbohydrates (%)	11.0	13.3
Fiber (%)	2.9	4.9
Ash (%)	0.7	1.0
Calcium (mg 100 g^{-1} FW)	7.0	14.0
Phosphorous (mg 100 g^{-1} FW)	21.0	39.0
Iron (mg 100 g^{-1} FW)	1.1	1.7
Citric acid (%)	1.63	2.30
Malic acid (%)	0.25	0.37
Tartaric acid (%)	0.18	0.25
Ascorbic acid (mg 100 g^{-1} FW)	11.0	43.0
Provitamin A (IU)	648	5000
Thiamine (mg 100 g^{-1} FW)	0.01	0.10
Riboflavin (mg 100 g^{-1} FW)	0.04	0.17
Niacin (mg 100 g^{-1} FW)	0.80	1.73

Sources: Camacho (2000), Durán (2007), Fischer (1995), Hermann (1994), Lieberei and Reisdorff (2007), Rehm and Espig (1991).

two drops of the ripe fruit juice externally to the eyes daily to strengthen the optic nerve and prevent cataracts (Durán, 2007). Although the cape gooseberry fruit has many benefits, only low levels of consumption have been recorded. In the year 2000, only 0.11 kg of this fruit was eaten by Colombian consumers per capita (CCI, 2002).

P. peruviana is widely used in folk medicine for treating diseases such as malaria, asthma, hepatitis, dermatitis, diuretic and rheumatism (Wu *et al.*, 2005). Its extract can also be used for preparing health drinks. Ahmad *et al.* (1999) reported that the plant is diuretic and the juice of its leaves is given for worm and bowel complaints, while heated leaves are applied as a poultice. An extract of the leaves shows antibiotic activity against *Staphylococcus* (Perry and Metzger, 1980). The extracts of different parts of the plant show anti-hepatotoxic (Arun and Asha, 2007) and anti-proliferative effects on hepatoma cells (Wu *et al.*, 2004). A supercritical carbon dioxide extract of cape gooseberry leaves exhibits enhanced antioxidant and anti-inflammatory activities (Wu *et al.*, 2006). Also extracts of calices confirmed the anti-inflammatory activity and validated its use in folk medicine (Franco *et al.*, 2007). Ingestion of cape gooseberry fruits decreases glycemia (Rodríguez and Rodríguez, 2007). The high β-carotene content of the cape gooseberry fruit has a potentially anticarcinogenic effect (Steinmetz and Potter, 1996). Leaf extract of this species exhibited moderate *in vitro* anticancer (breast, renal and melanoma) activity (Fouche *et al.*, 2008).

Unripe cape gooseberry fruits are poisonous (CRFG, 1997). Fruits of this species may be a threat to foraging animals. The National Research Council (1989) reported that leaves and stems are suspected of having caused erosion of intestinal membranes (diptheresis) in cattle.

17.2 Preharvest factors affecting fruit quality

17.2.1 Flowering and pollination

In the Cundinamarca state of Colombia, cape gooseberry flower bud development lasted between 18 and 21 days (Mazorra *et al.*, 2006). In India, flowering initiated 70 to 80 days after transplanting and 19 to 23 days passed between the flower buds' initiation and anthesis (Gupta and Roy, 1981). These authors observed that during flowering (three to four days) the corolla opened in the morning and closed in the evening. Lagos *et al.* (2008) found in the Nariño state of Colombia that the corolla opened between 7:00 and 10:00 h and closed between 16:00 and 18:00 h with petal fall five to six days after the first floral opening.

The yellow, bell-shaped flowers are easily pollinated by insects and wind (National Research Council, 1989), self-pollination is common (Gupta and Roy, 1981). The majority of fruits (85% of set fruits) developed under open pollination (non-artificial) (Gupta and Roy, 1981). Lagos *et al.* (2008) observed that two days before flower opening, pollen matured and stigma was receptive, a phenomenon that restricts auto-pollination. In addition, they observed mixed pollination with 54% of cross-pollination in *P. peruviana*.

The cape gooseberry flowers year-round in frost-free areas (National Research Council, 1989). The first flowers are often sacrificed to ensure the establishment of strong, healthy plants. Also, removing the first flowers avoids the fruit cracking when few but big fruits are formed in the lower part of the plant (Fischer, 2005).

17.2.2 Fruit growth, development and maturation

When fecundation occurs, the ovary has a length of 2.0 to 2.5 mm. At this moment the corolla abscises and fruit begins to grow, simultaneously with the calyx (Valencia, 1985; Mazorra *et al.*, 2006). The calyx grows at a faster rate than the ovary (Yamaguchi, 1983) and at the ripening stage the husk of the Colombian ecotype is about 2.5 times the length of the fruit (Valencia, 1985).

Fruit development in field trials in India lasted 50 days (Gupta and Roy, 1981) and 60 days for the Rashbhori cultivar (Majumdar and Mazumdar, 2002), in Germany 56 to 63 days (Wonneberger, 1985), in France 70 days (Peron *et al.*, 1989) and in Colombia between 60 and 80 days, depending on the agroecological site conditions (Galvis *et al.*, 2005). Thus, tropical altitude influences duration of fruit development. In the Boyacá state of Colombia (4°N) at 2690 m a.s.l. (12.5°C mean temperature), cape gooseberry fruits required 75 days to harvest, whereas at a lower altitude, 2300 m (17.0°C), development was faster, only 66 days (Fischer *et al.*, 2007). From New Zealand, Klinac (1986) reported a faster fruit development when rooted cuttings were used, rather than plants originated from seeds.

The size and weight growth of the fruit show a typical sigmoid curve. Whereas the fruit increases its size constantly during the 60 days of its development, the calyx stops its expansion 20 to 25 days after fruit set (Fischer, 2000). The fruit tends to grow more in longitude between days ten and 25, contrary to the following days during its maturation when it grows more in the transversal diameter (Fischer *et al.*, 1997a; Fischer, 1995). Also, fruits developed on the leaf axils of the main stems are slightly heavier than those from the lateral shoots (Mazorra *et al.*, 2003).

The cape gooseberry fruits possess the capacity to accumulate high amounts of water and sucrose until the consumer maturity stage (orange skin color), assuming a water supply up to the last moment before harvest, in detriment of postharvest quality and longevity (Fischer *et al.*, 1997b; Fischer and Martínez, 1999). During fruit development, carbohydrate patterns are similar between fruit and calyx, which confirms the close relation in carbohydrate metabolism between these two organs (Fischer and Lüdders, 1997), but anatomically the husk is more leaf-like (Fischer *et al.*, 1997a).

17.2.3 Maturity and harvest

The skin color of the cape gooseberry can be used as a maturity index (Galvis *et al.*, 2005). Harvesting should begin when the calyx begins to turn yellow, avoiding overmaturity (Bernal, 1991). Visual harvest determination utilizes the synchronous color changing of both calyx and fruit, having nearly the same color

(Plate XXXII: see colour section between pages 244 and 245). It should be done carefully to avoid the stem breaking and knocking off ripe fruits. Castañeda and Paredes (2003) observed fruit and color development in Granada (Cundinamarca state, Colombia). Fruits presented an intense green color during the first 35 days after anthesis, starting to change slowly to yellow, which was an intense yellow-orange in the skin and pulp at 64 days when consumer maturity was reached. At 84 days, fruit coloring was red-orange indicating the overmaturity stage.

Sometimes premature fruit-fall is observed, probably related to overmaturity, abruptly changing soil moisture and climate and varietal hormonal factors. Pre-blossom spray with Ethrel (500 ppm) enhanced fruit ripening by ten days (Garg and Singh, 1976).

Angulo (2005) defined physiological maturity of the cape gooseberry, ready for picking, when the calyx, mostly green colored, presents yellowish stripes. At this stage it is first possible to see the fruit shape inside the husk by holding it against direct sunlight. At physiological maturity (56 days after anthesis) Castañeda and Paredes (2003) measured 12.7°Brix, 3.52 pH and 1.215 g of citric acid per 100 g fruit fresh weight.

Harvest initiates, depending on site conditions (principally temperature), between four and seven months after transplanting (Galvis *et al.*, 2005). In Colombia, starting with the second production year, the fruit size decreases, thus plants give their maximum yield in the first season (National Research Council, 1989), while whole culture is possible for two or three years. In sites with higher temperatures, first harvest peak is highest and then peaks decrease in intensity, whereas in colder climates it is the opposite (Fischer, 1995).

It is recommended that the harvest is done two to three times per week during a harvest peak, in the early morning hours, avoiding picking during the rain or fruits with wet husks (Fischer and Almanza, 1993). Fruits should always be picked with their husk and with a peduncle with a maximum length of 25 mm (Icontec, 2004). In ecotypes and varieties where the peduncle is strongly attached, picking has to be done with small scissors. It is recommended that the scissors be disinfected between each plant in plantations with disease infestation. For packaging the harvest, Icontec (2004) recommend plastic packing boxes with 7.00 to 7.5 kg fruits, and a maximum height of 250 mm.

17.3 Postharvest physiology and quality

17.3.1 Respiration and ethylene production

Cape gooseberry ripening is associated with a conspicuous climacteric rise in carbon dioxide (Novoa *et al.*, 2006) and ethylene production (Trinchero *et al.*, 1999). Respiration peak of intact fruits occurred under field conditions in Colombia (Silvania, Cundinamarca department, 2100 m a.s.l.) at 64 days after anthesis (Castañeda and Paredes, 2003). Fruits without a calyx respire more than with an attached calyx (Villamizar *et al.*, 1993); also, supposedly, the intact calyx generates lower levels of ethylene.

Ethylene acts as a promoter of fruit softening as a consequence of cell-wall weakening caused by the activity of hydrolases (Fischer and Bennett, 1991). During ripening of 'Rashbhori' cape gooseberry fruits, Majumdar and Mazumdar (2002) found that water and oxalate-soluble pectic substances decreased while polygalacturonase activity increased: the latter was highly correlated with ethylene evolution, but pectin methylesterase activity was not clearly related to fruit ripening. With an Argentinean ecotype, polygalacturonase and α-glucosidase activity were hardly noticeable whereas pectin methylesterae and α- and β-galactosidase reach activity similar to that in the tomato fruit (Trinchero *et al.*, 1999).

17.3.2 Ripening, quality components and indices

The most noticeable change of cape gooseberry fruit during maturation and ripening is the change in skin color from green to yellow (Fischer and Martínez, 1999), in stages 2 and 3 (Fig. 17.2) when physiological maturity occurs and synchronously the calyx changes from light green to yellow, which makes this characteristic adequate for use as a maturity index as discussed before. In cape gooseberry fruit, at the same time as the color change, the weight of the fruit increases, reaching a maximum around maturity stage 5 (Fig. 17.2) (Fischer and Martínez, 1999). Total soluble solids (TSS), in green fruits with 9.3°Brix, peaked with 17.2 between stage 3 and 4 and then fell to about 13.7 at the overripe stage (Fig. 17.2). Total titratable acidity (TTA), due to its demand in respiration (Kays, 2004), decreases constantly from 39.5 mval/100 mL in green to 17.6 mval/100 mL in overripe fruits. Interestingly, β-carotene content, taking into account that the cape gooseberry is classified as a carotenoid fruit (Fischer *et al.*, 1997b), peaks at the orange color stage, and after that its fall is interrupted because of a concentration effect on the decreasing fruit size at stage 6 (Fig. 17.2).

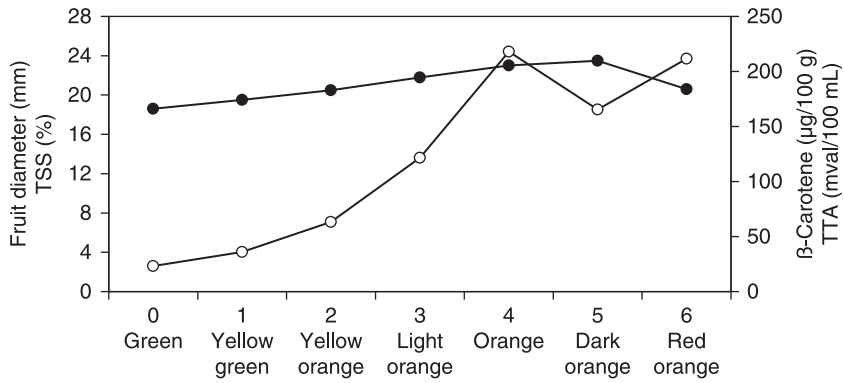

Fig. 17.2 Changes in diameter, total soluble solids (TSS), total titratable acidity (TTA) and β-carotene content of cape gooseberry fruits during six ripening stages. Source: Data from Fischer, (1995).

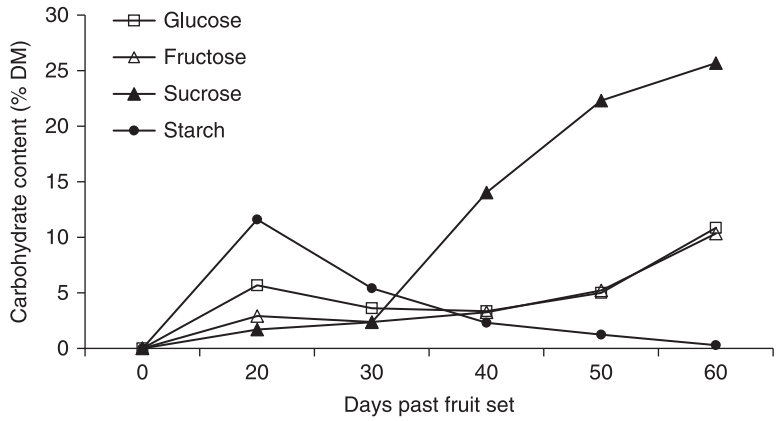

Fig. 17.3 Developmental changes of carbohydrate components of cape gooseberry fruits. Source: Data from Fischer, (1995).

Comparing carbohydrate patterns during fruit development, Fischer and Lüdders (1997) found an abrupt starch degradation from day 20 past fruit set, whereas sucrose content increased constantly, with high and increasing rates from day 30 (Fig. 17.3).

At harvest, at 56 days after anthesis, in Tunja (Colombia, Boyacá department, 2690 m a.s.l.) fruits of the Colombia ecotype had 17.3°Brix, 2.0% TTA (8.6 SSC/TAA), with a density of 1.06 g cm^{-3} (Almanza and Espinosa, 1995). Curiously, fruits of the Colombian-introduced African ecotypes Kenia and South Africa did not develop an intense yellow color (only dark ochre yellowish), ripened ten to 15 days later and had lower SST and TTA content and density than the Colombian provenience (Almanza and Espinosa, 1995). Trillos *et al.* (2008) found in 46 cape gooseberry proveniences, kept in the Colombian Germplasm Bank of Corpoica, a medium TSS content of 12.2°Brix (maximum 16.9°, minimum 6.1°) and a juice content of 2.0 mL (maximum 4.0 mL, minimum 0.8 mL) per fruit.

At harvest, Martínez *et al.* (2008) observed a reduced total soluble solids content in fruits of plants deficient in boron fertilization, whereas those with a lack of phosphorous applications had higher total titratable acidity. A deficient phosphorous or calcium nutrition of plants in pot culture diminished the eating quality of cape gooseberry fruits more than a lack of magnesium in the nutrient solution (Garzón and Villareal, 2009).

17.4 Postharvest handling factors affecting quality

17.4.1 Handling and grading

Generally, the berries are not washed or disinfected, regardless of whether the husk is attached or not (Gallo, 1992). A very high percentage of fruits are usually clean owing to protection from the calyx. Washing and disinfecting with low concentrations

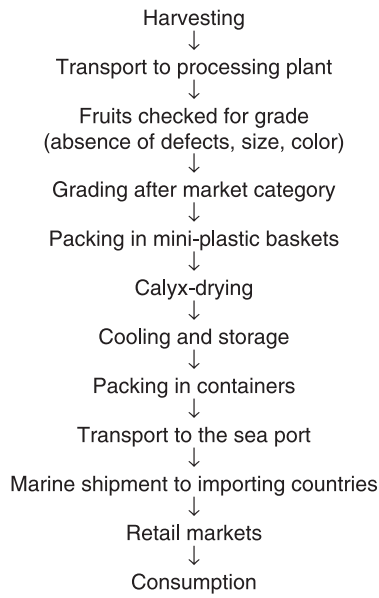

Fig. 17.4 Postharvest handling of cape gooseberry fruit with calyx.

of chlorine (20 to 50 ppm) decrease the microbial contamination but eliminate the natural anti-feeding compounds of the fruit (see point 17.1.1), thus Alvarado *et al.* (2004) found increased fruit pulp dehydration and diminished preservation time after disinfection. In all fruits destined for export with the calyx, the husk is carefully opened at the apical end and checked for defects (physical, physiological, pathological and entomological), size and color (Fig. 17.4) (Galvis *et al.*, 2005). Just like the fruit, the husk has to be free of defects. Generally, in the course of this process, fruit with discolorations (too green or too orange) or cracks are sorted out. Fruits have to be firm and fresh in appearance, with a smooth and shiny skin. If the calyx is present, the peduncle must not exceed 25 mm in length (Icontec, 1999).

In accordance with import requirements and/or the distance to the import country, the color of the calyx can be light greenish, normally straw-colored. The size is determined by the maximum diameter of the equatorial section of the fruit. For size code diameters, Icontec (1999) determined for caliber A ≤15.0 mm, B 15.1 to 18.0 mm, C 18.1 to 20.0 mm, D 20.1 to 22.0 mm, and for caliber E ≥22.1. Unit fruit weight is not standardized, but fruits (without the calyx) of 6 g are preferred; however in periods of high demand, fruits sometimes only weigh 4.5 g.

17.4.2 Calyx drying

Since cape gooseberry is mainly exported with an attached calyx, conserving the quality characteristics and protecting the fruit from damage, calyx drying is of

great importance in the postharvest life of this fruit. This is the reason that cape gooseberry importers require fruits with totally dried husks. The calyx, which is not edible, has a very similar carbohydrate pattern to that of the fruit (Fischer and Lüdders, 1997), and can weigh up to 2 g, although dried ones have only one-tenth this weight.

Generally, calyx drying is done after fruit grading, before or after packaging (commonly done in different types of small plastic baskets). It is recommended that drying be done after packing due to the ease of packing fruit with a fresh calyx compared to fruit with dry husks (Galvis *et al.*, 2005).

Colombian fruit export firms, generally, dry calices by convection, with forced air with RH lower than 50%, but the temperature can vary. Good results were found by Novoa *et al.* (2002) drying fruit calices at an air temperature of 24°C for six hours without affecting physico-chemical and sensorial characteristics during or after posterior storage. Longer drying periods cause fruit weight losses and accelerate the ripening process (Galvis *et al.*, 2005). Ten hours of drying with temperatures up to 25°C can be used for fruits with green or wet calices.

In the drying system by convection, a chamber (or tunnel) is used into which hot air is injected on one end through fans. The air, which passes through the small baskets packed with fruits, is removed with extractors at the other side. Novoa *et al.* (2002) observed a higher incidence of *Botrytis* on fruits that were dried at 18°C compared to 24°C. For the local market, calyx drying can be done on tables or on wire nettings. With an air temperature of 12°C, the aeration can last eight hours using fans and up to three days without artificial air movement (Herrera, 2000).

17.4.3 Packaging

The best packaging for cape gooseberry fruit is the natural attached dried calyx: it protects the fruit not only from physical damage but also against fungus, and favors the modification of the atmosphere surrounding the fruit (Galvis *et al.*, 2005).

For distribution to the wholesale markets, cape gooseberries are preferentially packed in plastic boxes or also those made of cardboard or wood (for 8 to 10 kg fruit weight). Icontec (2004) recommended a maximum height of 25 cm, with a capacity of 8 kg for fruit with a calyx and 10 kg without a calyx. For consumers, fruits are packed in perforated small plastic fruit containers or in small plastic baskets with a total maximum fruit weight of 200 g (with calyx) and 500 g (without calyx).

For export, packaging specifications depend on the importer and the target country requirements, normally small plastic baskets with 125 to 250 g fruit weight of cape gooseberries with calyx are used. Fruit packed in these baskets are commonly covered with a plastic film (polyvinyl chloride or micro-perforated polypropylene) (Herrera, 2000). The baskets are grouped into corrugated fiberboard boxes (e.g. eight baskets with 125 g each results in 1 kg fruit weight). For transport handling, these boxes are packed into mini-containers that are sized in accordance with the dimensions of the pallets. Requirements for package material (type, hygiene, etc.) and labeling must be in accordance with international standards, especially with those of the import country.

17.4.4 Temperature and relative humidity

Optimum conditions for medium- and long-term storage of cape gooseberry fruit (<6 months) vary between 2°C and 4°C, and 80 to 90% RH (Galvis *et al.*, 2005). In fruits stored with calyx, a high RH can cause diseases, which highlights the importance of good calyx drying before storage. A RH of 68% and 88% had no significant effect on fruit quality during 16-day-storage of cape gooseberries at 1.5°C (Alvarado *et al.*, 2004).

Mercantila Publishers (1989) recommended an ideal storage or transport temperature of 12 to 15°C for one to two months, and for 30-day storage in Colombia temperatures between 4°C and 6°C showed good results. The transport temperature for Colombian cape gooseberries is commonly set at ranges of 8 to 12°C.

In general, fruits with a calyx can be stored for a longer duration at different temperatures, 6°C (Villamizar et al., 1993), 12°C (Novoa *et al.*, 2006) and 19°C (García and Torres, 2005, cited by Galvis *et al.*, 2005). Villamizar *et al.* (1993) reported that fruit held at 6°C could be stored for 30 days with an attached calyx, but only for 20 days without a calyx, both at 18°C and 70% RH.

During a 33-day-storage period at 0 and 7°C, cape gooseberry fruit titratable acidity content decreased more at the higher temperature regime where a higher respiratory rate was also measured, supposedly responsible for the higher degradation of the organic acids used as a respiratory substrate (Kays, 2002). Also, the higher fungus infection in this treatment (7°C) could be due, in part, to the lower acidity of these fruits (Osterloh *et al.*, 1996).

Owing to its resistance to chilling injury, at as low as 1 to 2°C (Alvarado *et al.*, 2004), cape gooseberry fruits tolerate the quarantine cold treatment T107a well, which is required by APHIS-USDA as a condition to export these fruits from Colombia to USA. The treatment involves maintaining fruit pulp temperature at <2.22°C during definite periods (e.g. 14 days at 1.10°C, 16 days at 1.67°C or 18 days at 2.20°C), with the purpose of killing the Mediterranean fruit fly larva (Flórez, 2005). The treatment must be implemented in containers that are automatically cooled or in refrigerated ships during transit (USDA, 2004). In some cases the quarantine cold treatment is applied after air transport in Atlanta, Georgia (USA). The cold treatment for cape gooseberry fruit exported to the USA possesses variants, e.g. fumigation + cold treatment (T108), cold treatment + fruit fumigation (T109) and quick freezing (T110) (USDA, 2004). Also irradiation (T105-b-4) treatment is allowed to kill fruit flies in the cape gooseberry before entering the USA ports (Flórez, 2005).

17.4.5 Controlled and modified atmosphere

There is little information on the use of modified and controlled atmosphere storage of cape gooseberry. Gallo (1992) recommended an atmosphere of 3 to 10% CO_2 and 3% O_2 at 5 to 8°C and 85 to 90% RH. During a 4-week-storage in modified atmosphere at 7°C using three kinds of plastic film (polyethylene

terephthalate-polyethylene, bi-oriented polypropylene-polyethylene, and polyolefin) and four atmosphere mixtures (5% CO_2 and 5% O_2; 5% CO_2 and 10% O_2; commercial mixture and ambient air), the best results were shown with calyx-attached fruits (higher firmness) packed in polyolefin film (lower water loss), with no differences among active modified atmospheres (Lanchero *et al.*, 2007). Also, cape gooseberries packed in plastic baskets wrapped with micro-perforated polypropylene film lost only 3.6% of fresh weight during a 33 days' storage at 7.5°C, whereas fruit without film wrapping lost 5.0% after 16 days (López and Páez, 2002).

17.4.6 Ethylene

The cape gooseberry was classified by Gallo (1992) as a high producer of ethylene, up to 100 uL kg^{-1} h^{-1}. This has to be taken into account when using modified atmosphere packaging for advanced ripened fruits because it can result in the accumulation of ethylene, thus counteracting the beneficial effects of ripening delay. Application of the ethylene antagonist 1-methylcyclopropene (1-MCP) gas delayed the onset of ethylene climacteric in mature green fruits and transiently decreased ethylene production in yellow and orange cape gooseberry fruits (Gutierrez *et al.*, 2008). Also, this study revealed that 1-MCP application did not prevent decay in orange-colored fruits but reduced its incidence, thus suggesting that it may influence pathogen infection and development in ripe cape gooseberries.

Because of its high ethylene production, it is not recommended that cape gooseberry be mixed with other fruits that are sensitive to exogenous ethylene, e.g. the purple passion fruit (Shiomi *et al.*, 1996), since it accelerates endogenous ethylene production and can thus accelerate their ripening. If for some reason they must be mixed, ethylene scrubbers may reduce damage (Thompson, 2002).

17.4.7 Waxing

Waxed fruit, without the husk and using bee honey, which was emulsified with vegetable oil (with a ratio of 1:8) beforehand, better maintained the sensorial characteristics and the original fresh weight in storage, compared to non-waxed fruit (Rodríguez, 2003). Waxed fruits maintained total soluble solids and firmness for 41 days.

17.5 Crop losses

17.5.1 Chilling injury

Cape gooseberry fruits resist low storage temperatures and no chilling injuries are observed at temperatures as low as 1°C. Thus, 30-day storage at 1°C conserved fruit in good conditions (Garzón and Villareal, 2009). Alvarado *et al.* (2004) found no chilling injury at 1.5°C during 16 days.

17.5.2 Other physiological disorders

High fruit losses of cape gooseberry, up to 50% of all fruits not suitable for export, result from fruit cracking and splitting mainly caused by high water content in fruit, especially during rainy seasons or after the first rainfalls immediately following dry seasons (Fischer, 2005). Also, deficient fertilization with calcium and boron increased the percentage of cracked fruit from 5.5 to 13.0, when any of these two elements were eliminated in the nutrient solution (Cooman *et al.*, 2005). In cape gooseberry pot culture in greenhouses, irrigation with Mg-deficient nutrient solution resulted in 11.3% cracked fruits at harvest compared to 0.79% in the Ca-deficiency treatment (Garzón and Villareal, 2009).

Also, high nitrogen content in soil (due to excessive mineral or organic fertilization) can increase cracking, up to 30% (Gordillo *et al.*, 2004). High relative humidity conditions in the air were observed to cause fruit cracking, both in field and in storage (Fischer, 2005) due to transpiration inhibiting effects. This effect is more pronounced as low night temperatures occur (Kaufmann, 1972). Also, cuticle formation on the fruit is possibly negatively affected causing a low protective cuticular capacity under high air humidity conditions (Opara *et al.*, 1997).

To minimize cape gooseberry fruit cracking and splitting before harvest an optimum nutrient application with calcium, boron, potassium and magnesium is required, along with an avoidance of high soil humidity and excessive nitrogen applications. Also, products that contain carboxylic acids, complemented with calcium and boron, have shown to reduce this fruit disorder (Guerrero *et al.*, 2007).

Zapata *et al.* (2002) mentioned that at the end of storage, fruits could present damage due to dehydration, ruptures of the calyx and fruit cracking. Cracked fruits during storage can occur due to abrupt changes in RH or temperature (Fischer, 2005), especially when the RH is high.

17.5.3 Pathological disorders

One of the most important diseases in fruits and calyx, reported in Colombia, is *Phoma* sp. (Zapata *et al.*, 2002). This disorder initiates in the point where the fruit is inserted onto the peduncle with a black ring and finally develops a white mycelium on the fruit. Grey mold (*Botrytis* sp.) forms necrotic irregular spots developing a mycelium of grey color that can cover the whole fruit and calyx (Zapata *et al.*, 2005). When fruit are cracked, *Botrytis* can enter easily in the unprotected pulp causing a bitter flavour (Angulo, 2003).

A typical post-harvest disease of cape gooseberry in the Maharashtra region of India described by Rao and Subramoniam (1976) is *Fusarium equiseti* (Corda) Sacc., entering at points of injuries and bruises on stored berries and subsequently inciting a soft rot. In the fruit market of Aligarh (India), Sharma and Khan (1978) isolated on cape gooseberries the fungi *Alternaria alternata* (Fr.) Keissler, *Cladosporium cladosporioides* (Fres.) de Vries and *Penicillium italicum* Wehmer.

Other diseases that affect the leaves and calyx are grey spots (*Cercospora* sp., possibly *Cercospora physalidis* [Ellis, 1971]), the most important leaf disease of cape gooseberry, which impacts more during high humidity seasons (Blanco, 2000); and the bacteria *Xanthomonas* sp., causing grease spots (Zapata *et al.*, 2005). Disease control is based on good agricultural practices (healthy plant material, sufficient plant distance, sanitary pruning, etc.) and preventive sprays of fungicides.

The descendant drying of the calyx apex in fruits right before the harvest, as described by Blanco (2000) in Colombia, is caused by a *Cladosporium-Alternaria* complex. Most of the fruits with completely dried husks are abscised. Against *Alternaria*, Blanco (2000) recommended planting more resistant cultivars and applying fungicides at the moment when the secondary dissemination of the disease occurs.

Other, more seldom-observed diseases, mainly on leaves and sporadically on the husks, are *Ralstonia solanacearum*, and a mosaic virus ('mosaico de uchuva') similar to the potato virus X (PVX) (Zapata *et al.*, 2002). Powdery mildew can be found on leaves of cape gooseberry (CRFG (1997).

After 33 days' storage of cape gooseberry, Lizana and Espina (1991) found fungus of the genera *Cladosporium, Penicillium, Botrytis* and *Alternaria* on fruits kept at 7°C, whereas those at 0°C showed a significantly lower percentage of infection.

17.5.4 Insect pests and their control

Various types of insect pests can attack the calyx and fruit. The heaviest attack on calyx in Colombia is caused by the mite *Aculops lycopersia* in the peduncle zone, and also on leaves, giving it a greyish-ashy shade. Dry, warm weather with fast drying of affected tissues favors its incidence (Benavides and Mora, 2005). Possible control is with chemicals containing the active ingredients abamectin and fenbutatin oxide (Angulo, 2003). The leaf borer *Epitrix cucumeris* is another insect that causes great damage to the calyx and leaves, producing orifices of irregular size (Almanza and Fischer, 1993). It can be controlled by products based on the active substances deltamethrin or benfuracarb (Angulo, 2003). Adult and larval thrips (*Frankliniella* sp.) can damage apical leaves, flowers and husks. The affected tissues take on a whitish coloration, later turning silver and finally dark (Benavides and Mora, 2005). Against thrips, Angulo (2003) recommended a biological control with *Chrysoperla externa*.

Cape gooseberry fruit is infected by the borer *Heliothis* sp., which perforates the husk and consumes the pulp during any phase of its maturation (Benavides and Mora, 2005). This pest can diminish yields by more than 20%, and without the protection of the husk all fruits would be destroyed in a few days. Other fruit borers, with minor incidence such as *Copitarsia* sp. (Benavides and Mora, 2005) and *Lineodes* sp. (Angulo, 2003), were observed. Zapata *el al*. (2002) recommended biological control with products containing *Bacillus thuringiensis*. For heavy attacks of these fruit borers, products based with deltamethrin can be applied (Angulo, 2003).

17.6 Processing

Owing to its characteristics, the cape gooseberry has potential for fresh-cut processing and its size is appropriate for salads, fruit and vegetable. In the processing industry, the fruits are used to make juice blends or canned whole or with other fruits in pickled mixtures. The fresh berries can be easily frozen. Camacho and Sanabria (2005) established as a general value of ripe cape gooseberry fruits suitable for processing a TSS content of 14°Brix and 1.3% acidity (expressed as citric acid), which results in a maturity index of 10.8.

Cape gooseberries make excellent jam; in fact, in India, they are known commonly as yam fruit. In the United States, they are best known as preserves marketed under the Hawaiian name poha (National Research Council, 1989). Especially in Colombia, among the products derived from the fruit, there is 'bocadillo' (a paste of the fruit pulp with a sugar content of 72°Brix). Cape gooseberry syrup is a viscous sauce of sugar and pulp, with a lower concentration than bocadillo; about 60°Brix. Jam of this fruit is concentrated at 63°Brix. Excessive numbers of seeds may be screened off after crushing if the berries contain too many (Mazumder, 1979).

Drying of cape gooseberry fruits (without the calyx) has been done in different ways. Trials were performed on-farm in the direct sun and for 15 days in a plastic greenhouse (covered with two-layer plastic film) on trays. Also, dehydration has been done with hot air (60°C) and now with the osmodehydration technique (Camacho and Sanabria, 2005). The results are 'raisin like' with shriveled skin and a dark orange color with a pleasant sweet (somewhat bitter) taste, which can be kept for several months. Camacho and Sanabria (2005) successfully proved that preservation of osmodehydrated cape gooseberries in syrup considerably reduces fruit skin cracking.

In general, cape gooseberry products have good market acceptance and many of them can be processed by small companies.

17.7 Conclusions

The Andean cape gooseberry is well adapted to low storage temperatures which prolong postharvest life and facilitate shipping. The attached husk, which entirely encloses the fruit, is the 'best package' that maintains the fruit's characteristics and increases shelf life. Future needs and challenges include:

- Select cultivars that bear superior fruit types (i.e. large fruits, with a sweet and pleasant flavor, without cracking);
- Develop mechanical harvesting methods because handpicking the fruit represents the highest labor cost of the crop;
- Utilize its resistance to low temperatures for long-term storage and new storage methods;
- Research on vitamin, antioxidant and mineral content of the fruit in order to better promote its nutraceutical benefits;
- Standardize processing methods and study new uses for the fruit.

17.8 References

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Plate XXXI Six-month-old cape gooseberry plantation in Chocontá, near Bogotá, Colombia, at 2,650 m a.s.l. Photo: G. Fischer.

Plate XXXII Cape gooseberry fruit with opened husk. Visual harvest determination utilizes the synchronous colour changing of both calyx and fruit. Photo: G. Fischer.

18

Carambola (*Averrhoa carambola* L.)

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Abstract: The carambola (*Averrhoa carambola* L.) has been cultivated in tropical and subtropical regions for hundreds of years. The fruits are berries that originate from the ovary of the flower and usually have four to six fins (five being the most common). The fins of the fruit give it a star-shaped appearance, hence its other name: star fruit. This chapter describes the factors that contribute to or detract from carambola's postharvest quality, characterized by texture, appearance, flavor and aroma components. The roles of harvest maturity and postharvest treatments, particularly ethylene and 1-methylcyclopropene, are discussed.

Key words: star fruit, *Averrhoa carambola* L., postharvest technology, flavor, aroma volatiles, respiration, ethylene, 1-methylcyclopropene.

18.1 Introduction

18.1.1 Origin, botany, morphology and structure

The carambola (*Averrhoa carambola* L.) originated in Southeast Asia and has been cultivated in tropical and subtropical regions for hundreds of years. Carambola is also known as star fruit in the United States. There are other names including: five corners, five fingers, and numerous non-English names. One of the most interesting non-English names come from the Philippines where it is called 'balembing' or 'belimbing', which is an idiom also used to describe politicians who seem to have having multiple faces.

Carambola is a member of the Oxalidaceae family and the evergreen trees grow in tropical and subtropical regions. The fruit is a berry that originates from the ovary and usually has four to six fins (five being the most common) (Fig. 18.1). Other members of the family include bilimbi (*Averrhoa bilimbi* L.), also known as the tree cucumber, and the wood sorrels (*Oxalis* sp.). Bilimbi is similar to carambola but it lacks the pronounce fins of carambola, giving the cucumber-like appearance. Sorrels are herbaceous annuals that can become a nuisance weed in greenhouses because the mature seed pods are explosively dehiscent.

Fig. 18.1 Carambola fruit ready for harvest.

18.1.2 Worldwide importance

Significant production of carambola occurs in Taiwan, Malaysia, China, India, Philippines, Australia, India, Israel, Brazil, Peru, Guyana, and the USA (Florida and Hawaii). Carambolas are usually consumed in the country they are produced, except for high-quality carambolas grown in Malaysia that are exported to Europe.

The carambola was introduced to southern Florida in 1887 and at that time all of the available varieties were tart. However, the introduction of sweet varieties has caused commercial production to increase to 81 hectares with a value approaching $9.5 million and production of nearly 2,200 tonnes, and accounting for 13% of the total annual revenues for the state's tropical fruit industry (Kohout and Crane, 2004). In the native tropical habitat carambola trees bear fruit throughout the year, however in subtropical Florida the crop has two major harvesting seasons, August to September and December to February.

Morris Arkin was an amateur propagator from Coral Gables, Florida. Arkin collected carambola seeds and plant material from Thailand and Malaysia, and in the 1970s selected the sweet variety, 'Arkin'. Currently, 'Arkin' accounts for approximately 95% of the Florida carambola crop, while the remaining plantings are 'B-10' and 'Kary' (J. H. Crane, personal communication, 2007). 'B10' carambolas are sweet with good flavor but the trees require cross-pollination for proper fruit set. 'Kary' carambolas are also sweet but are better adapted to growing conditions in Hawaii. 'Arkin' carambolas typically have 80% less oxalic acid than 'Golden Star', which is a tart variety of carambola (Campbell and Koch, 1988). 'Arkin' carambola trees can reach 7 m in height with a canopy diameter of 5 m (Knight and Crane, 2002). The lower height of the trees permits planting under windscreens, which offer protection from wind scars. Less significant production of other varieties includes: 'Dah Pon', 'Hew 1' (from Thailand), 'Newcomb', and 'Thayer'.

In Malaysia the major varieties are also sweet. 'B-10' and 'B-17' are common, as well as 'Crystal Honey' (15 to 18°Brix). 'B-2' is used as a pollinator and is unique because the fruit ripens to a whitish, yellow color. In Taiwan 'Er-lin' is used as a pollinator for the more popular varieties, 'Meeshi', 'Soft-Sih', and 'Cheng-Sey', also called 'Chun Choi' (Green, 1987).

18.1.3 Retail demand

For produce buyers quality is the top concern, especially the appearance of the fruit. The primary complaint about carambola is bruising of the ribs (fins). Buyers are also concerned about consumers' knowledge of tropical fruits; however, carambolas are more recognized by consumers than many other tropical fruits produced in Florida. Only mangos, avocados, and papaya are more familiar to consumers than carambola. Despite being better recognized than many other tropical fruits, growers and retailers feel that an increased marketing effort could increase consumer's awareness of the fruit. Of the retail stores surveyed by Degner *et al.* (1997), 97% carried carambola while it was in season. Only mangos and papayas had higher rates of distribution, at 100%. Of the retailers who carried carambola, 47.3% indicated excellent sales, 35.6% indicated fair sales, and 17.1% indicated poor sales, suggesting that most retailers believe that carambola have good sales when compared to other tropical fruits. These retailers also noted that short seasonal availability and tart fruit are problems (Degner *et al*., 1997). Since tart varieties are not commonly produced commercially, the reports of tart fruit probably are a consequence of sweet varieties having been picked too early.

18.1.4 Culinary uses, nutritional value and health benefits

In the USA, carambola is often sliced and used as a garnish for salads, tropical fruit drinks and used to make wine. Around the world the fruit is also salted and pickled, cooked in puddings, mixed into curries, stewed with sugar and cloves,

made into preserves and jams, cooked with fish (China), boiled with shrimp (Thailand), or sliced and dried. The juice of the fruit has a light, refreshing flavor and is popular in Malaysia. There is potential for the fruit to be lightly processed and used in the fresh-cut industry as it has an attractive star shape when sliced transversely; however, prevention of oxidative browning is imperative (Weller *et al.*, 1997).

Each 100 g of fresh carambola contains 91% water, 31 kcal, 4% sugars and 2.8% dietary fiber (USDA, 2008). Evaluations of 14 tropical fruits produced in Florida showed that carambola have high antioxidant activity. High antioxidant activity has health benefits such as protection against cell damage (Mahattanatawee *et al.*, 2006). The majority of the antioxidants (70%) in carambola are present in tissues and not the juice, despite the juice constituting approximately 95% of the fresh weight of the fruit. These antioxidants exist as polyphenolic compounds (Shui and Leong, 2004). Despite the aforementioned health benefits; carambola should not be consumed by people diagnosed with kidney disease. The fruit contain oxalic acid, which has been associated with a loss in renal function. Various neurological problems can occur; even death has been reported (Moyses-Neto *et al.*, 1998). Contaminated orchard soils have been linked to accumulation of cadmium and other heavy metals in carambola fruit (Li *et al.*, 2006; Li *et al.*, 2007).

18.2 Fruit development and postharvest physiology

18.2.1 Fruit growth, development and maturation

Carambola fruit only accumulate carbohydrates while on the tree, becoming progressively sweeter as the color changes from green to yellow and then orange, as reported using the sugar/acid ratio (Narain *et al.*, 2001). This ratio is commonly used as an indicator of sweetness for many fruit crops. Carambolas are typically harvested commercially at the colorbreak (one-quarter yellow) stage (Plate XXXIII: see colour section between pages 244 and 245), because fruit harvested at later harvest maturities are more susceptible to damage and considered too fragile to pack and ship (Oslund and Davenport, 1983).

The effect of harvest maturity on flavor attributes was studied for 'Arkin' carambola fruit harvested at five stages of maturity (Plate XXXIII: see colour section). Soluble solids content (SSC) increased with later harvest maturity, ranging from 5.8°Brix to 6.2°Brix to 7.2°Brix for fruit at one-quarter yellow, one half yellow and one-quarter orange stages, respectively (Warren, 2009). Total titratable acidity (TTA, malic acid equivalent) decreased with increased harvest maturity, causing the SSC/TTA ratio to increase as harvest maturity increased (Table 18.1). Although fruit harvested at orange stage (over-ripe) had the highest SSC/TTA, informal taste panelists noted the presence of off-aromas.

During storage at 5°C SSC and TTA remained fairly constant, however, both decreased slightly in fruit stored at 10°C, most likely due to a higher metabolic rate (Campbell *et al.*, 1987: Siller-Cepeda *et al.*, 2004). Likewise, weight loss and

Table 18.1 Selected compositional parameters of 'Arkin' carambola harvested at five levels of maturity

Compositional parameter	Harvest maturity				
	One-quarter yellow	Half yellow	Three-quarters yellow	One-quarter orange	Over-ripe
SSC[Z]	5.8 c[Y]	6.2 b	6.5 ab	7.2 a	7.2 a
TTA	0.365 a	0.305 b	0.272 c	0.202 d	0.174 e
SSC/TTA ratio	15.9 e	20.3 d	23.9 c	35.6 b	41.4 a

Notes
[Y] Mean ($n = 4$) rows with different letters are significantly different at $P < 0.05$, according to Duncan's Multiple Range Test.
[Z] SSC = Soluble solids content.
TTA = Total titratable acidity (malic acid equivalent).

Source: Warren (2009).

color development were suppressed during storage at 5°C, as compared with those stored at 10 or 28°C. Ali *et al.* (2004) reported that delayed color development of carambola ('B-10') was more closely linked to the storage temperature than to use of modified atmosphere packaging (MAP).

Carambola firmness at harvest decreased more than 50% with increased harvest maturity, from 30.5 N at the one-quarter yellow stage to 14.0 N at the over-ripe stage (Warren, 2009). The yellow color stage is associated with changes in cell wall constituents, whereupon reaching the one-quarter yellow stage, cellulose accumulated while hemicellulosic materials and pectins decreased gradually (Mitcham and McDonald, 1991: Chin *et al.*, 1999).

18.2.2 Respiration, ethylene production and ripening

When harvested after the one-quarter yellow stage, carambolas continue to synthesize carotenoids and develop a full orange color. However, the fruit exhibits non-climacteric ripening behavior. Carambola respiration was fairly constant at 20°C, less than 20 mL CO_2 kg^{-1} h^{-1} at 20°C (Warren, 2009). It increased slightly while turning from yellow to orange, likely owing to senescence of the fruit. Ethylene production was very low at 25°C, about 0.4 μL $kg^{-1}hr^{-1}$. In another study fruit at full-ripe (one-quarter orange) stage had higher respiration and ethylene production rates; however, this was attributed to microbial activity (Oslund and Davenport, 1983). Lam and Wan (1987) found that respiration was slightly suppressed by storage at lower temperatures and ethylene production was undetectable at 5°C. They also reported that green fruit had higher respiration rates than riper fruit; this was attributed to higher physiological activity in less mature fruit. These fruit had higher respiration and ethylene production rates as they approached over-ripe stage, which the authors also attributed to senescence.

18.3 Maturity and quality components and indices

18.3.1 Flavor and volatiles

Carambolas have a unique aroma volatile profile contributing to a sweet, floral flavor. Using a capillary gas chromatograph/mass spectrometer combination (GC/MS), 41 aroma volatiles were identified in carambola (Wilson *et al.*, 1985). In another report 178 components were detected and identified by GC and GC-MS methods in the 'B.10' variety that is grown in Malaysia and exported to Europe (MacLeod and Ames, 1990). The main volatile components of that variety were esters, although lactone constituents (also found in peaches, apricots, and plums) were also detected.

More recently, 53 volatile compounds were found to contribute to the unique flavor of carambola fruit using headspace solid-phase micro extraction (SPME) and solvent extraction (GC/MS), and gas chromatography-olfactometry (GC-O) (Mahattanatawee *et al.*, 2005). Methyl benzoate (musty minty floral sweet) and ethyl benzoate (tropical sulfur-like floral) were two of the major compounds in concentration and aroma activity. Other compounds were identified that contribute to an overripe or unpleasant sulfur taste such as: 1-pentanol (apricot/banana), benzothiazole (sulfur/rubber), and quinoline (putrid/fishy) (Mahattanatawee *et al.*, 2005; Wilson *et al.*, 1985). Additional major constituents that have been reported include esters, aldehydes, alcohols, ketones, and some norisoprenoid compounds (Mahattanatawee *et al.*, 2005). Herderich *et al.* (1992) also identified C_{13}-norisoprenoid flavor precursors in carambola, which are by-products of carotenoid degradation. Carotenoids in carambola are produced in high amounts while the fruit are mature, and in 'Arkin' they are produced while nearing the overripe stage.

When harvest maturity was considered, 27 volatiles were the most commonly identified in 'Arkin' carambola samples (Warren, 2009). Although many more volatiles were identified in some of the fruit sampled, these were not reported because they were not found in most of the fruit. Fruit harvested at earlier maturities contained several aldehydes, pentanal, hexanal, 2-hexenal, ketones and furfural. Ethyl ether was found in fruit harvested at all maturities, described as having the aroma of sulfur, mold, cabbage, and gasoline (Rouseff, 2008; Acree and Arn, 2008). Dimethyl sulfide was detected in all but the one-quarter yellow and over-ripe stages, and 1-pentanol was detected only in fruit harvested at the half-yellow color stage. Volatiles detected most commonly in over-ripe fruit were: acetic acid (pungent stinging and sour) and megastigma-4,6(E)(8) Z-triene. Benzenecarboxylic acid, ethyl butyrate and ethanol were found exclusively in over-ripe fruit, the latter indicating anaerobic respiration and confirming that orange stage fruit are completely over-ripe (Warren, 2009).

There are several explanations for the discrepancies in the number of volatile constituents reported by various researchers. Variations in testing methods are most likely the main reason for differences in the number and types of volatiles identified. Some research focuses only on the volatiles that are in high enough quantity for humans to perceive. Varietal type and harvest maturity are other

possible reasons for the differences in the volatiles reported. Lastly, differences exist in storage and commercial treatments to which the fruit were subjected. Some of the volatile and flavor research has been conducted on fruit obtained from markets, where little time/temperature history was available, while other fruit was directly acquired from research stations and farms with known histories.

Other stresses can influence volatiles in fruits. Exposure to exogenous ethylene has been shown to reduce six of fifteen key volatiles in tomato fruit; high temperature water treatments and low-temperature storage can have similar effects (McDonald *et al.* 1996). Low-temperature storage caused tomato fruits to be perceived as being more tart in sensory analysis experiments, and the volatiles that contribute to flavor were suppressed (Maul *et al.*, 2000). Since carambola fruit also has a unique aroma profile, volatiles are most likely also affected by stress.

18.4 Preharvest factors affecting fruit quality

Carambolas are very susceptible to mechanical damage. Movement from wind results in considerable scarring and damage to fruit that swing and rub against other fruit and branches (Fig. 18.2 and Plate XXXIV: see colour section between pages 244 and 245).

Slight scratching of the fruit while on the tree leads to unattractive fruit at the retail level as scars darken and become more pronounced during storage. Production in Florida requires windbreaks and wind screens that prevent wind from disturbing fruit while on the trees. Windbreaks usually consist of mature Australian pine (*Casuarina equisetifolia*), while windscreens are constructed of poles with cables that support shade cloth. Windbreak techniques for production in other regions include; rows of palm trees, and intercropping with other fruit trees. As described above, harvesting the fruit later than the one-quarter yellow stage yields sweeter fruit. However, this would require the fruit to remain on the tree up to 10 days longer, increasing the likelihood of wind damage.

One drawback of harvesting carambolas at later maturity is that the extended harvest season delays flowing and new fruit set for the succeeding crop. However, selective pruning of branches lessens wind scarring, and thinning the young fruit stimulates the trees to produce in the off-season. Nunez-Elisa and Crane (2000) found that pruning in July and September increased panicles of flowers by 14 and 20% respectively, and that pruning in other months also proved successful. These practices could add significant value to the crop since there are no Florida-grown carambolas from March to July.

18.5 Postharvest handling factors affecting quality

18.5.1 Temperature management

The act of harvesting stresses the fruit by withdrawing its water supply, leading to accelerated ripening and water loss. It is important to cool harvested fruit as soon

Fig. 18.2 Wind damage of carambola fruit due to swinging against a branch.

as possible after picking, because ambient temperature and relative humidity dictate the speed of physiological reactions that lead to ripening and water loss. The low temperature threshold for carambola is 5°C to avoid chilling injury during subsequent handling and shipping. Storing carambola at 5°C and 85 to 95% RH effectively counteracts moisture loss, maintaining fruit firmness over a longer time (Ali *et al.*, 2004).

18.5.2 Physical damage

The physical appearance of carambola fruit at the retail level is a major postharvest problem reported by that sector. Mechanical injuries that occur during the growth, picking, or packing of the fruit cause the appearance to deteriorate and provide ports of entry for decay pathogens. Mechanical injuries include cuts, scrapes, impacts or vibration. Other defects that develop during handling and shipping

include: fin-tip browning, shriveled stem ends, surface browning (bruising caused by membrane disruption) and pitting. Carambolas are typically harvested at the one-quarter yellow stage, while the fruit are still firm, to reduce mechanical damage. However, fruit harvested as immature (<one-quarter yellow) are more susceptible to development of chilling injury symptoms, and they require more time to reach peak ripeness.

18.5.3 Weight loss

Moisture loss can become a serious problem because it leads to a loss in saleable weight. Mechanical damage during harvest and handling, and storage in low humidity promote weight loss (Kader, 2002). Carambolas have a naturally waxy surface that slows water loss through the skin; however, significant water loss occurs at the stem end of the fruit. Storage under high relative humidity (RH) conditions (85 to 95%) slows water loss and shriveling at the stem end by reducing the vapor pressure differential between the fruit and the surrounding atmosphere.

18.6 Physiological disorders

18.6.1 Chilling injury

Chilling injury is a physiological disorder that affects many crops (especially tropical and subtropical fruits). It develops when susceptible fruit are stored above freezing temperature but below a threshold temperature. The symptoms of chilling injury are epidermal tissue browning and/or pitting, uneven ripening, failure to ripen, water soaking, off-flavor development, and an increased susceptibility to decay pathogens. These symptoms generally do not appear until after the fruit is transferred from the low temperature to a higher temperature. The more physiologically mature a fruit is when placed into chilling temperatures, the less apparent the injury symptoms. In part, the major changes associated with fruit ripening have already taken place, thus making the fruit more resistant to exposure to colder temperatures (Kader, 2002). While chilling injury is not common in carambola stored at 10°C, Ali *et al.* (2004) reported chilling injury-like symptoms in fruit held at 10°C for 40 days in MAP.

18.7 Pathological disorders

Fruit that have been damaged on the tree or during harvest and packing operations are more susceptible to postharvest decay. Therefore, culling damaged fruit at the packinghouse is very important to remove this source of inoculum. The high RH conditions that minimize water loss also promote fungal decay. The most common postharvest decay organisms for carambola are *Cercospora averrhoae, Phyllosticta, Alternaria, Phoma* and *Phomopsis*. Anthracnose disease occurs on the fruit and is caused by *Colletotrichum porioides* (Wehlburg *et al.*, 1975).

18.8 Insects and other pests

Common insect pests are mealybugs, stinkbugs (*Nezaera sp.*), grasshoppers and fruit flies (*Dacus dorsalis*), and these can cause significant damage if not controlled in the field. Leaf minors cause blemishes on the fruit epidermis, especially during warm and humid seasons. Pesticides are successful in controlling insect pests. In the field other common pests are birds, snails and slugs. Below ground, reniform nematodes (*Rotylenchulus reniformis*) can cause decline in trees (Campbell *et al.*, 1985).

18.9 Postharvest handling practices

18.9.1 Harvest operations

In many production areas carambola is picked at earlier harvest maturity, while the fruit is still firm, to reduce mechanical injury. The fruit is hand-harvested, carefully stacked up to three layers deep in plastic boxes and transported to the packinghouse. In Florida, 53% of the harvested fruit is sold to a packer/shipper directly from the orchard, while 44% of the fruit is packed and shipped by the grower (Degner *et al.*, 1997).

18.9.2 Packinghouse operations

At the packinghouse the fruit is manually sorted, graded and sized. In humid production areas such as Florida, superficial sooty mold (*Leptothyrium* sp.) frequently grows on the epidermis. Generally, wiping the surface is sufficient to remove the sooty mold and improve appearance. However, in the process of sooty mold removal some of the natural protective wax of the epidermis may also be removed. To slow desiccation, the fruit are sometimes wrapped in wax-impregnated paper prior to packing. To minimize mechanical injury during shipping, corrugated fiberboard cartons are typically fitted with a foam bottom lining, into which fruit are place-packed, stem-end down, into individual cells (Fig. 18.3).

18.9.3 Control of ripening and senescence

In addition to refrigeration, carambola ripening can be suppressed using controlled atmosphere storage. Fruit stored in 2 to 4% oxygen and 8% carbon dioxide at 7°C maintained better color, firmness and flavor than those stored in air (Renel and Thompson 1994).

In the case where accelerated ripening is desired, postharvest ethylene treatments show some efficacy. Ethylene is a natural plant hormone in gaseous form, associated with ripening and senescence. Cultures around the world have used the properties of ethylene to enhance fruit ripening for centuries. The bible mentions the practice of farmers cutting the top of sycamore figs in order to speed growth and ripening in which the wound stress initiates an ethylene response.

Fig. 18.3 A typical shipping carton fitted with cardboard divider inserts.

Today, consumers often lightly slice the epidermis of papayas to accelerate ripening. Exposure of unripe fruit to an ethylene source was another practice. The Romans stored ripe apples in the same room with quince and the Chinese burned incense in storage rooms filled with pears to accelerate ripening (Reid, 2002). Inadvertent sources of ethylene include the purging of commercial ethylene ripening rooms, and exhaust from internal combustion engines such as forklift and truck operation in cold room and loading areas.

Ethylene production is associated with two systems within plant physiology. System 1 produces a constant basal rate of ethylene production. As indicated above, ethylene production is stimulated by stress or injury. Exogenous ethylene applied to non-climacteric fruit or vegetative tissue down-regulates (auto-inhibits) ethylene production but up-regulates respiration. System 2 is associated with the ripening of climacteric fruits, in which an autocatalytic rise in ethylene production occurs. Exogenous application of ethylene to mature, climacteric fruit auto-stimulates the climacteric rise in ethylene. During typical climacteric fruit ripening the rise in respiration is followed by or is in unison with a rise in ethylene

production (Burg and Burg, 1965). Ethylene binds to the receptor site and initiates chemical changes within the fruit, including conversion of starches to sugars, pigment degradation or synthesis, and volatile production.

For non-climacteric fruits such as carambola, application of exogenous ethylene may be used to enhance the external fruit color. Ethylene is routinely applied to citrus postharvest to de-green the fruit prior to packing (Eaks, 1970). When ethylene is applied to citrus, an increase in chlorophyllase activity is observed. Chlorophyllase is an enzyme involved in the process of degrading chlorophyll. Also, an increase in chlorophyllide A activity was observed by Amir-Shapira *et al.* (1987) when ethylene was applied. Exposure to ethylene led to a decrease in chlorophylls A and B in citrus and parsley leaves (Amir-Shapira *et al.*, 1987). Certain cultivars of tangerines (calamondins and Robinson tangerines) do not naturally de-green; ethylene is required. Following ethylene treatment, chlorophyll degradation was reported to continue for 24 hours after transfer to air before ceasing (Purvis and Barmore, 1981).

Exogenous ethylene was applied to mature-green carambola ('Arkin'), and was effective as a ripening agent. Color was enhanced with a 2-day exposure to 100 ppm ethylene at 20°C. A 1-day exposure did not affect color change, and a 3-day exposure promoted decay. The ethylene treatments had no effect on SSC or TTA concentrations (Sargent and Brecht, 1990). Miller and McDonald (1997) found that exogenous ethylene (0.1 mL L^{-1}) increased carambola peel scald, stem-end breakdown, fin browning, and enhanced mold growth. This high concentration of ethylene may have been phytotoxic to the fruit. The mature-green fruit had higher TTA, lower pH, and lower SSC than partially yellow fruit.

'Arkin' carambola at three harvest maturities (one-quarter, one half and three-quarters yellow) was exposed to ethylene (25, 50, 100 μL L^{-1}) at 20°C for 48 hours (Warren, 2009). Fruit treated with 100 ppm ethylene generally had a higher incidence of blemishes than those fruit treated with 50 or 25 ppm. Stem-end shriveling and fin margin browning developed regardless of harvest stage. Although the 100 ppm treatment had a de-greening effect, fin margin browning was exacerbated. Ethylene concentration was not correlated with the development of surface pitting/browning, nor did it result in more uniform color. Fruit harvested at three-quarters yellow ripened in 12.5 days, regardless of ethylene concentration, while fruit harvested at one-quarter and one-half yellow were ripe in 20.1 days.

The common goal of postharvest scientists is to study means for maintaining the quality of harvested fruits by delaying senescence. One method of attaining this goal is to limit exposure to ethylene gas. Another method involves the application of ethylene antagonists, particularly cyclopropene, 1-methylcyclopropene, and 3,3-dimethylcyclopropene (Sisler *et al.*, 1996a). Of these compounds 1-methylcyclopropene (1-MCP; *SmartFresh*™, AgroFresh, Inc., Philadelphia, Penn.), is the most stable of the cyclopropenes and active at 1000 times lower concentration in high-temperature applications. 1-MCP is an effective treatment for increasing the shelf life of apple and many other crops because of its approved commercial use and ease of application. Since 1-MCP is an ethylene antagonist the potential benefits of application to climacteric fruits are numerous. 1-MCP has

proven to be effective in delaying the ripening and senescence of climacteric and non-climacteric fruits. A good example can be found in plums, because there are both climacteric and non-climacteric varieties. Both types of plums treated with 1-MCP at 0.25, 0.50, and 0.75 μL L^{-1} showed positive effects including delayed physical, chemical, and biochemical changes; firmer fruit with lower percentage weight loss and lower sugar-to-acid ratio which indicates suppressed ripening (Martinez-Romero *et al.*, 2003). Some common benefits of 1-MCP application include: maintenance of firmness and color, reduction in respiration rate and ethylene production, and limiting weight loss (Sisler *et al.*, 1996b).

1-MCP out-competes ethylene by binding to a metal in the ethylene receptor. 1-MCP treatment at a concentration of 0.5 nL L^{-1} lengthened shelf life of bananas by 12 days during storage at 24°C (Sisler and Serek, 1999). The fruit ripened normally after this period. Mature green tomatoes benefitted by an 8-day delay in the rise in the respiration rate, and a 12-day delay in the rise of ethylene production, lengthening shelf life by eight days (Sisler *et al.*, 1996a; Sisler and Serek, 1999; Jiang *et al.*, 2004). The effectiveness of 1-MCP in maintaining firmness of fruit held at various temperatures has been demonstrated in bananas, and plums (Jiang *et al.*, 2004; Martinez-Romero, 2003). The carambola ('Fwang Tung') was harvested at the half-yellow color and gassed in a hermetically sealed container for 24 hours at 25°C with 1-MCP concentrations of 500 nL L^{-1} or 1 μL L^{-1}. Fruit respiration decreased significantly and the fruit maintained better color with 1-MCP treatments at 0.5 and 1 μL L^{-1}. Fruit that were treated did not have a significant delay in ripening (Teixeira and Durigan, 2006). All of the above treatments used the gaseous formulation of 1-MCP, which requires airtight chambers and 1-hour to 1-day exposure times with concentrations ranging from 10 to 1,000 nL L^{-1}.

A new formulation of 1-MCP permits application via aqueous solutions. This formulation was originally developed for preharvest applications to crops. The benefits of an aqueous application are: no airtight chambers required and shorter application times. This would allow large quantities of a commodity to be treated over a shorter time, such as on a packing line. Immersion for onr minute in aqueous 1-MCP (625 ug L^{-1}) was as effective as a 9-hour gaseous application of 500 nL L^{-1} (Choi and Huber, 2008). An aqueous application of 1-MCP on tomatoes delayed softening, suppressed ethylene and respiration climacteric peaks, and delayed the production of lycopene. It also increased polygalacturonase activity (Choi and Huber, 2008; Choi *et al.*, 2008).

1-MCP maintained the turgidity and green color of leafy vegetables such as choy sum, and bok choy (Thomson *et al.*, 2003). Leafy vegetables are especially prone to wilting because of their high surface to volume ratio. If the cold chain is disrupted, 1-MCP-treated vegetables maintain a better appearance than non-treated vegetables. 1-MCP has also been shown to reduce leaf abscission in spearmint cuttings produced as fresh herbs (Thomson *et al.*, 2003).

'Arkin' carambola harvested at several maturities were immersed in aqueous solutions of 1-MCP at concentrations of 50, 100, and 200 μg of 1-MCP a.i. L^{-1} and stored at 20°C (Warren, 2009). The highest concentration of 1-MCP maintained firmness of fruit harvested at the half-yellow stage comparable to

non-treated fruit harvested at the one-quarter yellow stage. Fruit harvested at the half-yellow stage yielded sweeter tasting fruit, and a price-sensitivity analysis showed it to be economically feasible. Although 1-MCP did not affect the compositional parameters of the fruit, aroma volatile production was suppressed and the outer edges of the fruit fins remained green. 1-MCP treatments at 50 and 100 $\mu g^{*}L^{-1}$ had similar effects but at lower magnitudes.

18.9.4 Coatings

Postharvest application of coatings can be an effective way to prevent moisture loss. Two and six percent carnauba wax applied to carambola, reduced moisture water loss but had no significant effect on total soluble solids, acidity, pH, color, flavor or sensory texture (Miller and McDonald, 1993). Waxing is also a potential treatment for slowing respiration. Applying a wax coating to citrus fruit restricted CO_2 permeation from the fruit, resulting in higher internal CO_2 concentration and reduced weight loss as compared to non-waxed fruit (Hagenmaier and Baker, 1993). The extended shelf life resulting from 1-MCP treatment can cause increased water loss. Waxed avocados treated with 1-MCP retained more weight than unwaxed fruit during storage, and application of wax or 1-MCP delayed peaks in respiration and ethylene production (Jeong *et al.*, 2003). Waxed fruit ('Arkin') lost about 50% less weight than the unwaxed fruit in storage at 5 or 20°C; while unwaxed fruit lost the same weight at either of these respective temperatures (Warren, 2009).

18.10 Processing

18.10.1 Fresh-cut processing

Fresh-cut processing transforms produce into a value-added product line that is more appealing and convenient to consumers. However, enzymatic browning of cut fruit surfaces is a major concern for fresh-cut produce. The extent and rate of browning is time and temperature-dependent; varietal differences have also been reported. Applying ascorbic acid decreased the incidence of oxidative browning on carambola slices during storage (Weller *et al.*, 1997). Vacuum packaged carambola fruit slices maintained acceptable quality up to four weeks at 5°C (Boynton *et al.*, 2002), although once sliced, fresh-cut produce should be stored from 1 to 3°C.

18.11 Conclusions

Carambola is increasing in popularity because of the availability of sweet varieties throughout most of the year. In addition to its eye-catching appearance, demand could increase further with the consistent availability of high-quality, sweet-tasting fruit by convincing customers to make repeat purchases. Several methods and technologies show the potential of permitting carambola harvest at the half-

yellow stage or later to exploit its natural sweetness, and should be explored. Combinations of 1-MCP, coatings, MAP and refrigerated storage could extend quality further. More research is necessary to determine the effects of 1-MCP on firmness, particularly to better understand the effects on impact resilience. Since 1-MCP influences fruit firmness and the aroma profile, further studies should incorporate sensory analysis when examining the interactions between 1-MCP and other treatments on resultant texture and flavor. These results would give valuable insight into the feasibility of harvest at advanced maturities.

18.12 References

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Plate XXXIII 'Arkin' carambola fruit harvested at different stages of maturity.

Plate XXXIV Latent wind damage is more prominent on fruit after storage.

19

Cashew apple and nut (*Anacardium occidentale* L.)

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Abstract: This chapter will focus on the fresh-market cashew apple, which is sold with the nut attached. The pseudo-fruit (apple) represent nearly 90% of the cashew (nut + apple). The cashew apple has a pleasant flavor and aroma, and high nutritive value. Despite these attributes, postharvest losses of cashew apple can reach 90%. Since ripe cashew apple is highly metabolically active, it has been considered too delicate and perishable for international trade. However, recent research demonstrates that, if properly harvested and handled, cashew apples can be kept in good condition for up to 25 days after harvest, depending on variety (clone).

Key words: *Anacardium occidentale*, postharvest biology, flavor, volatiles, respiration, ethylene.

19.1 Introduction

19.1.1 Origin, botany, morphology and structure

The cashew (*Anacardium occidentale* L.) originated in the northeast of Brazil and is believed to have been domesticated before the arrival of the Portuguese in the 16th century (Smith *et al.*, 1992). From Brazil, the cashew was introduced to the West Indies and Central America (Rosengarten, 1984). The Portuguese recognized the value of the cashew apple and nut and took the crop to their Old World colonies (Smith *et al.*, 1992). By 1590 the cashew tree had been introduced to East Africa and India where it was also used to help control erosion along the coastal regions (Woodroof, 1979).

Cashew belongs to the family Anacardiaceae, which also includes mango and pistachio. The tree gets its scientific name from the heart-shaped nut (Woodruff, 1979). The cashew apple is actually a swollen receptacle that is attached to the true fruit, comprised of the protruding shell that contains a single

nut. The cashew tree is an evergreen perennial that is hardy and fast growing, with a symmetrical, umbrella shaped canopy (Rosengarten, 1984). Although the tree resembles a large bush, it is a true evergreen tree and often attains heights of over 10 m (Woodroof, 1979). Roots grow vertically to a considerable depth and to a radius twice the canopy spread (Acland, 1971). Flowers are panicle-like, small pinkish, about 40% perfect and 60% male, and insect pollinated. About 70% of the perfect flowers fail to set fruit, resulting in only one or two mature nuts per inflorescence. Flowering to nut maturity takes about 55 to 70 days. The raw cashew nut is inedible due to the presence of anacardic acids within the cashew nut shell. These compounds cause an allergic skin rash on contact, necessitating specific processing techniques for the nut to become edible.

Ruffino *et al*. (2007) described the potential for commercialization of another species native to the semi-arid region in northeast Brazil. *Anacardium microcarpum*, known as the cajuí in that region, could be exploited in the same manner as cashew. It is about one-third the size of a cashew fruit.

19.1.2 Worldwide importance

The cashew nut entered world commerce at the beginning of the twentieth century (Smith *et al.*, 1992). Cashew production has been an important economic activity for many tropical countries, providing a variety of food and industrial products (Menezes and Alves, 1995). The most notable of its products is the cashew nut. Of the 30 to 35 products from the cashew tree, the nut is the most valuable. Among tree nuts, cashew ranks third in world economic importance after almonds and Brazil nuts (FAO, 2010). Current world production of cashew nut is 3 720 245 MT on 4 097 637 ha. Vietnam, Nigeria, India, Indonesia and Brazil are currently the world's leading producers of cashew nuts (FAO, 2010). Of the 1 850 966 MT of cashew apple produced on 681 003 ha, Brazil was the main producer with 1 659 810 MT on 610 000 ha (FAO, 2010). The cashew nut shell liquid (CNSL) can be extracted and used in various products in the chemical industry.

19.1.3 Culinary uses, nutritional value and health benefits

The brilliantly colored cashew apple is a very attractive product in the supermarket display (Plate XXXV: see colour section between pages 244 and 245). For the fresh market the fleshy cashew apple is sold with the nut attached, and the nut is generally discarded by the consumer. The fruit is consumed fresh or processed into a variety of products. It contains a significant amount of vitamin C, averaging 200 mg 100 g^{-1} of juice, about four times that of orange juice (Menezes and Alves, 1995). In several countries, cashew apple products such as juice, pulp, preserves, wine, vinegar, soft drinks and candies are widely commercialized, further raising the aggregate value of the cashew crop.

19.2 Fruit development and postharvest physiology

19.2.1 Fruit growth, development and maturation

The cashew apple and nut grow independently (Pratt and Mendoza, 1980). Following anthesis, growth of the nut is fast and uniform, reaching maximum size around 30 days (maturity stage 1, nut weight approximately 14 g). After this fast-growth phase, nut weight decreases about 15 to 40% as the shell dehisces and hardens. Initially the cashew apple grows slowly, and then growth rapidly increases after the nut has reached maximum size. Mature cashew apple color can vary from yellow to red and reaches maximum size in about 50 days. The edible portion represents about 90% of the entire cashew and weighs 70 to 90 g (Filgueiras *et al.*, 1999). Figueiredo *et al*. (2002) also found that after the development of cashew nut was completed (Stage 1), the apple began to grow and develop, with significant changes in physical characteristics. The seven stages of maturation are described, based on clone CCP-76 (Table 19.1) (Figueiredo *et al.*, 2002).

During maturity stages 1 to 7 (Plate XXXVI, see colour section between pages 244 and 245) the cashew apple increased, approximately five-fold in weight (32.2 to 169.8 g), two-fold in diameter (3.31 to 6.41 cm) and 1.5-fold in length (6.60 to 8.24 cm). The most accentuated increase in apple weight occurred between stages 6 and 7.

For nut harvest and/or extraction of the cashew nut shell liquid (CNSL), the apples are left on the tree to assure full maturity of the kernel, dropping to the ground seven to eight weeks following apple maturity (Acland, 1971; Wunnacht and Sedgley, 1992). A thorough explanation of nut extraction and processing was outlined by Montealegre *et al*. (1999).

Table 19.1 Maturity stages of clone CCP-76

Stage	Appearance	Stage	Appearance
1	Green (apple and nut)	5	Light orange
2	Green apple with dry nut	6	Orange
3	Light green apple	7	Deep orange
4	Beginning to yellow		

Source: Figueiredo *et al.* (2002).

19.2.2 Respiration, ethylene production and ripening

Cashew apple has a high respiration rate (62 to 72 ml kg^{-1} hr^{-1}) at 20°C, however the pattern is non-climacteric (Biale and Barcus, 1970). According to Pratt and Mendoza (1980), at 20°C respiration rates were approximately 50 ml $kg^{-1}hr^{-1}$ and ethylene production was steady but very low (200 to 400 nl $kg^{-1}hr^{-1}$). To achieve optimal quality the cashew apple must remain on the tree until it reaches maturity. During ripening, the cashew apple changes color due to chlorophyll loss and pigment synthesis, acids and astringency decrease, while soluble solids, reducing sugars and ascorbic acid increase. The tender skin becomes exceedingly waxy as the cashew apple ripens.

19.3 Maturity and quality components and indices

Fresh market cashew apple must be the correct shape and have uniform external appearance with no signs of physical injury. Pear shape is preferred and red fruit are increasingly preferred to yellow fruit. Other important quality characteristics for fresh market are low astringency, low acidity, and sweet flavor. Although physical appearance is important to consumers, no direct correlation has been found between external characteristics (e.g. color, size or shape) of different cashew apple varieties/selections and variations in composition (Filgueiras *et al.*, 1999).

For processing, misshapen cashew apple is tolerated provided there are no signs of disease or insect damage. The most important attributes for processing are juice yield, low astringency and sugar/acid ratio. Ripe cashew apple yields approximately 80% juice. Filgueiras *et al*. (1999) determined the average composition of ripe cashew apple (Table 19.2).

Consumption of fresh cashew apple is increasing in Brazil following the development and cultivation of new clones of dwarf cashew. Recent research has focused on increasing consumption and improving the quality of cashew apple by reducing astringency or tannin content and total acidity (Crisostomo *et al.*, 2002). Figueiredo *et al*. (2002) found that between maturity stages 1 and 7 cashew apple pulp firmness decreased approximately 80% (45.61 to 8.53 N). Anthocyanins, total carotenoids, SSC, SSC/TTA, tannins, vitamin C, and reducing sugars increased continuously during ripening. Data for cashew apple (clone CCP-76; Embrapa Tropical Industry, Fortaleza, CE, Brazil) at maturity stage 7 were: SSC/TTA = 43.6, vitamin C = 229 mg 100 g^{-1}, anthocyanins = 21.5 mg 100 g^{-1}, total carotenoids = 32 mg 100 g^{-1}.

Sixty-three volatiles were detected in the headspace of cashew apple (clone CCP-76) juice (Garruti *et al.*, 2001). From the 63 compounds detected, 49 were identified. The volatile profile was characterized by a variety of esters (38%), nine alcohols, seven aldehydes, two ketones, two lactones, three acids, one terpene and fourteen unidentified compounds. Volatile compounds were predominately esters, mainly methyl and ethyl esters of saturated C2 to C6 carboxylic acids (Garruti *et al*. 2001). Broinizi *et al*. (2007) determined that cashew apple (CCP-76) contained up to 50% β-carotene and 95% antioxidant activity (DPPH).

Table 19.2 Average composition of fresh cashew fruit

Component	Value
Moisture content	84.5–90.4%
pH	3.5–4.5
Soluble solids content (SSC)	9.8–14.0 °Brix
Total sugars	7.7–13.2%
Total titratable acidity, as malic acid	0.22–0.52%
Vitamin C	139–387 mg 100 g^{-1}
Tannins	0.27–0.72%

Source: Filgueiras *et al.* (1999).

19.4 Preharvest factors affecting fruit quality

Cashew trees produce a significant number of horizontal roots, which led to the erroneous assumption that the tree requires a period of drought to achieve proper flowering and that rainfall is sufficient for maximum fruit yields. It was also thought that cashew could only withstand drought if tree spacing was wide enough to prevent overcrowding (Acland, 1971). This premise was based on the fact that cashew orchards worldwide were planted with common rootstocks with supposed drought resistance. However, studies have demonstrated that the low productivity of cashew trees grown under drought stress (220 kg nuts ha^{-1}) is commercially unprofitable (EMBRAPA, 1996). Dwarf cashew trees have attained yields of 5000 kg nuts ha^{-1} with high-density plantings and appropriate cultural practices with proper fertilization and irrigation (Oliveira *et al.*, 1998).

19.5 Postharvest handling factors affecting quality

Harvested fruit are highly perishable and become unmarketable after 24 hours under ambient conditions. Several constraints affect postharvest quality of fresh cashew apple, including: use of improper harvest containers; delays between harvest and cooling; absence or ineffective use of rapid cooling; poorly designed packaging; temperature fluctuations during transport; high temperatures (above 20°C) during retail.

19.6 Physiological disorders

19.6.1 Chilling injury

Cashew fruit is not susceptible to chilling injury.

19.7 Pathological disorders

Freire and Cardoso (1995) cited the following principal diseases encountered in Brazilian plantations: Anthracnose *(Colletotrichum gloeosporioides*), black mold (*Diploidium anacardeacearum*) and gumnosis (*Lasiodipodia theobromae*). They also noted an important fungal disease on the African continent caused by *Oidium* sp. Principal pathogens in cashew nurseries include*: Sclerotium rolfsii, Pythium splendens, Phytophtora* sp. and *Cylindrocladium scoparium*.

Cashew apples are very susceptible to postharvest infection especially from *Rhizopus, Colletotrichum* and *Penicillium.* In Brazil the following postharvest chemical treatments are allowed for disease control in cashew apples: immersion in 0.25% aqueous citric acid containing 500 mg SO_2 L^{-1}, or 0.1% aqueous sorbic acid, or chlorinated water (100 ppm). Cashews are typically washed with ambient water (approximately 20°C) by immersion or spraying (Filgueiras *et al.*, 1999).

Washing cashew apples removes soil and reduces temperature by removing field-heat. High ambient temperatures at harvest lead to more intense metabolic activity, and consequently faster senescence. Washing water may also be used for disease control treatment. Local regulations should always be consulted prior to the application of any postharvest preservatives.

19.8 Insect pests and their control

The cashew tree has several serious pests and diseases that vary by growing region. Insect pests include the white fly (*Aleurodicus cocois,* Curtis), a caterpillar (*Anthistarcha binoculares*) a red beetle (*Crimissa* sp.) and a thrip (*Selenothrips rubrocinctus*). The flies, *Helopeltis anacardii* and *H. schoutedeni*, cause damage by feeding on leaves, young shoots and inflorescences (Acland, 1971). In Brazil, the most significant pests are: a caterpillar that attacks new shoots (*Antistacha binocularis*), the nut moth (*Anacampis* sp.), an aphid that feeds on inflorescences (*Aphis gossypii*), thrips (*Selenothrips rubrocinctus*), a trunk borer (*Marshallius* sp.) and another caterpillar (*Thagona* sp.) (Melo and Bleicher, 1995).

Extensive use of insecticides can be expensive and may reduce fruit set. The use of biocontrol and genetically resistant cultivars should be a more sustainable and environmentally safer approach to pest management (Smith *et al.*, 1992).

19.9 Postharvest handling practices

19.9.1 Harvest operations

As a non-climacteric fruit, the cashew apple must be harvested ripe for the fresh market, which imposes limitations on postharvest life and quality. Cashew apples are very bruise-sensitive, and should be hand-harvested with the nut attached before abscission from the tree (Rosengarten, 1984). Several indices can be used for identifying harvest maturity such as; color, firmness, composition and specific gravity. However, the most common method of harvesting cashew apple is when it is still firm, without signs of green color and easily detachable from the tree by hand. At this stage the flavor, aroma and sugar content are at the maximum, while acidity and astringency are at the minimum. An excellent review of postharvest handling procedures and standards for export markets was developed by Alves and Filgueiras (2002).

Harvesting instruments are not recommended for cashew apple destined for fresh market. The cashew apple skin is very delicate and care must be taken to prevent damage. Once harvested, cashew apples should be placed in single layers inside vented boxes lined with foam rubber. Harvested fruits should be kept in the shade while in the field and taken to the packinghouse as quickly as possible. Vehicles should have a cover that allows for ventilation during transportation. Packinghouses should be centrally located and roads kept in good condition to avoid mechanical damage during transportation.

For the processing industry, harvesting may be done by hand or by using a long pole with a collecting bag at the tip. Harvesting with an ordinary stick or by shaking branches is not recommended because of the damage caused when the fruit falls to the ground.

19.9.2 Packinghouse practices

Upon arrival at the packinghouse the following actions are recommended: washing, grading, packing, palletization, pre-cooling, and refrigerated storage. Cashew apples rejected during grading may be de-nutted and transformed into pulp, juice, preserves or other products, provided there are no signs of deterioration. Grading is determined by the number of cashew apples per retail tray. Cashew apples are layered in polystyrene trays (21 × 14 cm) in a single layer of four to eight fruits weighing about 600 g (Filgueiras *et al.*, 1999). The trays are covered with plastic film, labeled then placed into corrugated boxes designed to facilitate palletization. This procedure reduces damage caused by transportation and handling, and the plastic film also reduces water loss. Tray types 4 and 5 are preferred by consumers and attract higher prices.

Clone CCP-76 was immersed in up to 2% $CaCl_2$, then evaluated over 25 days at 5°C, however, there was minimal effect on postharvest quality parameters, such as soluble solids content, total acidity and ascorbic acid content (Figueiredo *et al.*, 2007).

19.9.3 Recommended storage and shipping conditions

Refrigerated storage recommendations are: 0 to 1.7°C and 85 to 90% relative humidity (RH) for up to 35 days with 22% loss (Singh and Mathur, 1953). At 5°C and 85 to 90% RH, 15 to 20 days' postharvest life can be expected (Alves and Filgueiras, 2002). When cashew apples are sealed with plastic film, the package atmosphere is modified, lowering the oxygen level and increasing carbon dioxide. This change in atmosphere, together with refrigeration at 5°C, reduces the respiratory rate and extends postharvest life to 15 days (Filgueiras *et al.*, 1999). Cashew apple stored at 5°C and 85 to 90% RH with MAP (1 layer PVC film) attained postharvest storage life of 10, 15 and 25 days for clones END-189, END-157, and CCP-76 and END 183 consecutively (Morais *et al.*, 2002).

19.10 Conclusions

Cashew apple has unique physical characteristics and shows promise for expanded production into niche markets. Due to its high perishability, integrated procedures are required to minimize mechanical injury during harvest and handling, and to rapidly remove field heat to slow senescence, since marketing is limited to about 14 days at 5°C and up to 25 days at 2°C. Future studies should investigate cooling

methods, particularly hydrocooling and forced-air cooling, and delays to cooling to determine potential for extending postharvest life while maintaining nutrients and antioxidants.

19.11 Acknowledgements

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Plate XXXV Cashew apple on display in a supermarket. Photo: S.A. Sargent.

Plate XXXVI Cashew apple maturity stages 1 to 7. Photo: Ricardo E. Alves.

20

Chili plum (*Spondias purpurea* var. Lutea)

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Abstract: The chili plum (*Spondias purpurea* L.) is an exotic fruit with a climacteric pattern of respiration belonging to the Anacardiaceous family. It is consumed in both the fresh and processed states. The fruit has a yellow pulp, pleasant aroma and sweet, sour taste. Its vitamin A content is higher than that of cashew and guava, and some papaya and mango cultivars. The chili plum's relatively short shelf-life of five to six days after harvest at ambient temperature and widespread fruit-fly infestation are two major limitations to increased utilization of this fruit. Fruits can be successfully stored for up to 14 days at 12.5°C. Fruits stored at 12.5°C and then subsequently transferred to 30 to 32°C, ripened normally with a shelf life of four days. Storage at temperatures below 9 to 10°C results in chilling injury and ripening is also inhibited. Chili plums have a caloric density of 74 kcal/100 g^{-1} edible portions, which is significantly higher than the 39 to 58 kcal/100 g^{-1} for peach, apricot, and mango and cherry. The higher caloric density is attributed to its total carbohydrates of 19.1% and fructose, glucose and sucrose which together account for 65% of the soluble matter. Unlike the other fruits, chili plum retains a fair amount of starch in the mesocarp. It is a moderate source of potassium (250 mg/100 g^{-1} edible portion) and an excellent source of vitamin C (48 mg/100 g^{-1} edible portion). Analysis of volatile flavour compounds showed 2-hexenal to be the main flavour compound present.

Key words: *Spondias purpurea*, chili plums, ethylene, maturation, temperature management, fresh-cut, storage conditions.

20.1 Introduction

20.1.1 Origin, botany, morphology and structure

The chili plum is a popular fruit grown in the Caribbean and Central and South American regions. Native to Ecuador, it is highly polymorphic and cultivated on both sides of the Andes, distributed mainly on the western coastal plain of the Andean ridge (Barfod, 1987). Common names include 'moyo', 'sta broseno',

'jismoyo', 'yellow plum', 'jocote amarillo', 'mombin jaune', 'prune des antilles' and 'jobo'. The tree normally grows to about 3 to 10 m in height and has a pronounced spreading habit. The main branches tend to grow horizontally and secondary shoots develop on their upper part, giving rise to some vertical growth. Its pennated leaves are made up of ten to 20 pairs of elliptic alternated leaflets, 3 to 6 cm long. The fruit is a smooth and shiny ellipsoid drupe measuring 2.5 to 4.0 cm in length and 1.5 to 2.5 cm in diameter (Barbeau, 1994). Tiny yellow-reddish flowers appear in April/May. Fruits mature during the rainy season, from July to September. They may differ in size and shape and also in the intensity of the yellow colour.

20.1.2 Worldwide importance and economic value

Although quite common, chili plum trees are found scattered in backyard gardens throughout the Caribbean basin rather than in organized orchards. Adult trees produce several thousand fruits with an average yield per tree ranging from 40 to 50 kg (Barbeau, 1994). Koziol and Macía (1998) examined the economic aspects of chili plum production in Ecuador and reported that the area devoted to cultivation averaged more than 1800 hectares between 1987 and 1992, accounting for 4500 metric tonnes of harvested fruit. They estimated that a yield of 10 000 metric tonnes per year would be sufficient to make industrial processing of the fruit commercially viable. Production levels below 4500 metric tonnes per year would limit commercial operations to processing at the level of a cottage industry.

Once harvested, mature-green chili plum fruits ripen in four to five days and have a shelf life of an additional two to three days. Fully tree-ripened fruits on the other hand have a shelf life of just one to two days after harvesting. Their limited shelf life, combined with the fruits' susceptibility to physical damage during transport, restrict the export of fresh chili plums. Macía (1997) reported that the sale of fresh chili plums did not benefit small-scale producers in Ecuador because the majority of the profits were absorbed by middlemen, who purchased fruits in bulk and transported them to markets in the larger cities. He argued that chili plum farmers would have to focus on 'value-added products' rather than the sale of fresh fruits to ensure commercially viable production. He justified this claim by highlighting an example whereby small farmers were paid US$0.10 to 0.30 per kg for fresh chili plums, whereas a 300 g jar of chili plum jam could be sold for US$1.45. With production costs for such a jam roughly estimated at US$1.00 per kg, the small farmers' profit could increase to about US$3.83 per kg of processed chili plum fruits.

20.1.3 Culinary uses, nutritional value and health benefits

The seed accounts for 34% of the weight of the chili plum and the peel another 8%, while the pulp accounts for 50 to 58% of fresh fruit weight (Leung and Flores, 1961, Winton and Winton, 1935). According to Koziol and Macía (1998), chili

plum fruits have a caloric density of 74 kcal/100 g^{-1} edible portions, which is significantly higher than the 39 to 58 kcal/100g^{-1} for peach, apricot, and mango and cherry. This is attributed principally to its higher concentrations of total carbohydrates (19.1% in the chili plum) and, unlike the other fruits, chili plum retains a fair amount of starch in the mesocarp. The total concentrations of the three sugars, sucrose (5.97–7.21g/100g^{-1} edible portion), fructose (2.53g/100g^{-1}) and glucose (2.00g/100g^{-1}), account for 65% of the total soluble solids measured as ^{o}Brix.

The fibre content is low (0.2 to 0.7 g/100g^{-1}), while there is a considerable amount of starch in the unripe fruit (8.45 g/100g^{-1}), which is about four times higher than the ripe fruit. The free sugars and starch are readily available as fermentable substrates, which is advantageous for the development of a very refreshing and effervescent wine (Koziol and Macía, 1998).

The pectin content (0.22g/100g^{-1}) is low, but is still sufficient to make a jam without the need to add pectin. Given the acidity of the fruit (pH of 3.3) and the fact that jams form without additional gelling agents, it is most likely that native pectins are of the high methoxyl type with degrees of esterification in excess of 50% (Mitchell *et al.*, 1978).

Chili plums are a moderate source of potassium (100 to 300 mg per serving) (Guthrie, 1979). A 100 g edible portion of chili plums would provide 63% of the potassium requirements for children 4 to 6 years old, 44% for children 7 to 10 years old, 16% for adolescents 11 to 14 years old, 12% for adolescents 15 to 18 years old and 10% for adults (Koziol and Macía, 1998).

The vitamin C content of chili plums according to data obtained from Koziol and Macía (1998) is the highest compared to fruits such as apricot, cherry, peach and mango. Accordingly, a 100 g edible portion would provide 98 to 100% of the recommended dietary allowance (RDA) for children 1 to 14 years old and 82% of the RDA for people over 14 years old. The composition of other nutritional components as analysed by Koziol and Macía (1998) include: water 79.7%, protein 0.9%, fat 0.24%, ash 0.7%, total carbohydrates 18.1%, calcium 17 mg, iron 0.30 mg, sodium 9 mg, phosphorus 42 mg, zinc 20 mg, carotene 119 mg, thiamine 84 mg, riboflavin 40 mg, niacin 1.0 mg, citric acid 30 mg, malic acid 110 mg, oxalic acid 30 mg and tartaric acid 20 mg.

20.2 Fruit development and postharvest physiology

20.2.1 Fruit growth, development and maturation

Filgueiras *et al*. (2001) reported that chili plum weight increased from 13.62 g to 14.05 g when predominantly green (i.e. immature) to 15.91 g when predominantly yellow (i.e. fully ripe). The same authors also reported that fruit length and width were greatest in ripe fruits. The percentage of the fruit that is seed decreases during growth and development. Immature fruits were made up of 20.58 to 23.63% seed, whilst the composition of ripe fruit was 18.4% seed. The percentage of

Table 20.1 Chili plum dimensions at different stages of maturity

Fruit maturity	Length (mm)	Diameter (mm)
Immature green (M1)	27.82[a]	22.77[a]
Mature green (M2)	31.13[b]	26.36[b]
Breaker or turning (M3)	31.23[b]	26.64[b]
LSD(0.05)	2.39	2.16

Source: Mohammed (2002).

pulp increased as the fruit matured. The percentage fruit pulp increased to 81.58% at the yellow ripe stage compared to 75.71 to 79.41% at the immature green and predominantly green stages of development. Fruit dimensions are shown in Table 20.1 (Mohammed, 2002).

20.2.2 Respiration, ethylene production and ripening

Sampaio *et al*. (2007) investigated respiratory activity and associated changes in chemical constituents during maturation of chili plums. They reported that the pre-climacteric stage was marked by initial CO_2 production of 24.4 ml $kg^{-1}h^{-1}$ and initial oxygen absorption of 25.5 ml $kg^{-1}h^{-1}$. The minimum production of CO_2 was 11.0 ml $kg^{-1}h^{-1}$, while the minimum absorption of O_2 was 15.5 ml $kg^{-1}h^{-1}$ after 102 and 108 hours respectively after harvest. The maximum production of CO_2 of 54.2 ml $kg^{-1}h^{-1}$ and O_2 absorption of 49.0 ml $kg^{-1}h^{-1}$ occurred at 186 hours after harvest. Sampaio *et al*. (2007) also calculated the respiratory quotient (RQ) of chili plums at the pre-climacteric, climacteric minimum, climacteric maximum and post-climacteric stages to be 0.96, 0.63, 1.11 and 0.59 respectively. The RQ value of 1.11 at the climacteric maximum represented the oxidation of carbohydrates while the 0.96 accounted for the oxidation of proteins and the 0.63 and 0.59 indicated consumption of lipids.

Sampaio *et al*. (2007) also investigated the physicochemical changes of mature-green chili plums during storage at 27.8 to 29.2°C. Total soluble solids (TSS) increased from 9.1°Brix at the mature-green stage to 13.7°Brix at the climacteric maximum where fruits were fully ripened. At the same time total titratable acidity (TTA) decreased during maturation and ripening from 1.35% initially to 1.31% at pre-climacteric, 1.0% at climacteric maximum and eventually to 0.8% at the post-climacteric stage. This decrease in organic acids as ripening progressed suggested the involvement of the acids as a source of energy during respiration (Coombe, 1976; Kader, 1986). The total acid content of 1.3% and 1.49% in ripened chili plum fruits in earlier studies reported by Oliveira *et al*. (1999) and Bora *et al*. (1991) is noteworthy. Sampaio *et al*. (2007) in their study commented that the TSS/TTA ratio increased significantly at each stage in the climacteric curve while the opposite occurred for vitamin C content. Changes in pH, TTA and TSS/TTA are shown in Table 20.2 (Graham *et al*. 2001).

Table 20.2 Changes in pH, TTA, TSS/TTA in chili plums after 15 days storage

Parameters	Storage period (days)	Temperature (°C) 4–5			9–10			20–21			30–31		
		M1	M2	M3	M1	M2	M3	M1	M2	M3	M1	M2	M3
pH	5	2.79a[y]	3.16.i	3.09h	2.93e	3.05g	3.23k	2.89b	3.16i	3.29m	2.92d	3.09h	ND[x]
	10	2.89b	3.05g	3.23k	3.09h	3.26e	ND	ND	ND	ND	ND	ND	ND
	15	2.94f	3.17a	ND	2.90c	3.09h	ND	ND	ND	ND	ND	ND	ND
LSD(0.05)							0.03						
TTA(%)	5	1.14m	0.73a	0.76b	0.95h	0.87e	0.73a	1.06k	0.78c	0.76b	0.98I	0.82d	ND
	10	1.01j	0.93g	0.90f	0.98.i	0.76b	ND	ND	ND	ND	ND	ND	ND
	15	0.95h	0.76b	ND	1.09c	0.76b	ND	ND	ND	ND	ND	ND	ND
LSD(0.05)							0.02						
TSS/TTA	5	3.50a	10.90e	11.80e	6.30b	10.30e	18.40h	15.10fg	20.30i	28.20j	13.80f	20.20.i	ND
	10	8.00bc	11.90e	20.60i	8.17c	14.40fg	ND	ND	ND	ND	ND	ND	ND
	15	8.40cd	10.50e	ND	10.22de	15.74g	ND	ND	ND	ND	ND	ND	ND
LSD(0.05)							2.00						

Notes
ND[x] no data taken because fruits were completely decayed.
[y] Means followed by the same letter(s) are not significantly different ($P < 0.05$).
M1 = immature fruits, M2 = mature-green fruits and M3 = turning fruits.
Pre-storage pH: M1 = 2.67, M2 = 2.85 and M3 = 2.94
Pre-storage TSS/TTA ratio: M1 = 4.67, M2 = 8.85 and M3 = 10.94.
Pre-storage TTA: M1 = 1.19, M2 = 0.89 and M3 = 0.83.

Source: Graham *et al.* (2001).

Sampaio *et al*. (2007) described the behaviour of chlorophyll and carotenoid pigments of chili plums during ripening with the former illustrating a continuous decrease in contrast to the latter, which had a continuous increase. The authors attributed this to changes in pH, oxidation and the activity of chlorophyllase. The sequence of colour changes of the chili plum peel showed a transformation from an initial dark green to light green at the climacteric minimum; from light green to orange yellow during the climacteric rise in respiration and maintenance of an orange yellow colour during the climacteric peak and senescence.

In other studies Graham *et al*. (2001) reported an overall suppression of respiration in chili plums stored at 4 to 5°C and 9°C. However, at 20 to 21 °C and 30 to 31°C, respiration increased, inducing ripening in three to four days. At 20 to 21°C, immature and half-ripe fruits exhibited a more pronounced climacteric peak in comparison to mature-green and turning or breaker fruits. However, Graham *et al.* (2001) did not observe the respiratory climacteric in fully ripened fruits that they observed in fruits harvested when immature, mature-green or turning yellow. They also reported on the increase in evolution of C_2H_4 in immature, mature-green and turning fruits with peak C_2H_4 occurring between days three to five at 20 to 21°C, with C_2H_4 levels then declining rapidly. Peak C_2H_4 production preceded peak CO_2 production rates in immature and turning chili plums.

20.3 Maturity indices and quality components

The stage of maturity at which chili plums are harvested impacts significantly on their ultimate flavor and market life. Harvest maturity has a direct effect on the fruits' flavor components, physiological deterioration, susceptibility to physical injuries, resistance to moisture loss and susceptibility to invasion by organisms causing decay. The maturity of chili plums is determined by skin colour changes and fruit size and shape (Plate XXXVIIa: see colour section between pages 244 and 245). Chili plums are usually classified as:

- immature dark green (M1)
- mature light green (M2)
- slightly turning (light cream yellow) or breaker (M3)
- tree ripe (uniform yellow) (M4)

Immature dark green (M1) fruits may fail to ripen or ripen abnormally. These fruits lack a fully developed surface cuticle, which increases their susceptibility to moisture loss, they have the lowest total soluble solids content and highest acid content compared to fruit at other stages of fruit maturity and are highly susceptible to physical damage. Mature green (M2) and, in particular, breaker (M3) fruits are ideal for eating as a fresh fruit dessert or for processing into sweet or sour pickles. M3 fruits have a higher level of consumer acceptance than M2 fruits. Tree-ripe fruits (M4) have the highest level of consumer acceptance but also have a shortened shelf life due to flesh softening which renders them highly susceptible to physical damage, damage by birds and microbial invasion. Usually, by the time

M4 fruits reach the consumer they have become overripe, with poor eating quality. Postharvest losses of M4 fruit are high.

20.4 Preharvest factors affecting fruit quality

Nutritional status is an important factor in quality of chili plums at harvest and during storage. Excessive nitrogen delays fruit maturity, induces poor colour development and inhibits colour change from green to yellow. However, nitrogen deficiency leads to small fruit development accompanied by poor flavour and unproductive trees (Barbeau, 1994).

Since the chili plum seeds are not fertile, the plant is mainly propagated through large cuttings, 60 to 180 cm long. The selection of cuttings is based on the most vertical new growths one to two years old, selected at the end of the dry season. However excess water at planting time could jeopardize plant growth as the wounds do not heal, causing the cuttings to rot. With this technique, production begins the following year, climaxing after four to five years (Barbeau, 1994).

Chili plums are highly susceptible to fruit flies (*Anastrepha* spp) (Plate XXXVIIb and XXXVIIc: see colour section between pages 244 and 245). Other pests include mites. Fungal attacks are another limitation as infested fruits become covered with a grey ash-like dust which also spreads rapidly along the branches thereby reducing fruit size, appearance, taste, flavour and overall marketability and display quality (Barbeau, 1994).

20.5 Postharvest factors affecting quality

20.5.1 Temperature management

Management of fruit temperature and relative humidity is paramount for extending the shelf life of fresh chili plums. Removal of field heat following harvest can be achieved by room cooling (9 to 10°C, 85 to 95% RH) or by hydrocooling. Chili plums should be stacked in refrigerated rooms with air spaces between pallets and room walls to ensure good air circulation. Transit vehicles must be cooled before loading the fruits. Delays between cooling after harvest and loading into transit vehicles should be avoided. Maintaining the cool chain throughout the handling system is essential to optimize quality and shelf life.

20.5.2 Physical damage

Chili plums have a very thin skin and are eaten with the skin intact. It is important to minimize physical damage due to abrasions caused by over packing and fruits rubbing against each other during handling and transportation, punctures arising from harvesting containers, harvesters' finger nails or from protruding objects during distribution and transportation, as well as bruising caused by impact and vibration during transport. These physical injuries compromise fruit appearance,

accelerate water loss, provide sites for fungal and bacterial invasion and stimulate respiration and ethylene production, which reduces shelf life.

20.5.3 Water loss

The percentage fresh weight losses in chili plums are related to stage of maturity at harvest, storage temperature and storage duration. Graham *et al*. (2001) reported that immature fruits had higher percentages of fresh weight losses irrespective of storage temperature and duration than mature-green and turning or breaker fruits. This could be attributed to differences in the thickness of the cuticle on the skin surface, which offers more protection against moisture losses as fruit maturity progresses. Graham *et al*. (2001) also demonstrated that fruits stored at 20 to 21°C and 30 to 31°C exhibited more moisture loss than fruits stored at 4 to 5°C and 9 to 10°C, obviously owing to greater respiratory activity at the higher versus lower storage temperature. However, regardless of temperature and stage of maturity, chili plums showed accelerated increases in percentage fresh weight losses as storage time advanced. Chili plum fruits with higher percentages of fresh weight losses appeared to have a rougher skin surface, and were notably less juicy with thinner edible pericarps.

20.5.4 Atmosphere

Chili plums benefit from the saturated modified atmosphere created during storage in sealed low-density polyethylene (LDPE) or high-density polyethylene bags. Consequently the high relative humidity surrounding fruits reduces water loss, chilling injury symptoms and overall appearance. Accordingly, fruits acquire a longer shelf life and can be marketed over longer periods. These fruits have a more acceptable taste because they are juicier, firmer and the edible pericarp is thicker (Mohammed, 2002).

20.6 Physiological disorders

20.6.1 Chilling injury

Chili plums are very sensitive to storage under refrigerated conditions. Graham *et al*. (2001) stored fruits at three different stages of maturity under refrigerated conditions. They reported chilling injury (CI) shown as skin pitting in fruits at the immature green, mature green and turning or breaker stage after only four days when stored at 4 to 5°C (Plate XXXVIId: see colour section between pages 244 and 245). CI was lower after four days stored at 9 to 10°C. Pitting was extensive in the immature green fruits and least advanced in the turning or breaker fruits. Mature-green fruits kept at 9 to 10°C for 15 days and subsequently transferred for two days at 20 to 21°C had moderate chilling injury damage. Immature green fruits on the other hand showed severe CI damage. Mature green fruits stored continuously for 15 days at 4 to 5°C and then transferred to 20 to 21°C for one day

had severe CI symptoms with tiny pits coalescing into larger depressed areas with a definite brown discolouration. Similar symptoms were noted in mature green fruits stored at 9 to 10°C for 15 days upon transfer to 20 to 21°C for just two days.

20.6.2 Other physiological disorders

Chili plum fruits are susceptible to heat injury when exposed to temperatures for extended periods over 35°C. Heat injury symptoms include development of scalds and the presence of hard lumps of unripened flesh directly underneath the skin (Mohammed, 2002).

20.7 Pathological disorders

Graham *et al*. (2001) reported that chili plums stored at 20 to 21°C and 30 to 31°C had a shelf life of eight days before decay set in, with the incidence of decay being more prevalent and rapid in mature green and breaker fruits compared to immature green fruits (Table 20.3). The major cause of fruit decay was attributed to stem end rot caused by a fruit-rot fungus of the *Phoma* species (Plate XXXVIIe: see colour section between pages 244 and 245). In another experiment, Graham *et al*. (2001) found that fruits stored at 30 to 31°C ripened in three to four days and remained marketable for an additional two days, beyond which fruits were completely decayed (Fig. 20.1).

While fruits stored at 15°C and 17.5°C initiated ripening after ten days, excessive softening eventually resulted in decay amounting to 65%. Fruits stored at 12.5°C maintained a dark-green skin colour without evidence of decay up to 14 days. During this period fruits had a TSS of 11% and were still firm. Upon

Table 20.3 Incidence of decay in chili plums stored for eight days at 20–21°C and 30–31°C

		Temperature (°C)					
Parameter	Storage period (days)	20–21			30–31		
		M1	M2	M3	M1	M2	M3
Decay (%)	4	0[Y]	0	13.33ab	0	20.00bc	13.33ab
	5	0	0	13.33ab	6.70a	20.00bc	26.70c
	6	13.33ab	13.33ab	40.00d	53.30e	73.30f	86.70g
	7	46.70de	73.30f	86.70g	100h	100h	100h
	8	100h	100h	100h	100h	100h	100h
$LSD_{(0.05)}$				11.37			

Notes

[Y] Means followed by the same letter(s) are not significantly different ($P < 0.05$).

M1 = immature fruits, M2 = mature-green fruits and M3 = turning fruits.

Source: Graham *et al.* (2001).

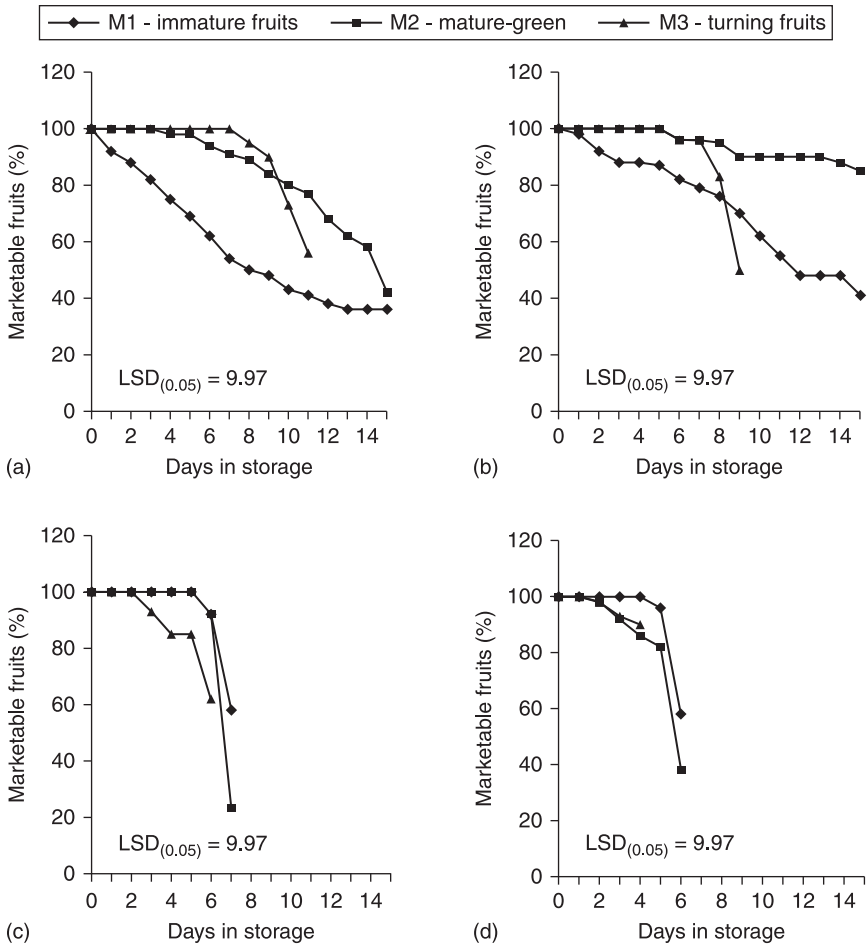

Fig. 20.1 Percentage of marketable chili plum fruits after 15 days of storage: (a) fruits stored at 4 to 5°C; (b) fruits stored at 9 to 10°C; (c) fruits stored at 20 to 21°C; (d) fruits stored at 30 to 31°C. Source: Graham *et al.* (2001).

transfer to 30 to 31°C for 4 days following 14 days of storage at 12.5°C fruits ripened uniformly and were highly acceptable according to organoleptic testing.

20.8 Insect pests and their control

A major threat to the expansion of chili plums as a fresh fruit regionally and beyond is their high susceptibility to the Caribbean fruit fly (*Anastrepha* spp.) (Barbeau, 1994). Graham *et al*. (2001) found live fruit fly larvae in chili plums subjected to a hot water treatment at 45°C for ten and 15 minutes respectively

after six days of storage at 20 to 21°C. Their investigation showed that while live larvae of variable sizes were found in control fruits, the larvae in fruits heat-treated at 45°C for ten and 15 minutes were small and generally of the same size. Dead larvae and eggs were detected in fruits treated at 45°C for 20 minutes, and at 50°C for ten, 15 and 20 minutes respectively. However the heat treatment at 45°C for 20 minutes was more successful than the 50°C regime, since the former accounted for no heat injury symptoms as opposed to the latter treatment, where scalding manifested as brown-coloured necrotic lesions (bronzing) dominated the surface of affected chili plum fruits.

20.9 Postharvest handling practices

20.9.1 Harvest operations

Chili plums fruits are borne in clusters. Fruits in any one cluster may differ in maturity. The stem end of each fruit is attached with a fragile and extended pedicel. Harvesting of fruits is normally conducted manually in order to select fruits at physiological maturity. The abscission layer becomes weakened as the fruit begins to turn. Upon ripening, it is easily dislodged by strong winds and birds. Because of the fragile nature of the pedicel upon harvesting, fruit stem ends are very susceptible to physical damage, which ultimately results in stem end rot and multiple infections. Abrasions, punctures and compression damage also affect fruits during harvesting and are sites for secondary infections. Harvested fruits should be packed in well-ventilated, shallow, light-coloured containers to optimize quality and reduce postharvest losses associated with the types of physical damage outlined above. Fruits should be placed in shade if there is any delay between harvest and transport to the packinghouse.

20.9.2 Packinghouse practices

Due to the climacteric nature of chili plums, fruits must be pre-cooled to remove field heat via room cooling or hydrocooling. It is imperative that fruits are washed in chlorinated water (100 to 150 ppm) followed by a rinse and air-drying. Fruits placed in packing lines should be equipped with conveyor belts that are well padded to minimize bruising. Sorting and grading must be exercised prior to packaging to achieve uniformity in size and fruit maturity to suit market requirements. Sanitation protocols must be monitored and implemented throughout all packinghouse operations. Since fruits are eaten with the unpeeled skin every effort must be made to ensure they are sufficiently sanitized to eliminate the presence of food-borne diseases (Mohammed, 2002).

20.9.3 Control of ripening and senescence

Changes from the typical green skin colour to a light yellow colour as well as flesh firmness are the best visual indicators of chili plum fruit ripening, and are a good

predictor of potential shelf life. Skin colour and flesh firmness changes are directly related to the stage of maturity at harvest and controlled by temperature. Mature-green and breaker-stage fruits will ripen properly without exogenous ethylene application. Generally ethylene application to fruits harvested at the turning or breaker stage will only ripen the fruit more uniformly without speeding up the rate of ripening. Adequate air circulation and maintaining a relative humidity of 90 to 95% are necessary to assure uniform fruit ripening and prevention of fruit shrivelling during the ripening process (Mohammed, 2002). Physiologically mature fruits stored at 28 to 30°C ripened in three to four days whereas at 15 to 17°C they ripened in ten to 11 days. At even lower storage temperatures of 9 to 10°C, fruit ripened in 14 to 15 days. Storage of fruits at 4 to 5°C would also extend shelf life up to 15 days but chilling injury and decay would occur. Graham *et al*. (2001) indicated that chili plums could be successfully stored up to 14 days at 12.5°C before being subsequently transferred to storage conditions of 30 to 31°C where fruits ripened normally with an additional shelf life of four days. Mohammed (2002) found that chili plums harvested at the breaker stage, or stored until they had ripened to that point, could tolerate subsequent chilling temperatures of 5 to 6°C and maintain good organoleptic quality.

20.9.4 Recommended storage and shipping conditions

Overseas markets require blemish-free chili plum fruits harvested at or just before maturity, i.e. with a light yellow skin colour, and subjected to a hot water treatment at 45°C for 20 minutes to remove pathogens. Prior to shipment, fruits should be stored in shallow, ventilated one-ply cardboard cartoons at 12.5°C and 90 to 95% relative humidity. These conditions should be maintained throughout shipment for a maximum 7 to 8 days to allow display at overseas retail outlets at 20 to 22°C for another four to six days (Mohammed 2002). At display outlets, fruits could be repackaged into smaller portion sizes in sealed low-density polyethylene (LDPE) bags in order to maintain quality (Mohammed, 2002).

20.10 Processing

20.10.1 Fresh-cut processing

Chili plums have flesh 0.25 to 0.32 cm thick around a very porous seed or stone when at the fully-mature to tree-ripe stages of maturity. Fresh-cut fruit is currently only produced at the cottage-industry level. An appetizer or snack is made by slitting the fruit flesh with a knife in two or three places and then sprinkling the slits with salt and pepper. They can then be packaged in low-density polyethylene (LDPE) bags and sealed. These snacks are popular at bazaars, cafeterias, sport events and other public functions as ready-to-eat items. Alternatively, some vendors cut the fruit in half and serve it with other fresh-cut fruits in stretch-wrapped styrofoam containers (Mohammed, 2002).

20.10.2 Other processing practices

Sammy (1994) described the diverse range of value-added products using chili plums at the mature-green and ripe stages. They have been used in high-sugar products such as jam, jelly, fruit cheese, preserves, candy, cordials and squashes, as well as high-salted products such as pickles canned in brine and sauces. They have also been used in fermented products such as wines and yoghurt, and in dried and dehydrated products either whole or in slices. Sammy (1994) recommended that, for high-sugar products, a concentration of 60 to 70% sugar is required which, through its osmotic effect, prevents the spoilage of these products by micro-organisms. For high-salted products, the fruits are immersed in pure, granulated uniodized salt (1 to 3%) for flavor, and in vinegar containing 4 to 6% acetic acid for flavor and preservation. Salt (2.5 to 8%) is also used as a selective agent facilitating the growth of lactic acid bacteria during the preparation of fermented chili plum pickles. For fermented chili plum pickles, mature green fruits sanitized in a chlorine dip (50 ppm) are allowed to ferment for two to three weeks in a brine solution made up of 25 to 50 g salt and 50 ml vinegar per litre of water. The fermented plums are repacked in fresh brine that is flavoured and acidified. The final stage involved pasteurizing at 85°C for 15 to 20 minutes or by using a combination of chemical preservation with sodium benzoate (0.1% w/w), potassium sorbate (0.1% w/w) or potassium metabisulphite (0.03% w/w) and pasteurization (Sammy, 1994). For dried and dehydrated products, fully mature, ripe, firm fruits are blanched for five to 15 seconds in boiling sodium hydroxide (10 to 20 g l^{-1}) to roughen the skin and accelerate the drying procedure. This is followed by dipping the treated fruits for ten to 15 minutes in a 0.5% sodium metabisulphite solution (5 g l^{-1}), to prevent browning. Fruits are then soaked for 12 to 18 hours in a sugar solution containing two parts of sugar and one part of water by weight to withdraw moisture out of the fruit via osmosis and then dried to a moisture content of 12 to 14% (Sammy, 1994).

20.11 Conclusions

Major challenges for the fresh chili plum trade are the highly perishable nature of the fruit and its very short production season. Whether for fresh consumption or processing into value-added products, it is imperative to select only fruits at the mature green, breaker or turning stages of maturity. Investigations have been conducted on the use of temperature management supplemented with atmospheric control to reduce or alleviate chilling injury without inhibiting ripening, so that the fruit can reach optimum eating quality. As the chili plum is a potential export, the use of hot water or hot moist air treatments must be explored to counteract problems associated with fruit fly infestations. The significance of enzymes for fruit softening also warrants further investigation so that methods to counteract the rapid textural changes during ripening can be developed. In addition, improved understanding of packaging requirements to reduce physical damage would be

beneficial to ensure that the best quality fruit are supplied for processing into value-added products.

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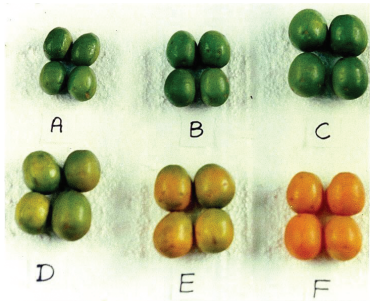
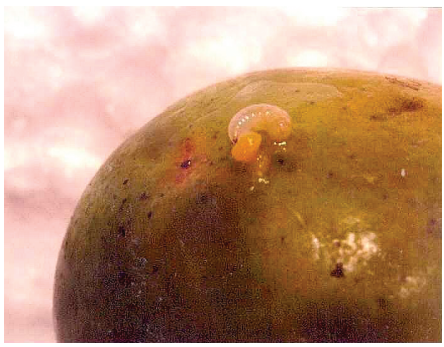


(a)

(b)



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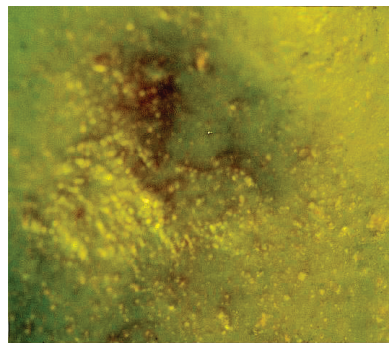

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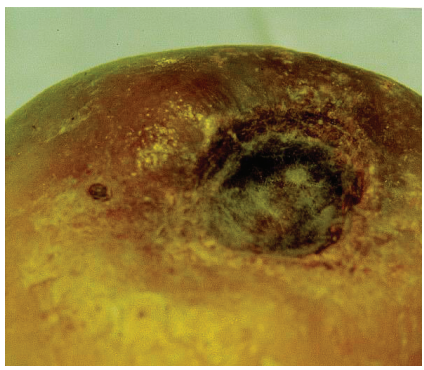

(e)

Plate XXXVII (a) Chili plum at six stages of maturity; (b) Chili plum with fruit fly infections; (c) Chili plum with fruit fly larvae; (d) Chili plum with severe chilling injury; (e) Chili plum with stem end rot.

21

Citrus *spp.*: orange, mandarin, tangerine, clementine, grapefruit, pomelo, lemon and lime

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Abstract: This chapter reports on aspects related to citrus fruit development and maturation in relation to quality during postharvest. Maturity and quality indices are discussed in relation to production environment and market demand. The consumption of citrus fruit and its human health-related issues are presented. Postharvest keeping quality is discussed in relation to preharvest and postharvest factors (such as climate, growing conditions and production practices, harvest practices, factors causing postharvest loss of quality, etc.) and to postharvest handling practices and used technologies. The most common pests, diseases and physiological disorders are briefly described with their main causes and remedies. Safety and quality assurance issues as well as best harvest and postharvest handling practices, including packinghouse operations, storage and transport conditions are also discussed.

Key words: World production, postharvest quality, maturity standards, storage conditions, commercial uses, health-related issues.

21.1 Introduction

21.1.1 Origin, climatic zones, botany, morphology and structure

Citriculture has been practiced for over 4000 years. It is believed that the true citrus fruit originated in southeastern Asia. Movement of the various types of citrus into the various parts of the world occurred with movement of civilizations, settlers and traders (see summaries provided by Spiegel-Roy and Goldschmidt (1996) and by Davies and Albrigo (1994)). Citrus fruits are grown in nearly all countries located in the citrus belt defined by the 40° north–south latitudes where minimum temperatures are generally greater than −7°C. The evergreen citrus

species and cultivars (oranges, mandarins, grapefruits, lemons, limes, pummelos and citrons) grow and produce fruit under a wide range of climates (equatorial, tropical, subtropical, Mediterranean, cool, hot, humid, semi-arid) and soil conditions (deep, shallow, heavy clay, light sand, somewhat saline, calcareous, somewhat acid, etc.) with varying degree of success.

Citrus is sensitive to extreme temperatures. Sensitivity of the tree to frost and to heat varies with species and rootstocks and is a major factor limiting the regions and localities where citrus can be successfully grown and can produce an adequate crop. Hot temperatures (generally greater than 13 to 15°C at night) delay fruit coloring, as is the case in the autumn months in the Mediterranean area and almost all year round in tropical zones. Hot temperatures in spring-time accelerate flower opening, petal fall and the whole process of fruit setting and growth. If too high, they can cause excess flower and fruitlet drop *via* a reduction in cell division and activation of the process of abscission. This reduces tree load, leading to fewer if potentially larger fruit, provided that trees are under optimal irrigation and mineral nutrition. Excess heat during later stages of fruit growth may result in reduced fruit size and delay in maturation. Uninterrupted high temperatures such as in the tropics enhance fruit growth and maturation with rapid decrease in fruit acid and sugar content, resulting in fruit of inferior quality compared to fruit of similar orange or mandarin varieties grown under a Mediterranean climate with cooler temperatures during maturation.

Citrus cultivars with red-pigmented rind and juice are well adapted to areas with low midwinter temperatures but with relatively high humidity, such as in Sicily or even Northern areas of Morocco. Blood oranges with high anthocyanin content develop well in these areas. In contrast, pigmented grapefruit develop better color under relatively higher temperatures such as in Texas and Florida.

Citrus trees are evergreen (except for *Poncirus trifoliate*, which sheds its leaves in winter) and do not have a true dormancy (Monselise, 1985). In general, little or no growth occurs in any citrus tree organs at temperatures below 13°C. Flowering is partly determined by environmental factors. It occurs during low winter temperatures under Mediterranean and subtropical conditions, and can be affected by water stress conditions in tropical regions. Flowering is also determined by endogenous factors, mainly tree nutritional status and hormonal balance. Carbohydrate levels have been reported to play a role in the control of flowering (Goldschmidt *et al.*, 1985). A relationship between flowering and tree nitrogen levels has also been reported (Lovatt *et al.*, 1988). Hormonal control of flowering has been shown mainly with exogenous applications of gibberellic acid, which inhibits the process (El-Otmani *et al.*, 1995; 2000).

Citrus pollination may occur by wind or insect and may cause seed formation, a non-desirable trait for fruit destined for the fresh market. Cases of self-incompatibility occur. A very important example is Clementine mandarin, which produces a very low crop if not cross-pollinated or if the trees do not receive a foliar application of gibberellins (GA_3 mainly) at floral anthesis-to-petal fall (El-Otmani *et al.*, 1994). Parthenocarpic fruit development (i.e. the development of fruit without seeds) without the stimulus of pollination occurs in Satsuma mandarin. Seedless fruit is sold at premium price compared to the same fruit with seeds.

The fruit of citrus is a hesperidium berry arising through growth and development of the ovary, consisting of a variable number of carpels (generally nine to ten in the most important commercial cultivars such as oranges and mandarins) covered by a leathery peel and making the edible portion, the endocarp. These carpels contain seeds and juice vesicles.

Generally speaking, citrus fruit is composed of three morphologically distinct regions. The exocarp is the outer layer mostly known as the flavedo. It is colored and is comprised of the epidermis covered by a waxy cuticle layer and with one or more layers of parenchyma cells beneath it. Within the epidermis are multicellular oil glands containing essential oils (Spiegel-Roy and Goldschmidt, 1996). During the early stages of fruit development, the flavedo is green. As fruit undergoes maturation, chlorophyll pigments are lost and chloroplasts are replaced by chromoplasts containing carotenoid pigments (Goldschmidt, 1988).

The inner layers of the peel consist of a white spongy albedo (constituting the mesocarp). This tissue tends to thin as fruit grows and in many mandarins such as the Clementine it disintegrates and is almost absent in mature fruit. Physiological disorders such as 'creasing' and 'splitting' have been shown to be related to this disintegration and/or cracking in the albedo (see El-Otmani and Ait-Oubahou, 1999 and the references therein). Renewed growth of the albedo resulting in an increase in peel thickness during fruit maturation and senescence has also been reported for certain cultivars such as Satsuma and Clementine mandarins. This renewed growth may lead to a disorder named 'puffing' with large air spaces between the pulp and the rind.

The rind protects the fruit from damage while on the tree and also during handling postharvest, and from desiccation during storage. Its thickness depends on the cultivar (with thicker peel in pummelo and grapefruit and thinnest in mandarins), the climatic conditions (thicker and harder peel under dry hot conditions) and the stage of fruit development.

The pulp (endocarp) is made of juice sacs filled with juice and enclosed in a thin white membrane. Juice vesicles are initiated at bloom time. Their cells divide and get filled with water, acids, sugars, minerals, pigments, etc. as fruit grows and matures. Seeds can be found in the locules adjacent to juice vesicles.

21.1.2 Worldwide importance

World production and acreage

Available statistics indicate that there are about 8.7 million hectares of citrus grown in the world for a total production close to 122 million tons (FAO, 2010).

Major producing countries

Table 21.1 gives the list of the twenty largest citrus producing countries in the world by rank according to production. The three largest citrus fruit producing countries are China (22 million tons/year), Brazil (21 million), and the USA (about 12 million) and they total almost half the world tonnage which is close to

Table 21.1 Citrus production and acreage for the twenty major citrus producing countries, 2008

World rank	Country	Production (tons)	Surface area (ha)
1	China	22 019 156	1 966 711
2	Brazil	20 774 752	945 913
3	USA	11 692 770	339 286
4	Mexico	7 502 917	549 191
5	India	7 168 700	810 100
6	Spain	5 911 600	342 008
7	Italy	3 900 572	166 861
8	Iran	3 756 000	245 000
9	Nigeria	3 400 000	732 000
10	Egypt	3 230 986	355 374
11	Turkey	3 026 940	113 061
12	Argentina	2 722 000	148 500
13	Pakistan	2 459 500	193 211
14	Indonesia	2 322 581	63 695
15	S. Africa	2 192 253	71 980
16	Japan	1 292 250	63 130
17	Morocco	1 239 000	80 200
18	Columbia	1 235 754	84 650
19	Thailand	1 130 000	97 600
20	Syria	1 047 930	35 330

Source: FAO (2010).

Table 21.2 Distribution of total world planted citrus area and production by type

Citrus type	Surface area planted (ha)	Production (tons)
Oranges	4 188 870	67 695 802
Tangerines, mandarins and Clementines	2 154 345	28 556 834
Lemons and limes	1 013 348	13 439 211
Grapefruit and pomelos	265 473	4 943 602
Other citrus	1 094 229	7 452 302
Total	**8 716 265**	**122 087 751**

Source: FAO (2010).

122 million tons/year (Table 21.2). They are followed in rank by Mexico and India with a little over 7 million tons each. Most of the Chinese citrus plantings are very young and, therefore, their production has been, and will be for a few years, steadily increasing.

Within the Mediterranean Basin, Spain is the largest producer with 6 million tons/year followed by Italy (4 million) and Egypt (3 million). In Africa, Egypt is leading followed by South Africa (2.2 million tons/year) and Morocco (1.3 million).

Trade and economics

Each year, about 11 to 12 million tons of fresh citrus fruit are traded in the international market (FAO, 2007). Of that total, 50% is oranges and 30% is 'easy peelers'. In addition, the major exporting countries are located within the Mediterranean Basin with Spain as the most important exporter (28% of total world exports) followed by the USA (8%), and Turkey (8%).

21.1.3 Main varieties and their characteristics

Table 21.2 provides an overview of the distribution of the main citrus types produced whilst Table 21.3 lists the major countries producing them.

Ladaniya (2008) has reported on the main citrus cultivars and their respective harvest season. Oranges constitute about 55% of the total of world citrus production followed by the 'easy peeling' group including mandarins, tangerines and Clementines (23% of total), lemons and limes (11%) and grapefruit and pomelo (4%). China is by far the largest producer of 'easy peelers' (with Ponkan,

Table 21.3 Citrus production by type (in 1000 tons) for the major citrus-producing countries, 2008

Country	Total citrus production	Oranges	Tangerines, mandarins and Clementines	Grapefruit and pomelos	Lemons and limes	Other citrus
China	22 019	3454	15 623	568	917	1458
Brazil	20 775	18 390	1273	72	1040	ni
USA	11 693	9139	478	1408	638	30
Mexico	7503	4307	469	395	2224	108
India	7169	4397	ni	187	2429	156
Spain	5912	3367	1974	50	499	22
Italy	3901	2527	786	7	550	30
Iran	3756	2300	702	54	620	80
Nigeria	3400	ni	ni	ni	ni	3400
Egypt	3231	2138	758	2	330	2
Turkey	3027	1427	756	168	672	3
Argentina	2722	766	520	176	1260	ni
Pakistan	2459	1721	640	ni	98	ni
Indonesia	2323	ni	ni	ni	ni	2322
S. Africa	2192	1436	135	381	233	7
Japan	1292	65	1066	ni	5	156
Morocco	1239	750	450	1	22	16
Colombia	1236	353	68	ni	65	750
Thailand	1130	350	670	22	82	6
Syria	1048	603	25	290	130	ni

Note: ni – not indicated.

Source: FAO (2010).

Tankan and Satsuma mandarins as the main cultivars (Chinese Society of Citriculture, 2008)), followed by Spain, Brazil and Japan. Spain is the largest producer of Clementines in the world, whereas Japan produces mainly Satsumas. The USA is the largest producer of grapefruit, whereas China is the largest producer of pomelos. Lemons and limes are mostly produced in Mexico, India, Argentina and Brazil. Ponkan and Kinnow mandarins do well in Asia (in countries such as India, Pakistan and China) whereas Clementines are more adapted to western parts of the Mediterranean Basin.

Saunt (2000) illustrates fruits of the main citrus varieties grown around the world and describes some of their key characteristics.

Oranges

As indicated above, oranges are the main citrus type in production terms. This group includes early cultivars (mainly navels such as 'Fukomoto' and 'Newhall'), mid-season cultivars (such as 'Washington' and 'Cara Cara' navels and 'Salustiana', 'Shamouti' and 'Hamlin' blonde oranges) and late cultivars (such as 'Navelate' and 'Lanelate' navels, and 'Valencia' orange with its various selections such as 'Midnight', 'Cutter', 'Olinda', etc.). Fruits of most of these varieties (particularly navels) are almost always seedless.

Navel oranges are generally large fruits and present a secondary fruit at their stylar called a 'navel' (hence the term navel orange). Insects and microorganisms may penetrate fruit through this opening and cause fruit decay on the tree or postharvest. They have an excellent eating quality. 'Valencia' orange is the most commonly grown citrus variety worldwide because of its high juice content, high sugar content and good rind firmness, making it possible to store it for periods of four to six months and to ship to distant markets. If fruit is stored for long periods on the tree, its peel regreens. Peel regreening occurs at the stem-end of the fruit and is accelerated by warm spring temperatures and by nitrogen fertilization.

Blood oranges are produced mainly in countries and areas where they have originated, such as Italy. They have a very limited market niche but are being publicized in the marketplace for their high anthocyanin content and antioxidant properties (see sections below). The blood orange color is more intense under cool climates such as in the Northern rim of the Mediterranean basin compared to the Southern rim.

Clementines

Fruit of this group has a thin and easy-to-remove skin. This group is also called 'easy peelers' or 'candy fruit' and is well liked by children (to take to school as snack fruit) and adults (as it does not leave a lot of oils on the hands when peeled). Fruits are generally flat at their ends and are subject to 'puffing' once they reach maturity. They are also sensitive to excess rainfall, as the skin soaks up water and becomes more susceptible to poor postharvest handling, and to decay. Fruits are generally seedless as the variety is self-incompatible but can contain seeds if planted near an orchard with a good pollinating variety such as 'Wilking', 'Nova',

'Ortanique', 'Fortune'. On young trees, or on trees grafted on vigorous rootstocks and during years of light crop, the fruits are bigger with a thicker rind, and are of lower eating quality with lower acid and lower sugar content. Early cultivars usually reach internal maturity while their rind color is still green due to the warm autumn temperatures. The initial green color is accentuated by good tree health and nitrogen fertilization. This group contains many selections differing mainly in their season of maturation and appears to be well adapted to climatic zones of the Western Mediterranean basin. Spain and Morocco are the two largest Clementine-producing countries in the world.

Mandarins and hybrids

Satsuma (with its many varieties), 'Kinnow', 'Fairchild', 'Ortanique', 'Nova', 'Fortune' and 'Nadorcott', are some of the most common types of mandarin encountered worldwide. Satsumas have good size fruit, yellow-orange skin at maturity and are well adapted to cool climates such as in Northern Spain, Turkey, Northern China, Japan and Northern California. Under warm and dry conditions, fruits have a thicker yellow peel, and internal quality is poor with an insipid taste at maturity. Fruits are seedless.

Mandarin hybrids such as 'Kinnow', 'Fairchild', 'Ortanique and 'Fortune' are very juicy with high acid and high sugar content and a very adherent peel. Often, growers have to keep them for a long period on the tree to lose most of their acids and become palatable before they can pick them. When this is the case, fruits can develop physiological disorders such as 'creasing'. In addition, 'Fortune' mandarin has a thin peel and is very sensitive to cold temperatures both in the field and postharvest (Agustí, 2000). When this occurs, the fruit develops a disorder named peel 'pitting'. Seediness is a major drawback for varieties such as 'Fairchild' and 'Kinnow' particularly when destined for export to markets such as Europe or North America.

The 'Nova' hybrid of mandarin is very susceptible to 'splitting', a disorder most often starting at the stylar-end. It can also occur in 'Ortanique'. The 'Nadorcott' hybrid (more known as 'Afourer') is believed to be a nucellar seedling of W. Murcott (Nadori, 2006). Morocco has developed a market and a label to identify the vaiety as a distinctive brand. It has adequate size with excellent eating quality. However, it can show symptoms of chilling injury when stored for a long period of time under temperatures below 8°C and then brought back to ambient temperature.

Grapefruit

Fruits of this group are very large in size (8 to 13 cm in diameter), and flat at the ends or pear-shaped. The pulp is juicy with an acid-sour taste (due to naringin content). There are white types and red types. 'Star Ruby' is the major cultivar of grapefruit currently grown worldwide due to its pink-reddish color containing high lycopene levels, a compound reported to have antioxidant activity. Color intensity is related to heat units available during fruit development and maturation.

Lemons and limes

Lemon flowers almost all year round and thus produce fruit almost throughout the year. Fruit may contain many seeds. Juice is highly acid and usually plentiful except when the tree is under some biotic (virus disease for example) or abiotic (such as water deficit) stress.

There are two types of limes: sweet limes and acid limes. Acid lime fruits are ovoid and generally much smaller with thinner peel than for lemons. The peel is smooth and greenish-yellow at maturity, whilst the pulp is much more acid than that of lemons. The most commonly grown lime is 'Mexican' lime, which does well under hot climates. Sweet limes are much bigger and more spherical with a yellow medium thick peel. They are juicy with a flat taste due to lack of acid. They do not have significant commercial value.

21.1.4 Destination and uses

In the Mediterranean countries, citrus fruits are produced mainly for fresh fruit consumption. USA (Florida mainly) and Brazil are the leading producing countries of processed citrus fruits. In USA most of the production is consumed domestically. Indeed, domestic consumption of orange juice in the USA is higher than its production (UNCTAD, 2010). However, the USA still plays a role as a fresh citrus fruit exporter (between 1978/79 and 1999/2000 the excess of exports of fresh oranges over domestic production ranged from 20 to 30%). In Asian countries, production of citrus fruits is mainly consumed in their domestic markets.

According to UNCTAD (2010), citrus fruits are mainly consumed in developed countries, but consumption per capita is increasing in developing countries. Fresh citrus consumption per capita in the mid 2000s is close to 30 kg/year in developed countries and about 12 kg/year in developing countries (UNCTAD, 2010). Fresh orange consumption is declining in developed countries in the main for two reasons: it is being replaced by orange juice consumption, and improvements in transportation and storage favor wider and longer availability of substitute fruits. However, fresh orange consumption has expanded in many emerging economies such as Mexico, India, Argentina, Brazil and China. In countries with a Mediterranean climate such as Spain, Morocco, Turkey, California (USA) and others, due to consumer preference, orange production is also losing ground in favor of 'easy peelers' such as Clementines and mandarins.

A report by UNCTAD (2010) also indicated that in the mid 2000s, exports of fresh citrus fruits represented roughly 10% of total citrus fruit production. The bulk of exports of fresh citrus fruits are from countries the Northern Hemisphere, accounting for around 62% of world fresh citrus fruit exports in 2003. The Mediterranean region plays a prominent role as a fresh citrus exporter, providing nearly 60% of global fresh citrus fruit exports. Southern Hemisphere countries, such as Argentina, Australia and South Africa, are increasing their presence in international trade by providing off-season citrus fruits to the North.

21.1.5 Nutritional value and health benefits

Citrus fruits have long been recognized for their nutritional and health benefits to humans. In addition to the flavors that rank them among the most preferred fruits and juices, oranges and other citrus fruits are commonly recognized as an important source of vitamin C, one of the main reasons for the large consumption of fresh citrus fruit and juice worldwide. The beneficial effects of citrus fruit to human health are not only due to their content of vitamin C but also to their content of several other phytonutrients (Economos and Clay, 1999). Table 21.4 summarizes the nutrient values of fresh fruit of the main cultivated species. An important property of fresh citrus fruits is their low energy value, a negligible sodium concentration and its replacement by potassium, which may be important for low-fat and restricted diets.

Citrus fruits are probably one of the main sources of vitamin C for human nutrition, and oranges and lemons are richer in vitamin C than other citrus fruit. Although the amount of vitamin C in any one fruit can be very variable and tends to decrease rapidly after harvest, a single orange can fulfil the entire recommended

Table 21.4 Nutrients of fruit of different citrus species (values are as per 100 g of edible portion)

Nutrient	C. sinensis	C. reticulata	C. paradisi (red and pink)	C. paradisi (white)	C. limon
Water (g)	86.75	85.17	88.06	90.48	88.98
Energy (kcal)	47	53	42	33	29
Protein (g)	0.94	0.81	0.77	0.69	1.10
Total lipids (g)	0.12	0.31	0.14	0.10	0.30
Carbohydrates (g)	11.75	13.34	10.66	8.41	9.32
Fiber (g)	2.4	1.8	1.6	1.1	2.8
Calcium (mg)	40	22	12	12	26
Iron (mg)	0.1	0.1	0.1	0.1	0.60
Magnesium (mg)	10	9	9	9	8
Phosphorus (mg)	14	18	8	8	16
Potassium (mg)	181	135	148	148	138
Vitamin C (mg)	53.2	26.7	31.2	33.3	53.0
Vitamin A (IU)	225	681	1150	33	22
Vitamin E (mg)	0,2	0,2	0,15	0,13	0,15
Thiamin (mg)	0.087	0.058	0.043	0.037	0.040
Riboflavin (mg)	0.040	0.036	0.031	0.020	0.020
Pantothenic acid (mg)	0.250	0.216	0.262	0.283	0.190
Folate (mg)	30	16	13	10	11
β-carotene (μg)	71	155	686	14	3
α-carotene (mcg)	11	101	3	8	1
β-cryptoxanthin (μg)	116	407	6	3	20
Lycopene (μg)	0	0	1419	0	0
Lutein + zeaxanthin (μg)	129	138	5	10	11

Source: Adapted from USDA National Nutrient Database (2009).

diary intake for a typical adult. Contemporary interest in vitamin C emphasizes its antioxidant functions in protecting cells against damage from free radicals. Degenerative diseases, such as cancer and cataracts as well as degeneration and infection of macular area of the eye, may be prevented by vitamin C. In addition, vitamin C plays an important role in the formation of collagen in humans, a critical function in the fortification of ligaments, blood vessels and bones, and in wound healing. It also plays a role in the absorption of inorganic iron and in treatments of anaemia and stress. Intake of vitamin C is also beneficial not only for the prevention of winter colds but also in reducing the length and severity of the symptoms (Carr and Frei, 1999).

Citrus fruits are also an important source of folate, potassium and carotenoids. Some of these carotenoid pigments (α- and β-carotene and β-cryptoxanthin) are the precursors of vitamin A whilst the red pigment lycopene (present in red and pink grapefruits) also has significant antioxidant activities (Maiani *et al.*, 2009). Other naturally occurring compounds with important physiological properties are polyphenols (phenols, hydroxycinamic acid derivatives), flavonoids (flavanones, flavones, flavanols and anthocyanins), coumarins and terpenes that, in general, protect against chronic diseases such as cancer and heart disease and have anti-viral, anti-allergic, anti-inflammatory and anti-proliferative activities. Other health benefits of citrus compounds are related to prevention of diseases such as liver problems, obesity, diabetes, asthma, kidney stones, bone metabolism, osteoporosis and other age-related diseases (Silalahi, 2002).

21.2 Fruit development and postharvest physiology

21.2.1 Fruit growth, development and maturation

Bain (1958) divided 'Valencia' orange fruit development into three major stages: cell division (stage I), cell enlargement (stage II) and fruit maturation (stage III). This division is valid for most citrus fruit, but the duration of each phase varies according to cultivar (shorter for early-maturing cultivars and longer for late cultivars) and climate (shorter in hot tropical areas and longer under a mild Mediterranean climate).

The cell division stage starts at anthesis and covers the fruit-setting phase. The increase in fruit size during stage I is mainly from cell division, which leads to increased peel thickness. The peel reaches its maximum thickness at, or soon after, the end of stage I. This was reported for oranges (Bain, 1958; Hotzhausen, 1982), mandarins (Kuraoka and Kikuki, 1961), and grapefruit (Herzog and Monselise, 1968). It is noteworthy that the number of cells formed at this stage is critical for final fruit size and therefore, it is critical that the tree have optimum access to nutrients and water.

The cell enlargement phase (stage II) corresponds to the fruit growth stage, resulting mainly from the growth of the pulp. The cells of juice sacs enlarge and fill the locules (segments). Their juice, sugar content and pigment development increase towards the end of this stage. The peel tissues individualize into flavedo

(compact tissue) and albedo (spongy tissue) at early stages of this phase. The peel becomes thinner as the fruit grows. It is noteworthy that the final cell size at the end of the enlargement phase is critical for final fruit size, a major component of fruit quality in the marketplace.

Stage III corresponds to the fruit maturation stage. Fruit continues to grow with the rate of growth depending on the cultivar and the climatic conditions (Davies and Albrigo, 1994). Renewed growth and thickening of the peel may occur during this stage, particularly under warm, growth-favoring conditions (Herzog and Monselise, 1968). Excess peel growth may lead to rind separating from the pulp causing fruit 'puffing'. Puff fruit are very sensitive to postharvest handling as they are highly susceptible to injury. In certain cultivars such as 'Nova' and 'Fortune' mandarins, 'Valencia' orange, etc., the albedo may crack, resulting in the development of weak areas in the peel, thus making fruit more fragile and highly susceptible to rough postharvest handling.

21.2.2 Respiration, ethylene production and maturation

Citrus fruit is 'non-climacteric'. Its maturation is unlike many other fruits such as bananas and avocadoes in which, when ripening takes place, abrupt texture and compositional changes take place within the fruit. These changes occur concomitantly with a 'climacteric rise' in respiration and ethylene production by the fruit (Theologis *et al.*, 1992). In citrus fruit, such changes are slow and gradual. In addition, respiration declines continuously throughout fruit development and ethylene production is extremely low (Goldschmidt *et al.*, 1993). Furthermore, in contrast to the other fruits, which can be picked fully mature but not ripe and be ripened postharvest, citrus fruit contains no starch and cannot be picked and ripened postharvest. It has to be fully mature on the tree before harvest. However, internally mature fruit but with greenish rind can be picked and degreened postharvest for it to attain a color that is more attractive to the consumer.

21.3 Composition, maturity and quality components and indices

Citrus fruit contains water, soluble sugars (mainly fructose, glucose and sucrose), acids (mainly citric and malic), pectins, vitamin C, carotenoids and flavonoids. Hesperidin and narinjin are the major flavonone glucosides of orange and grapefruit, respectively. Naringin is a bitter compound (mainly in grapefruit) whereas hesperidin is tasteless (Spiegel-Roy and Goldschmidt, 1996).

Fruit and juice color is a result of about 115 different pigments (Gross, 1987). Each species and hybrid has its unique carotenoid composition, which is responsible for its specific color. In yellow citrus, the total amount of carotenoid is low and the carotenoids present are colorless. Orange-colored fruit contain large amounts of color carotenoids. In pink and red grapefruit, lycopene and β-carotene are the major carotenoids. The color in blood oranges is due to another

class of pigments, the anthocyanins. Presence of these pigments in fruits is higher in cooler climates such as in northern Morocco and Italy.

Most citrus organs contain essential oils located in oil glands. In fruit, the flavedo is particularly rich. These oils are widely used as flavoring additives in foods and beverages and in the cosmetic and pharmaceutical industries. Limonin is the main bitter compound of citrus juices (Ting and Rouseff, 1986). Limon oil contains more than 100 compounds (Kesterson *et al.*, 1971), which vary with the species, the variety and even between fruit within the tree. Taste is the main index of fruit eating quality. It is the result of the interaction of many juice constituents including acids, sugars and aromatic constituents as well as the juiciness of fruit, pulp firmness, etc. During maturation of citrus fruit, significant changes in these constituents occur within fruit tissues and affect fruit palatability. Flavor is the combination of basic taste (due to sugars, acids, bitter principles, phenolics, limonoids, etc.), aroma and mouth-feel sensations that are perceived simultaneously by the brain during food-eating (Goff and Klee, 2006). Aroma is the result of sensations induced by volatile compounds (Schwab *et al.*, 2008). Macromolecules such as pectins may create a certain mouth-feel, interact with volatile compounds and taste-related compounds to give rise to a certain perception of flavor (Rega *et al.*, 2004).

Juice titratable acid content (TA) decreases with maturation as a result of decomposition of citric acid, which is the main acid in citrus fruits (Monselise, 1986). In contrast, there is an increase in juice sugar levels, usually expressed as total soluble solids (TSS). The TSS:TA ratio is very sensitive to these changes, and is often used as the 'maturity index' for citrus fruit destined for fresh consumption. In Morocco, for example, this ratio should be at least 7:1 for oranges and mandarins destined for export to foreign markets such as Europe or North America, with a TSS of at least 9.5 and 9.0% respectively. The legal standard ratio in California is at least 8:1 for navel oranges, whereas for Florida, tangerines can only be harvested when their TSS levels are above 9% and TSS:TA greater than 7.5 (Grierson, 2006).

Because the TSS:TA of 8:1, considered the minimum maturity standard for California navels, has proved to be too low for consumer acceptability, Obenland and his group tested a formula developed by Jordan *et al.* (2001), which takes into account the fact that receptors in the tongue have a different response to sugars and acids (Obenland *et al.*, 2009). The formula is: BrimA = TSS − k (TA) with the constant k being a given characteristic of a fruit product. There was a better correlation between flavor hedonic scores and sugar and acid concentrations using BrimA (with k = 3) than with the TSS:TA ratio. It has been suggested that the accuracy of BrimA index is superior in predicting flavor liking because it more efficiently considers low acid fruit.

Fruit juice content increases as fruit matures to reach a maximum value at full maturity and decreases, thereafter if fruit is stored on the tree for a long period of time and temperatures are high and air humidity is low. In Morocco, fruit for export (which accounts for 50 to 60% of total production) has to have a minimum of 35% juice for oranges and 40% for Clementines. For lemons, the only fruit

maturity standard used is juice content which has to be at least 25% by weight. Minimum lemon juice content for California is 30% (Grierson, 2006).

Other quality parameters include fruit size, which varies greatly with cultivars and species (under-sized and over-sized fruit is discarded in the packing house or in the field), color (for exports from Morocco peel color should be typical of the variety over at least one-third the surface of clementine fruit rind whilst a greenish color is accepted for oranges on a maximum of one-fifth the surface of the fruit rind), absence of rind blemishes, absence of seeds, and presence of calyx as an indicator of freshness and an obstacle to invasion by decay organisms such as fungi. Early in the season, fruit is generally mature internally but retains a green rind. It can be degreened using ethylene. Fruit that satisfies minimum internal standards and size characteristics is then separated into grades (such as in Florida and other parts of the world) or categories (such as in Morocco), defined according to external appearance and intensity of blemishes (due to rust mite discoloration or wind scarring for example), which vary between countries and even regions according to grade/category characteristics defined for that country or region.

21.4 Preharvest factors affecting fruit quality

Orchard factors have a significant influence on fresh fruit quality. In this section, a summary of these factors is provided.

21.4.1 Plant factors

The most basic factor that influences fruit quality is the scion/rootstock combination. In fact, for a given site, the choice of the right variety is essential, particularly if there are factors related to soil or pests and diseases that can negatively affect fruit production and quality and that can be alleviated by rootstocks. Fruit size is an essential component of fruit quality and it is mainly related to the variety. It is well known that some varieties of Clementine and mandarin trees usually yield small fruits, which may or may not be accepted by a given market but there are wide variations within species. Given the right conditions, Clementine selections such as 'Orogrande', 'Nour' and 'Larache' for example produce fruit with adequate size whereas, under the same conditions, 'Oronules', 'Caffin' and 'Cadoux' produce smaller fruit. Fruit from the spring bloom is of a much better quality than fruit of the summer bloom. The latter has small size, thicker coarser peel, lower juice content and lower sugar and acid concentrations.

'Nour' Clementine is an alternate-bearing cultivar and in the 'Off-year', it produces a small crop with fruit with thicker and coarser rind that is of suboptimal quality compared to that of a regular crop. 'Cadoux' Clementine is also an alternate-bearing cultivar with probably the best eating quality (good juice content, sugar/acid ratio, flavor, etc.). In the 'On-year', it yields a large crop but

with relatively small fruit size and thin peel, making it of less commercial value and more susceptible to rough handling and postharvest decay.

Navels from northern latitudes such as Morocco or California have adequate peel thickness, juicier fruit with high sugars and deep-orange colored peel. In the lower latitudes of the Souss region of southern Morocco, where air is less humid and autumn temperatures are relatively high, they have relatively thicker pale orange peel with less sugar, less acid and relatively pale juice color at maturity.

'Valencia' oranges are adapted to a wide range of climatic zones producing fruit with adequate quality. This variety produces fruit with excellent internal quality with high juice and sugar content and deep orange juice color under relatively hot and humid conditions such as in Brazil and Florida, compared to dry climatic conditions.

The fruit of 'Fortune' and 'Kinnow' mandarins can reach optimum peel color and good juice sugar content quite rapidly, but their acidity remains high for a long period of time. If fruit of these varieties is kept on the tree for acid dissipation, the peel enters a senescent phase with the potential development of disorders such as peel softening, 'creasing' and 'pitting'.

The rootstock has a significant effect on citrus tree growth and development and thus on fruit growth and final quality (Davies and Albrigo, 1994; Aubert and Vullin 1998). Until the disasters caused by the Tristeza disease on citrus worldwide, sour orange was the most used rootstock in citrus production because it is resistant to *Phytophthora* gummosis disease, tolerant to soil calcareous conditions (as most soils are alkaline with high active lime contents) and good tree growth and development and produces good fruit quality. Trees on sour orange as well as on trifoliate type rootstocks (such as *Poncirus trifoliata* and its hybrids (citranges and citrumelos)) are slow-growing and produce fruit with adequate size and excellent eating quality with higher sugar and acid content but a well balanced sugar/acid ratio, and with a longer shelf-life. The trees have better longevity.

In contrast, trees grafted on the lemon type rootstocks (such as *Citrus macrophylla*, Volkamer lemon, Rough lemon, Sweet lime, etc.) are more vigorous. They have faster vegetative growth, bear fruit more rapidly and produce larger size fruit with good crop loads. In particular, *Citrus macrophylla* and Volkamer lemon are used on Clementine and mandarin (average tree density: 700 to 900 trees/ha) in the Mediterranean region to overcome the problem of small fruit size. Full mature 'Nadorcott' mandarin (also known as 'Afourer') grafted on *Citrus macrophylla* produces fruit with coarser and thicker peel (3.5 mm compared to 3.1 mm for sour orange), lower sugar (9.8° Brix *vs.* 10.8° Brix) and acid (0.85% *vs.* 1.3%) contents, and inferior taste although they have a higher sugar/acid ratio (11.2 *vs.* 8.3) (Elmalhi, 2009). These fruits also hold poorly on the tree and postharvest. The negative effect of these rootstocks is accelerated under hot climates in the lower latitudes where fruits rapidly lose their acids and sugars.

Cleopatra mandarin rootstock has been reported to be suitable with mandarins and their hybrids but not with grapefruits and oranges as these tend to produce small fruits with delayed maturation (Rouse and Zekri, 2006).

21.4.2 Environmental factors

The most important environmental factor affecting citrus growth and development is temperature. In fact, under the high temperatures prevailing in tropical zones, fruit growth and development is rapid and fruit size may become very large. In the Mediterranean climatic zone, fruit growth is slower, particularly during the cool winter months, resulting in fruit with smaller size compared to the tropics (Spiegel-Roy and Monselise, 1996). These differences are mainly due to accumulated heat units, the values of which are shown to correlate with fruit development and maturation (Reuther, 1973). Early-maturing cultivars require less heat units compared to late-maturing cultivars.

Under hot tropical conditions, fruit is mature and marketable for a very short period of time, whereas in cooler climates fruit matures during an extended period of time, during which it can be harvested and marketed with high quality and a much longer postharvest shelf life. Fruit coloring is also influenced by temperature: warm temperatures delay chlorophyll degradation and carotenoid development whereas cool temperatures cause the opposite effect. Thus fruit from tropical areas remains a greenish pale yellow at full peel color. In subtropical and Mediterranean areas, fruit color in early maturing cultivars starts to develop in the autumn and is enhanced by cool night temperatures. When warm temperatures prevail, fruit remains green while minimum internal fruit quality is reached. In addition, peel of fruit grown under hot and humid climates is more turgid and tender than that of fruit grown in drier areas, thus making it more susceptible to peel blemishes and more sensitive to postharvest handling and decay organisms. Such fruit therefore has low storage potential and can senesce rapidly.

Climate also has an effect on fruit quality. Fruit developing in a hot climate has high total soluble solids:acid ratio due mainly to its low acidity. High soluble solids content is highly desirable for fruit processing but when acid content is too low, fruit edible quality is poor. Thus, citrus fruit for fresh consumption is preferably produced under subtropical and Mediterranean climatic zones. Under these conditions, fruit color is good, internal quality at maturation is balanced and fruit can be stored for a long period or shipped over long distances with no negative effect on its quality, provided that fruit is harvested at the optimal maturation stage and that postharvest conditions are optimal. In the valleys, fruit from trees close to the ocean mature and color earlier than fruit from inland areas.

Extreme temperatures depress fruit growth and development. Hilgeman *et al.* (1959) reported that, for 'Valencia' oranges grown in Arizona, summer temperatures greater than 38°C reduced fruit growth and final fruit size. They also showed that: 1) 96% of the variation they observed in fruit size was due to differences in tree load, bloom date, and summation of degree-days above 38°C and 2) fruit growth negatively correlated with summation of degree-days below 0°C in the November-February period. On the other hand, Hales *et al.* (1968) indicated that air relative humidity below 37% was critical for enlargement of 'Valencia' orange fruit.

Rain is good for tree growth and fruit development but only to a certain extent. In many tropical areas such as Brazil, rain is plentiful and relatively well

distributed throughout the growing season. Fruit reaches adequate size and adequate internal quality without the need for irrigation. However, in subtropical and Mediterranean climates, rainfall is irregular between seasons and varies also from year to year. Thus, irrigation is mandatory for adequate tree and fruit growth and development. Summer and early rains are excellent as they leach salts from the root zone of trees, thus creating good conditions in the rhyzosphere in the root which has positive effect on fruit growth, particularly for early maturing cultivars which often yield small size fruit. When rainfall is excessive, however, overall aesthetic fruit quality will suffer since fruit blemishes may occur as a result of contact of large raindrops with the peel, particularly for soft-skinned fruit. In addition, under heavy soil conditions, heavy rains make it impossible to enter the orchards at the optimal time for harvesting mature fruits or for undertaking necessary cultural operations such as pruning, foliar fertilizer application (for microelements mainly), and pesticide applications against insects, mites or diseases. In particular, heavy rains may cause brown rot (due to *Phytophthora*) and sour rot (due to *Geotrichum candidum*) on fruits, and gummosis on tree trunks and branches. Excess rain can also cause root rot (due to *Phytophthora sp*., *Fusarium sp*., etc.).

High air relative humidity can result in accumulation of heavy dew on leaves and fruits, which can cause build-up of cell turgor pressure particularly in the rind, making it prone to damage from picking, with workers putting pressure on the fruit during harvest, or from careless transport of fruit loads on rough roads, or from rough postharvest handling. Under high humidity conditions, often occurring during the months of November to January, thus coinciding with maturation of most of the Clementine cultivars, it is common that harvest does not start until noon or even later when fruit turgor pressure has declined. Another example is Florida lemons, which mature during the rainy season and are thus commonly very turgid. It is very common to leave harvested lemons in the field overnight to allow fruit (and particularly peel) turgor to decrease before transporting them to the packinghouse.

Wind can cause significant drop of flowers, fruitlets and mature fruit, particularly if winds are strong and are associated with dry and hot (or freezing) conditions. High winds can also cause scarring of the fruit thus reducing its appearance.

Soil texture has an effect on maturation and the final quality of fruit. In sandy soils, fruit maturation and coloring are hastened by about one to two weeks compared to heavy soils. In addition, trees planted on raised beds grow faster, produce bigger fruit, and fruits mature earlier than for trees planted on flat soil. This is particularly true for Clementines, which may otherwise produce smaller fruit if grafted on vigorous rootstock such as *Citrus macrophylla*.

Fruit position on the tree has a significant effect on fruit development and final quality. Fruit exposure to excess direct sun may cause peel sunburn, which may cause fruit deformation, and in turn decreases aesthetic quality. In the case of Clementine mandarin, insufficient light inside the tree canopy produces fruit with thin and pale yellowish-orange peel, lower sugar content and lower sugar/acid

ratio. Sites and Reitz (1949, 1950a, 1950b) indicated that fruit on the upper outside portion of the tree has the highest sugar content, the highest sugar/acid ratio and develops a more desirable fruit color. In the Northern hemisphere fruit from the lower portions of the tree have bigger fruits, whilst small fruits from higher up the tree contain higher sugar and acid concentrations in their juice (Wallace *et al.*, 1955; Tominaga and Daito, 1982).

21.4.3 Plant health

Pests and diseases that attack citrus are numerous. They include virus and virus-like diseases, bacteria, nematodes, snails and mollusks, insects (fruit flies, scales, leaf miner, etc.), and mites (see the following sections). When flowers are damaged, they either fall or remain on the tree to give rise to damaged (scarred) fruit. When damage is caused to leaves, tree photosynthetic capacity is reduced, thus reducing available photosynthates for growth and so reducing development of various tree organs including fruits, resulting in reduced fruit size. In a similar manner, when damage is done to the trunk, transport of assimilates is reduced and the various tree organs are undernourished, thus causing general tree stunting, and reduced growth, yields and fruit quality. When the roots are damaged, for instance by nematodes, water and nutrient uptake from the soil is reduced with a negative impact on general tree physiology and growth. If fruit damage is slight (little scars), fruit may be sold as a low-grade fruit category but, if the damage is great (such as fruit punctured and decaying), fruit is discarded either in the field or at the packinghouse.

Besides pests and diseases, injury to tree organs may be caused by freeze injury, excess heat, salt and water stress including drought stress and flooding injury, and pesticide phytotoxicity.

21.4.4 Cultural practices

Cultural practices modify climatic effects within the grove, and thus have a significant effect on tree growth and development and consequently on fruit quality at harvest and postharvest.

Plant spacing

Tree spacing has a very significant effect on fruit quality, as it affects solar radiation received by the trees. Insufficient light within the orchard and the canopy will lead to lower photosynthetic efficiency of the leaves and, consequently, to lower carbohydrates available for tree and fruit growth and development. In addition, flowering requires light, and in citrus, many flowers are produced inside the canopy. Some varieties such as the 'Nour' Clementine tend to produce vegetative growth profusely in the spring. Fruits tend to be hidden by the leaves, slowing their growth and color development. Under these conditions, mature fruits have lower total soluble solids and lower eating quality. Therefore, planting spacing should be adequate for maximum light interception by the leaves and

maximum light penetration into the deeper layers of the canopy. The current trend worldwide is towards high-density plantings accompanied by changes in tree size and shape management through pruning to ensure maximum light penetration into the tree canopy and the efficacy of foliar treatments and of pest management practices.

Pruning

Control of tree size and shape is essential for optimum fruit production and quality. Maximum flowering and optimum fruit size and quality occur when the trees receive maximum sunlight. Maximum sunlight interception occurs when there is no excess crowding between trees and when light penetration within the tree canopy itself is optimum.

Pruning can also be used to regulate crop load from year to year, particularly for alternate bearing cultivars: such is the case for some varieties of mandarins and Clementines. When tree load is low ('off-year'), fruit peel texture, rind color and internal quality are poor (Tucker *et al.*, 1991). When the load is in excess ('on-year'), fruit tends to be small with thinner peel and matures earlier. Inside heavily shaded canopies, fruit has lower soluble solids than outer fruit exposed to sunlight. Shaded fruits have a greenish poor color and stay pale yellow when degreened. In fact, pruning after a light crop and before an expected heavy crop can increase fruit size and contribute to reducing alternate bearing. Pruning, which usually occurs in the winter and before spring flowering in most mandarins and Clementines, removes a certain number of shoots, reducing subsequent numbers of fruit and increasing fruit size and quality. In addition, pruning increases the number of shoots that will bear fruit the following year (expected to be a light crop year), thus increasing yield, avoiding production of large fruit of low quality and reducing alternate bearing. Pruning, topping and hedging have been reported to increase fruit size, improve fruit color and peel characteristics and the shelf life of fruit destined for the fresh market (Tucker *et al.*, 1991).

Girdling

Girdling used to be well implemented in citrus production in many countries around the world and for various objectives (Agustí, 2000). This practice causes interruption of phloem transport from the leaves to the roots which results in increased assimilate availability at the canopy which consequently increases fruit set, fruit size and final yield and fruit quality. However, repeated girdling has a negative long-term effect on tree vigor and longevity. Therefore, girdling is rarely practiced nowadays, as more friendly techniques such as use of growth regulators have been proven to be as efficient, particularly when the right regulator is used at the optimal concentration and physiological stage of the target organ (El-Otmani *et al.* 2000; El-Otmani, 2006).

Irrigation and tree water status

Irrigation and water availability in the root zone have a significant effect on fruit size and quality. Excessive water supply may disturb the physiology of the root

system, which in turn may reduce fruit quality. Stage III of fruit development (fruit maturation) is less sensitive to drought than stages I (fruit set and maximum cell division) and II (fruit growth and juice sac filling). Studying the effect of regulated deficit irrigation (RDI) on 'Nules' Clementine to economize additional water, Ginestar and Castel (1996) indicated that flowering and fruit set periods are the most sensitive periods to water deficit in relation to yield.

Rouse and Zekri (2006) reported that good irrigation increases juice content and total soluble solids:acid ratio; reduces soluble solids and acid content; increases fruit size and weight; increases green fruit at harvest but decreases rind thickness; increases incidence of blemish from wind scar, scab and *Alternaria* brown spot but reduces plugging; and reduces stem-end rot incidence. However, over-watering increases green mold in postharvest storage. It also increases fruit susceptibility to a peel disorder named 'oleocellosis' in degreened Clementines and mandarins due to high fruit turgidity, particularly if air humidity is also high and if fruit handling is rough. Supplying too much water to trees following a long period of drought may also cause fruit 'splitting' as a result of sudden increase in turgor pressure within the fruit pulp.

Application of water stress via controlled deficit irrigation was tested by the authors' group on Clementine mandarin and had no significant effect on fruit size when the deficit was applied in stage III of fruit growth. If the stress is prolonged and its intensity is great, fruit juice content may be lower. Kuriyama *et al.* (1981) reported that, for Satsuma mandarin, when soil moisture was kept high during fruit growth (July to September) and was lowered during fruit maturation (October to November), fruit maturation was accelerated, peel color developed quicker, fruit puffiness decreased, juice color was more intense and overall quality was better.

Fertilization and nutrition

Macro- and micro-nutrition of citrus trees has a significant effect on fruit quality and storage ability of citrus fruits, as reported by citrus nutrition pioneers such as Embleton *et al.* (1975) and Koo and Reese (1977). The effects of irrigation and nutrition on fruit quality are related and may be substantial since they are usually supplied to the tree at the same time. In general, excessive levels of both irrigation and nutrition reduce fruit quality. This negative effect is even worse in young trees with fruit having low sugars, low acid and thick coarse rind. Besides irrigation, nitrogen (N), phosphorus (P), potassium (K) and Magnesium (Mg) nutrition are the most important practices that influence fruit quality. Supply of nutrients will depend on the following factors among others: the variety/rootstock, tree age, tree density, expected yield, soil type and soil levels of available nutrients, seasonal conditions, desired final fruit size and expected time of harvest.

Because N is highly mobile in the soil and within the plant, and can be reduced by pruning, fallen leaves and the crop itself, deficiencies may well occur and have a significant detrimental effect on yield and fruit quality. In addition, excess N will also affect yield and fruit quality. Increasing N will increase juice content and color, total soluble solids and acid content. Conversely, it will decrease fruit size

(thus packout) and total yield, increase rind thickness and green fruit percentage at harvest. Excess N will also reduce the storage life of fruit, increase incidence of 'creasing' but decrease incidence of peel scarring, mite russeting and rind plugging. It will also reduce stem-end rot incidence and green mold in storage (Rouse and Zekri, 2006).

Increasing K supply beyond the minimum level required to maintain adequate yield and fruit size and quality may increase fruit size, but will increase juice acidity which will reduce the sugars/acid ratio, thus delaying maturity. It will increase the proportion of green fruit and peel thickness. It also reduces incidence of 'creasing' and the risk of fruit 'splitting'. In postharvest storage, it will reduce stem-end rot.

Phosphorous is less mobile in the soil and, therefore, loss of P by leaching is not a problem in most cases. P is rarely considered a problem in relation to fruit quality since P deficiency is rarely observed in the field. P deficiency symptoms include coarse and thick but well-colored rind, hollow cores, and high juice acidity. Increasing soil P will reduce fruit acid content, increase sugar:acid ratio, increase green fruit and wind scarring but decrease peel thickness.

Magnesium slightly increases total sugars and sugar:acid ratio. It also slightly increases fruit size but decreases peel thickness.

Management practices to improve fertilizer (mineral and organic) efficiency should include leaf, soil and water analyses to determine tree nutritional status, level of soil fertility, amount of nutrients supplied by irrigation water and tree production potential. Nutrient supply can be achieved not only through soil but also through foliar applications, particularly in situations where supply through the root system is inefficient such as in the winter when soil temperatures are low (El-Otmani *et al.*, 2001) or when the root system is damaged such as by nematodes or decayed by fungi.

Weed control

Weeds can compete with trees for water and nutrients, which may have a negative impact on fruit size and quality. Weeds may also serve as hosts for citrus pests such as mites and snails, and these pests may use the weeds as a bridge to go from soil to the tree where they cause damage on fruits and other organs. Clean cultivation will produce adequate fruit size and yield with blemish-free fruit, thus increasing pack-out.

Plant growth regulators and other field sprays

Plant growth regulators and pesticides are used in the field for various objectives with the final goal of enhancing yield and fruit quality in the field and postharvest. Pesticides are used to keep losses from damage to the crop or decay of fruits and any negative impact on fruit aesthetic quality within acceptable threshold limits. They can be used either pre- or postharvest. However, inadequate application of pesticides (over use, poor timing of application, inappropriate method of application, weather conditions during application, etc.) may cause phytotoxicity with fruit blemishes. In addition, pesticide residues at harvest may surpass

acceptable safety limits thus negatively impacting quality and acceptability of the fruit in the marketplace.

Plant growth substances are used at various phonological and physiological stages of tree growth to manipulate crop load, increase fruit size, enhance fruit quality or prolong fruit shelf life on the tree and/or postharvest. For maximum results, timing of application, dosage, type of formulation, spray solution composition and characteristics, climatic factors, and method of application are critical. Detailed information on these factors and on the main uses in the most important citrus producing countries has been summarized (see El-Otmani, 2006; El-Otmani *et al.*, 1995; El-Otmani *et al.*, 2000).

Auxins such as 2,4-D, 2,4-DP, 3,5,6-TPA are used to increase fruit size and to delay fruit calyx abscission (calyx is seen as a sign of freshness of harvested fruit and it protects the fruit from fungal invasion through the fruit stem end). Gibberellins are used to improve fruit set and promote seedless fruit in self-incompatible cultivars such as Clementine, seedlessness being an important trait for fruit destined for fresh consumption. Gibberellins and auxins are also used to store fruit on the tree. When fruit reaches maturity, it can be either harvested and stored in cold rooms if it has reached the legal minimum size (minimum size varies with the cultivar); alternatively, it can be stored on the tree using appropriate measures such as applying growth regulators such as gibberellins (GA_3), which delay fruit coloring and thus rind senescence, or an auxin-like substance such as 2,4-D which delays fruit abscission and thus preharvest fruit drop. Ethylene is also used postharvest to degreen mature fruit (see section 21.9.2 on degreening).

21.5 Postharvest handling factors affecting quality

About 75% of the total citrus fruit production in the world is destined for fresh consumption (USDA-FAS, 2010). Therefore, maintenance of good external appearance, without visible injuries or defects, and preservation of internal organoleptic and nutritional quality, are essential to provide high-quality citrus fruit for domestic and foreign markets. Throughout the whole postharvest chain, fruit are subjected to many environmental and handling factors that may influence their storage life and quality. Temperature and humidity are the two main factors affecting postharvest storage of citrus fruit, but other factors such as mechanical damage or atmospheric conditions may also have adverse effects and limit fruit postharvest life.

21.5.1 Temperature management

Proper temperature management is probably the most critical factor in reducing postharvest losses of citrus fruits and extending their postharvest life. Cold storage is the most efficient and widely used technique to preserve citrus fruit quality, extend the marketing season and provide continuity of market supply. Low temperature treatment is also a quarantine requirement for export to Japan and the USA.

Citrus fruit, as is the case for other crops from subtropical origin, is sensitive to chilling injury (CI) when stored at low non-freezing temperatures (Grierson, 1986). CI symptoms are usually manifested by pitting and darkening of the peel (see section 21.6.2), which reduces external quality and marketability of the product. The response of chilling-sensitive citrus fruit to low temperature is influenced significantly by pre-harvest climatic factors and growing conditions, which may modulate the timing and intensity of development of CI symptoms.

Susceptibility of fruits of different citrus species and varieties to CI is also determined by their genetic origin. Grapefruits and lemons are among the most susceptible fruits to CI, whereas mandarins and oranges are more resistant. Hybrids (tangelos, tangors and mandarin hybrids) display moderate susceptibility to CI, particularly cultivars with a genetic background including grapefruit (Grierson, 1986). Fruit of the same variety, and thus with the same genetic background, but grown and harvested in cooler countries, has a higher threshold of temperature tolerance than fruit harvested in humid and warmer climates. Marsh grapefruit harvested in Florida cannot be stored at temperatures lower than 10°C whereas those from Israel tolerate such temperature for prolonged periods without CI symptoms (Grierson and Ben-Yehoshua, 1986). In Mediterranean countries, Valencia late oranges are stored at around 4°C whereas tropical-grown fruit may develop CI at 10 to 12°C. There is therefore no single criterion to use to recommend an optimal storage and management temperature for the different citrus cultivars grown in very distinct areas.

Among the critical factors that affect fruit susceptibility to CI are the variety, seasonal conditions, pre-harvest treatments, the duration of storage, the effect of waxing or wrapping, pre-cooling and transport conditions. Storage temperature should be low enough, but just above the threshold of tolerance to CI induction, to reduce respiration, metabolic rate and water loss, and to inhibit decay (Grierson and Ben-Yehoshua, 1986). Table 21.5 summarizes the temperature and time recommended for successful refrigerated storage of some important Citrus species and varieties. Temperatures below those indicated or prolonged storage may result in CI.

Refrigerated transport is used in many citrus-growing countries not only for export but also for domestic markets. The efficacy of the refrigerated storage is improved by air-forced pre-cooling, which is becoming also a commercial practice in many citrus packinghouses. Recommended temperatures for loading and transport for a period of a week are 4 to 10°C for oranges and mandarins, 12 to 15°C for lemons and 14 to 15°C for grapefruits. It is important to maintain a high relative humidity (85 to 90%) in the truck during the whole transport period. To ensure successful refrigerated transport, it is important to adopt the following rules: minimize the time between fruit packing and pre-cooling, ensure that final fruit temperature storage is adequate for the variety, maintain the recommended temperature after pre-cooling, maintain adequate speed and the amount of cool air circulating in the back of the vehicle carrying the fruit or in the cold room used before and after transport.

Several countries such as the USA and Japan require strict quarantine security treatments against Mediterranean fruit fly (*Ceratitis capitata*) for importing citrus

Table 21.5 Recommended storage temperature and duration for fruit of selected citrus species and varieties

Species and varieties	Temperature (°C)	Duration (weeks)	Species and varieties	Temperature (°C)	Duration (weeks)
Limes	9–10	6–8	**Oranges**		
			Blanca	2–3	8–12
Lemon			Lanelate navel	2–3	8–12
Fino	12–14	10–12	Washington navel	2–3	8–12
Verna	12–14	12–16	Navelina	2–3	8–12
			Navelate	3–4	6–8
Mandarins and hybrids			Caracara	3–4	6–8
Nadorcott	4–5	4–6	Powell	4–5	4–6
Clemenules	4–5	6–8	Salustiana	2–3	8–12
Hernandina	4–5	4–6	Valencia late	2–3	10–14
Satsuma	2–4	4–6	Verna	2–3	10–14
Minneola tangelo	5–6	4–6	Midknight Valencia	4–5	6–8
Ortanique	5–6	4–6	Blood oranges	5–7	4–8
Fortune	9–10	2–4			
Nova	9–10	2–4	**Grapefruit**	12–14	6–10

fruit from other countries. For the USA, such treatments require exposure of fruit to 1.1, 1.6 or 2.2°C for 14, 16 or 18 days, respectively. Legislation for export to Japan demands a pulp temperature of 2°C for 16 days for lemons and 17 days for oranges and mandarins. These quarantine treatments may be applied before or during shipment. However, fruit of many citrus cultivars cannot withstand these quarantine requirements and thus different postharvest treatments to induce resistance to prolonged cold storage have been developed. These include:

- *Conditioning at moderate temperature*. Exposure of citrus fruit to moderate temperatures of 15 to 18°C for several days prior to cold storage has been long demonstrated to induce resistance to chilling in sensitive cultivars, such as Marsh grapefruit (Chalutz *et al.*, 1985), lemon (Aung *et al.*, 1998) or Fortune mandarin (Schirra and Mulas, 1995). These treatments are very effective under commercial conditions, in combination with other postharvest treatments, and have been adopted for export of grapefruit from Florida to Japan. Conditioning grapefruit for 7 days at 15°C has been shown to ensure a good quality fruit during quarantine cold treatment with very low peel disorder and decay incidence (Ismail *et al.*, 1986; Wardowski and Brown, 1993). Similar treatments have also been successful in shipment of lemons (16°C for seven days) and oranges (16°C for three to four days) from Mediterranean countries to Japan.
- *Curing and hot water dips*. These treatments are based on the application of higher temperatures for reduced periods of time. Hot humid air or curing is very effective in inducing chilling tolerance and decay resistance (Lurie, 1998; 2006). Exposure of citrus fruit to humid air at 30 to 37°C for one to three days

is very effective for fruit of many citrus cultivars (Schirra *et al.*, 2000a; McDonald *et al.*, 1993; Martínez-Téllez and Lafuente, 1997). Under these conditions, it is very important to maintain a high relative humidity during the curing period, as a high rate of water loss may be detrimental to fruit quality. An enhanced loss of acidity may occur and may also have a deleterious effect on fruit taste. Despite the effectiveness of curing in protecting fruits from CI, commercial application has been difficult to implement. Hot water dips are alternative heat treatments and are highly efficient in the induction of heat tolerance and resistance to decay (Wild and Hood, 1989; Rodov *et al.*, 1995; Schirra and D'Hallewin, 1997). These treatments involve shorter exposure (a few minutes) to high temperatures (45 to 53°C) and are much more feasible commercially. In addition, hot water dips are also convenient for application of fungicides and other chemicals. However, some studies have shown that such elevated temperatures may cause heat damage in the peel of fruit of several cultivars (Lafuente *et al.*, 2005). An alternative hot water dip treatment has been developed in Israel to deal with this problem referred to as 'hot brush washing'. In this treatment, fruit are brushed for few seconds in water at 60°C, inducing a high tolerance to decay and to CI (Porat *et al.*, 2000). Experimental evidences indicate that the biochemical and molecular mechanisms induced by curing and hot water dips are different (Sapitnitskaya *et al.*, 2006; Maul *et al.*, 2008).

- *Intermittent warming*. These treatments are based on warming the fruit to moderate temperatures during cold storage. Warning (at 20°C) may be done once a week for around 16 to 20 h for sensitive fruits such as grapefruits or 5 h for mandarins. Variations of these treatments include warming for a few days at 15°C after a few weeks of storage at 1 to 3°C. Intermittent warning has been applied in Israel but its practical application on a large scale is very limited (Schirra and Cohen, 1999; Cohen, 1999).
- *High CO_2 atmosphere*. Storing citrus fruits in high CO_2 concentrations may reduce CI. The response is variable, probably depending on the ripening stage of the fruit, thus making the reliability of the treatment doubtful. One problem with such treatments is the limited tolerance of citrus fruit to elevated CO_2 concentrations (3% for oranges and mandarins, and 5% for lemons and grapefruits) as these levels may generate off-flavors and have other detrimental effects on fruit quality.
- *Waxing and coating*. Waxing has been demonstrated to reduce CI and the effect is likely to be related to altered gas concentration. Waxes (such as shellac) restricting gas exchange are more effective in reducing CI than more permeable waxes (such as carnauba). Polyethylene-based waxes are also effective in reducing CI in less sensitive fruit, as a result of restricted water loss and transpiration. A disadvantage of waxing is the build-up of ethanol and acetaldehyde and the generation of off-flavors. Individual film wrapping is an efficient alternative for controlling CI. The effect of wrapping on CI is similar to that of waxing but it has advantages related to its permeability characteristics to gas (Miller *et al.*, 1987, Purvis, 1985a; Cohen *et al.*, 1990; McDonald *et al.*, 1993; Baldwin *et al.*, 1995).

- *Fungicides*. Fungicides such as Imazalil and TBZ have been shown to reduce CI in fruits of many citrus species susceptible to CI (Schiffman-Nadel *et al.*, 1975, McDonald *et al.*, 1991; Schirra *et al.*, 2000a). This effect may be increased if the fungicide treatment is carried out together with immersion in hot water, which allows a reduction in the fungicide concentration required.
- *Squalene*. Based on the observation of Nordby and McDonald (1990) that squalene increased during maturation of grapefruit, it has been reported that application of squalene protects grapefruit from CI. The protective effect of squalene in other citrus fruits and their mode of action is still to be determined.

21.5.2 Preventing water loss

Water loss is one of the most important postharvest factors affecting fruit quality. Following harvest, fruit is separated from the plant, which is the source of water and nutrients. As a result, the water lost by harvested fruit *via* transpiration cannot be replaced. Water loss is the main cause of fruit weight loss and this may generate important economic losses, promote shrivelling and loss of shine (Fig. 21.1a), softening and spoilage, and accelerate fruit senescence. Mandarin fruit lose water more rapidly than oranges and grapefruit.

Water loss as low as 2% causes a decrease in fruit respiration with an increase in internal CO_2 concentration. Water loss of 5% results in a significant decrease in the commercial appearance of the fruit (Grierson and Ben-Yehoshua, 1986). Good postharvest water loss management should not only prevent water loss but also prevent water condensation on the fruit surface, since this will be an ideal medium for development of postharvest-related decay organisms.

In citrus fruit, water is mostly lost by the flavedo rather than by the pulp. Under controlled postharvest conditions, the rate of water loss is about five to six times higher in the flavedo than in the pulp, and most of the weight loss is due to water withdrawal from the peel (Ben-Yehoshua, 1969). Fruits are covered by a layer of natural epicuticular waxes that are the first external barrier to water exchange. These deposits of waxes are not uniformly distributed on the fruit surface and some areas have reduced wax deposits and low stomata. These features may explain the manifestation of fruit disorders in specific areas of the fruit, such as stem-end rind breakdown in Valencia late oranges (Albrigo, 1972). Cuticle thickness appears to play a more limited role in control of transpiration compared to its chemical composition and structure (Ben-Yehoshua, 1987).

The rate of water loss during storage is not uniform, being higher during the first few days after harvest than during the rest of the storage period. To control excessive loss of water during postharvest storage, relative air humidity should be maintained as high as possible. However, different studies have demonstrated that vapour pressure deficit (VPD) between fruit peel and the environment is more directly related to water loss than relative humidity. In a classic study Wells (1962) found that weight loss in lemons, oranges, and grapefruit increased 50% with a two-fold increase in VPD.

Resistance of peel tissue to diffusion of water and other gases (CO_2, O_2 and ethylene) varies with fruit type. Citrus fruit has a high density of stomata on the peel (around 1,400/cm^2) but with a limited gas exchange, probably due to the deposits of large wax plugs in the stomata. Water vapour transport is very rapid, and presumably occurs through a water-phase route across cell walls. Gases like CO_2, O_2 and ethylene have a very similar resistance coefficient and are likely to be diffused through an air-phase in the cuticle (Ben-Yehoshua *et al.*, 1985). This model of water movement envisages that evaporation of water from the cuticle surface would create suction force drawing water from the inner tissues.

Measurements of water and turgor potential in grapefruit stored under low and high relative humidity corroborate this model, indicating that the longer the water stress, the higher the decrease in water potential of the inner albedo. Rehydration of water stressed fruit produces a recovery of potential that is restricted in waxed fruit, which develop a higher incidence of rind staining in navel oranges and Marsh grapefruit for example (Alferez *et al.*, 2010; Alquezar *et al.*, 2010). Increase in ethylene by water stress is a primary response of citrus fruit to this situation. Rehydrating fruits previously dehydrated under low relative humidity by storing them in high relative humidity induces a marked stimulation of ethylene production that appears to be related to the changes in peel turgor and to the damage provoked in albedo cells (Alferez *et al.*, 2003). An increase in abscissic acid (ABA) in response to water stress is a well-documented phenomenon in citrus fruits, which also involves activation of ABA-biosynthetic genes (Rodrigo *et al.*, 2006). The relationships between these two hormones in the adaptation of citrus fruits to water stress are complex. Results indicate that water stress is related to the development of peel pitting in navel oranges (Alferez *et al.*, 2005).

The first postharvest procedure to prevent water loss is an adequate control of relative humidity during the whole handling, storage and transport process. In addition to careful handling, fruit should be processed immediately after harvest to avoid excessive exposure to ambient temperature. In cold rooms, air movement around the fruit should be minimized to avoid transpiration but ambient relative humidity should be as high as possible.

Waxing has been the standard procedure for many years to reduce water loss in citrus fruits. Waxing reduces respiration and transpiration and gives the fruit a shiny look. Postharvest waxing is necessary for several reasons: a) replacement of natural waxes lost during transport and washing, b) reduction of decay, c) improvement of external appearance of the fruit (Fig. 21.1a), d) sealing minor injuries and blemishes (so that they do not develop further) and e) application of fungicides in waxing mixtures. The technology of waxing and the mode of action of the different chemicals and wax formulations commercially available in different countries have been studied extensively (see review by Petraceck *et al.*, 1999). Wax formulations must be a compromise between allowing desirable gas exchange but restricting water transpiration. Thickness is a critical factor, since too thick a coating would cause anaerobic respiration, increased CO_2 and reduced O_2 concentrations within the fruit, thus generating off-flavors. In contrast, too thin coatings will not be effective.

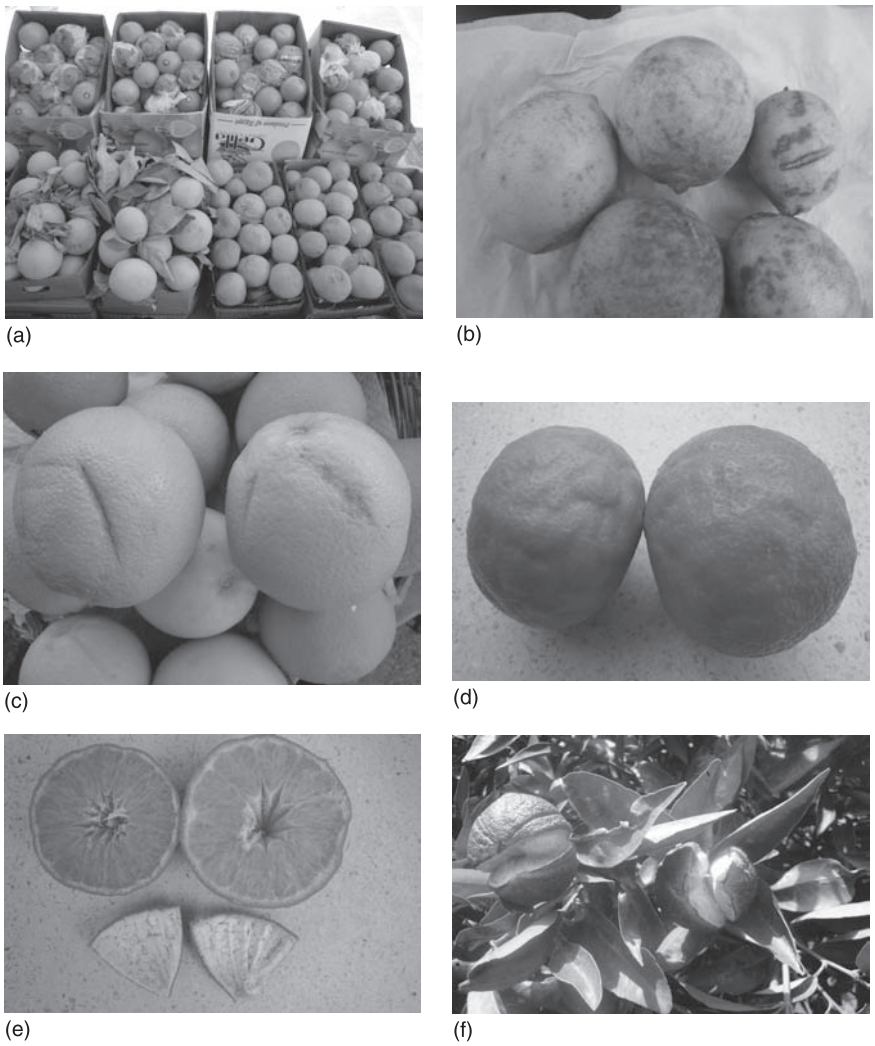

Fig. 21.1 Fruit with rind blemishes and disorders: (a) Displayed fruit with shriveled peel and loss of shine [front row of packages: Valencia (left packages) and Fairchild mandarin (right packages)] as they received no postharvest treatment including waxing, and Washington navel fruit with shine and freshness (back row of packages) as they were waxed in a packinghouse and packed in a shipping box; (b) Lemon fruit immersed for 10 minutes in a 2 g/liter aqueous solution of 2,3,4-triphenyl tetrazolium chloride showing scars from fruit rubbing against tree thorns (upper right fruit) and damage from mites (surface of all fruit); (c) Fruit of Washington navel with damage from picking boxes as a result of box overfilling; (d): Nova mandarin fruit with creasing symptoms; (e) Nova fruit with creasing: see cracks in the albedo; (f) fruit of Nova mandarin with splitting.

Wax application in the packing-line should be carried out on surface-dried fruit to ensure an efficient coating, making it important to dry the fruit before coating (Ben-Yehoshua, 1987). Spraying the wax onto fruits is currently the most common method of waxing, after which the fruit are passed throughout an air-drier with a temperature of around 60°C. The most commonly used waxes are emulsion waxes, which contain wax in soap or detergent. In emulsion-based water waxes, the wax is melted and emulsified, and boiling water is added. The most common components are polyethylene (with greater resistance to water vapour diffusion but less effect on gas permeability), shellac (which provides shine on the fruit surface and is more resistant to gas diffusion), carnauba (from leaves of the Brazilian tree *Copernica cerifere*), sugarcane wax, bee wax and wood resin. Combinations of paraffin and polyethylene wax and carnauba wax are also used. Paraffin wax offers good control of water loss while carnauba provides shine. Water-type waxes often have the following combination: polyethylene (4%), paraffin (2%), shellac (4%) and colophony or wood resin (4%).

Other packaging systems such as seal-packaging have also been developed, providing efficient control of water transpiration and shrivelling. These packaging systems create a water-saturated atmosphere around the fruit, alleviating water stress and delaying softening and fruit deterioration. The beneficial effects of micro-perforated polyethylene films have been related to the prevention of water stress rather than to the modification of internal concentration of CO_2 and O_2 (Ben-Yehoshua *et al.*, 1983).

21.5.3 Preventing physical damage

Physical or mechanical damage consists of wounds and injuries caused to the fruit by physical factors. The peel of citrus fruits is quite soft, especially for mature and over-mature fruits. It is very susceptible to injury and damage by external agents. Peel damage can occur before harvest to fruits on the tree by scratching and rubbing of fruit against stems, branches and thorns and by birds and insect pests. Affected areas can be detected by dipping fruit for ten to 30 minutes in an aqueous solution of 2,3,4-triphenyl tetrazolium at 1 to 2 g/liter (Fig. 21.1b). However, handling procedures during harvest, transport and packinghouse operations are the main causes of physical damage in citrus fruits (Fig. 21.1c). Fruits of different species and varieties have different anatomical and structural resistance to mechanical damage. Grapefruit or oranges with thick peel and a large albedo layer may resist impact better than fruit with thinner peel. Mandarin fruit, with a much reduced albedo layer, are prone to develop 'creasing' and 'puffing' and are among the most sensitive cultivars to mechanical damage by improper handling practices.

The major effect of mechanical damage on the postharvest losses is not the damage itself. Injuries are the principal site for infection by wound-invading pathogens such as *Penicillium, Diplodia* and other fungi. Bruising, plugging, stem-end tears, scratching and pitting of fruit are common injuries observed in fruits collected from pallet and packinghouse bins and are the result of improper harvesting and handling operations (Grierson and Ben-Yehoshua, 1986). Careful

pre- and postharvest handling is the best way to reduce mechanical damage in citrus fruit, although it is time-consuming and requires high labor costs (Grierson and Ben-Yehoshua, 1986). Mechanical harvesting produces a much high proportion of damaged fruits than manual harvest. Currently, mechanical harvesting is only used at a very limited scale but mainly on fruit for processing where its impact on fruit quality is of less importance.

The wounding of harvested citrus fruit tissues causes important metabolic changes that appear to activate defence responses to protect fruit against infection by pathogenic agents and to cause wound healing. One of the first responses of citrus fruit to wounding is an increase in ethylene production (Hyodo and Nishino, 1981; Lafuente *et al.*, 2001). Different stresses activate ethylene biosynthesis that in turn stimulates other metabolic pathways related to defence responses (Stepanova and Alonso, 2009). Genes from ethylene biosynthetic enzymes (ACC synthase and ACC oxidase) have been isolated and characterized (Mullis *et al.*, 1999; Katz *et al.*, 2004). These genes are induced by wounding and by *Penicillium* infection and published results indicate that ethylene production mediates the response of citrus fruits to these stress conditions (Marcos *et al.*, 2005). Previous studies have reported that wounded fruits stored at 25 to 29°C under high relative humidity accumulate lignin and colored phenolics (Ismail and Brown, 1975). Phenols and lignin-like compounds accumulating in the flavedo act as a biochemical barrier that protects fruit from fungal attack. These compounds may be toxic to the fungus and are also involved in sealing the wound and, thus, in preventing fungal colonization of the wound. Wounding activates the expression of phenyl-alanine ammonia lyase (PAL) and increases its activity (Lafuente *et al.*, 2001). PAL is the first enzyme and the entry point of phenylpropanoid metabolism, which, among others, is responsible for the synthesis of lignin metabolic precursors. It is noteworthy that heat conditioning stimulates wound healing and increases lignin and gum deposition (Mulas *et al.*, 1996; Schirra *et al.*, 2000a). New molecular techniques have revealed that heat conditioning activates the expression of a cascade of phenylpropanoid biosynthetic genes that are likely related to the healing process (Sanchez-Ballesta *et al.*, 2003). Interestingly, some of these genes are also stimulated by ethylene (Establés-Ortiz *et al.*, 2009) suggesting that the increase in wound-induced ethylene may be a mediator of the fruit's response, inducing production of biochemical barriers for wound healing and prevention of pathogenic infection.

21.5.4 Storage atmospheric conditions

Several gases play a role in storage of fresh citrus fruits. These include ethylene, O_2, CO_2, ozone and ethylene. The effect of ethylene is discussed in sections below. These gases can be used in controlled atmosphere (CA) storage systems to maintain fruit quality and increase shelf life.

Changes in the concentration of atmospheric O_2 and CO_2 can be used to supplement refrigerated storage, which, for many fruits and vegetables, provides an excellent way to extend their shelf life and quality (Kader, 2002). Early research

indicated that high CO_2 concentration delayed peel degreening and extended the storage life of lemon and lime, and reduced CI in grapefruit (Hatton *et al.*, 1975). However, more recent results suggest that citrus fruits are more difficult to store in CA, except acid citrus types where maintenance of green color and delay of senescence are feasible objectives.

The main limitations for the use of CA storage are the stimulation of anaerobic respiration and physiological stress leading to development of off-flavors. In Valencia late oranges, high CO_2 concentrations at 5°C induced severe damage and peel browning and increased ethanol and acetaldehyde in the pulp. Low levels of O_2 reduced respiration, but after transfer to a normal air atmosphere, respiration increased again in parallel with a build-up in ethanol (Ke and Kader, 1990). Oranges can tolerate up to 5 to 10% O_2 in combination with 0 to 5% CO_2, which results in delay of senescence and retainment of firmness (Ke and Kader, 1990). Mandarin fruits are sensitive to high CO_2 concentrations and recommended levels for Satsuma mandarin are 8 to 12% O_2 and 0 to 2% CO_2 (Ladaniya, 2008). In Clemenules and Murcott mandarin it has been shown that reduced O_2 concentrations (1 to 5%) at 5°C did not improve the keeping quality of the fruit but rather increased ethanol and acetaldehyde levels in the pulp (Luengwilai *et al.*, 2007). Grapefruits are more tolerant to CA. Oxygen concentrations of 3 to 10% and CO_2 concentrations of 5 to 10% delayed senescence and maintained firmness of grapefruits kept at 13 to 15°C (Ladaniya, 2008). It is interesting to note that the ability of mandarin fruit to accumulate larger amounts of ethanol and acetaldehyde in the internal atmosphere compared to grapefruit is related to major aldehyde dehydrogenase activity and to a more impermeable cuticle to gas diffusion (Shi *et al.*, 2007). In general, it can be concluded that, in many cases, CA does not provide substantial beneficial effects on the storage of citrus fruits, which are sensitive to development of off-flavors at high CO_2 concentrations. Concentrations of CO_2 with a fungistatic effect (>10%) also generate off-flavors. As a result, the commercial use of CA storage in citrus fruit is very limited (Yahia, 2009).

Ozone gas is one of the strongest oxidizing agents for sanitizing and disinfection. Its use in postharvest handling of fruits and vegetables has long been studied. It can be used as an alternative to hypochlorite for sanitizing and disinfecting water tanks, which are one of the most important sites for pathogen accumulation and contamination in packinghouses. One important advantage of ozone in water is that it decomposes quickly to oxygen, leaving no residues. Ozone is very effective in the control of fungal spore germination, bacteria, protozoa, and viruses, as these may be killed at relatively low ozone concentrations (1.5 μg/ml). After two minutes' exposure to ozone in water, more than 95% of the spores of the typical citrus-infecting fungi are killed. The ability of ozone in the air to react with ethylene may also be beneficial in reducing ethylene levels during storage. Ozone treatment did not alter quality parameters in navel and Valencia oranges or Fortune and Ortanique mandarins during storage at 5°C, but the development of 'oleocellosis' symptoms was reported (Garcia et al., 2000). However, ozonated water has been shown to be inefficient in reducing decay once

pathogens have penetrated and invaded fruit tissue through wounds, even at very high ozone concentrations (120 ppm for five minutes, for example). The inability of ozone in water to control the infection in citrus fruit is similar to other sanitizers (i.e. hypochlorite and chlorine dioxide). Exposure of citrus fruit to ozone in air retarded fungal spore production, but after ozone removal, spore production was restored.

One practical problem with ozone fumigation in the packing house is its poor penetration inside the packages through the open vents of the box, making it difficult to reach the deeper fruit layers inside packages to control sporulation (Palou *et al.*, 2003). In general, despite the fact that ozone treatments may provide some benefit in postharvest handling and storage of citrus fruits, practical use of this technique in commercial packinghouses is limited. Ozone in the air or in water must be generated on-site. The presence of organic compounds (from the fruit or debris) in the water tank can react with ozone and cause its concentration to plummet, making it difficult to maintain the required concentration in the water tank. Moreover, ozone solubility in water is low, and above 1 ppm ozone gas can be liberated into the air and cause a potential safety hazard. Because of its strong oxidizing potential, ozone can be toxic to humans. Exposure to harmful concentrations is dangerous and requires special equipment (Smilanick, 2003). Finally, ozone is a potent oxidizer of organic compounds and can reduce the concentration of typical citrus fungicides in water tanks, in one study by more than 95% for imazalil, TBZ and orthophenylphenate after 30 minutes (Palou *et al.*, 2001a).

21.6 Physiological disorders

21.6.1 Preharvest disorders

The most important preharvest physiological disorders that can reduce the external quality of citrus fruit are creasing, puffing, splitting, granulation and rind scars. The causes of these disorders are diverse and can be related to climatic conditions during fruit growth and maturation, soil quality, plant mineral status, rootstock, variety, irrigation, etc.

Creasing is reported to be common in different citrus varieties produced all over the world like Australia (Treeby *et al.*, 1995), California (Jones *et al.*, 1976) and South Africa (Holtzhausen, 1981). From year to year, depending on the orchard, rootstock and period of harvest, the percentage of fruit presenting creasing disorder can be more than 50% (Gilfillan *et al.*, 1980; Ait-Oubahou *et al.*, 2008). Creasing is more apparent in mature to overmature fruit. Affected fruit show an irregular skin structure with pronounced deformation and cracks first in the albedo followed by separation of parts of the flavedo (Fig. 21.1d). The main factors affecting the development of creasing include the variety itself, the rootstock climate conditions during the production season, nutritional status especially potassium deficiency during cell division, fruit skin thickness and irrigation scheduling (Boyer 2004; Treeby *et al.*, 1995 and 2000). Fruit with very thick peel show less creasing than those with a thinner skin. If fruit of sensitive varieties are stored on the tree, they

may totally be lost due to creasing development. To reduce its occurrence on sensitive varieties, spraying trees with calcium and gibberellic acid in late summer has shown good results in reducing the extent and severity of the disorder on fruit (Ait-Oubahou *et al.*, 2008; Treeby and Storey, 2000).

Puffing is often observed in mature Clementine mandarin fruit following heavy rain or irrigation after a long period of drought. The disorder is characterized by the separation of the peel from the pulp. This separation is caused in part by the continuous growth of the peel while growth of the pulp has stopped. 'Puff' fruit is fragile and easily bruised during postharvest handling. Spraying trees with 10 ppm of GA_3 before fruit color break reduces the occurrence of puffing in Satsuma mandarin (Agustí *et al.*, 1981). The reduction is even greater when GA_3 is combined with 1.8% of ammonium nitrate. The application of 2,4-DP (a synthetic auxin) during cell enlargement has led to a reduction of the disorder by over 80% (Agustí *et al.*, 1994).

Splitting is frequent in oranges and mandarins in all producing countries. Nova mandarin (Fig. 21.1e), navel orange and tangelos are more sensitive than other varieties. Splitting can be seen in early July in the Northern Hemisphere and increases until early September. The exact causes of the disorder are not well understood. Factors such as the age of the tree and drought stress, caused by high temperatures in the summer followed by excessive irrigation or heavy rains, have been related to the appearance of the disorder on sensitive varieties. Fruit that takes in too much water, resulting in swelling and a loss of skin elasticity, tends to split more easily than fruit from orchard that is irrigated continuously and regularly (Zekri and Rouse, 2002). The thickness of the fruit affects the extent of the problem. Fruit with thin rind due to low potassium content can split easily (Sauls, 1995). Application of a mixture of GA_3 and 2,4-DP using one or two applications has led to a significant reduction in splitting (Almela *et al.*, 1994).

Granulation can be a serious phenomenon that affects the quality of citrus fruit even if their appearance looks good. Fruit loses its juice content and the juice cells become dry and lignified. Several varieties including Nules Clementine, Nova mandarin, sweet oranges and lemon are prone to this disorder. At the moment the causes are not fully known. However, the work of Spanish scientists (Agustí *et al.*, 2004) has demonstrated that several factors such as tree age, climatic conditions during fruit growth, fruit position on the tree, rootstock and late harvesting tend to increase the percent of fruit with granulation. They have demonstrated that sweet orange 'Lane late' grafted on vigorous rootstocks such as *Citrus volkameriana* tended to produce fruit with severe granulation in comparison to 'Carrizo' citrange, 'Cleopatra' mandarin and Citrumelo.

Scars and *blemishes* affect the external quality of fruit. The main cause of skin damage at early stages of fruit development can be attributed to rubbing against leaves, thorns and branches during windy periods. The use of windbreaks reduces the phenomenon that in some varieties such as sweet oranges and mandarins can affect over 30% of the production in windy areas. Scars and blemishes can also be caused by mites and insects. Affected areas can be detected by dipping fruit in an aqueous solution of 2,3,4-triphenyl tetrazolium at 1 to 2 g/liter (Fig. 21.1b).

Regreening is a physiological disorder occurring on late varieties such as as Valencia orange where maturation occurs in high temperature conditions. Fruit peel regreens during the spring months when temperatures rise higher than 30 to 32°C for a significant period of time. Chlorophyll synthesis and transformation of chromoplasts to chloroplasts are stimulated. The disorder can be treated by nitrogen fertilizer and vigorous rootstocks.

21.6.2 Postharvest disorders

Citrus fruits are prone to developing various physiological peel disorders which are manifested by a myriad of morphological symptoms during postharvest handling, storage or commercial retailing. More than 70 different physiological disorders or peel blemishes have been described in fruits of multiple varieties and species of citrus and, as a result, their classification is difficult (Grierson, 1986; Lafuente and Zacarías, 2006). Many physiological disorders on fruit outer tissues are manifested by injuries, darkening of cells and browning resulting from rupture of oil glands and release of their oil content on adjacent cells. However, the causes of these blemishes may differ and their identification and correct diagnosis can be complicated. How fruit peel tissues, with a complex anatomy consisting of large oil glands surrounded by epidermal and flavedo cells and inner albedo, respond to different environmental stresses is still largely unknown, and is the key issue for the development of successful methods of control. In general, postharvest physiological disorders may be classified in two categories: a) chilling injury, a major postharvest disorder affecting fruits of many cultivars, and b) non-chilling peel disorders, a series of different blemishes induced by several factors. The following is a description of most relevant postharvest disorders, their causes and methods of control.

Citrus fruits, like many other subtropical species, are sensitive to *chilling injury* (CI) when exposed to low non-freezing temperatures. The critical temperature at which CI develops varies among species and varieties, but can be modulated by growing conditions. In general, oranges and mandarins are more resistant to CI than lemons, grapefruits and limes (Table 21.5). CI symptoms usually develop as pits and depressions on the fruit surface tissues that darken with time, forming sunken brown-collapsed areas (Plate XXXVIIIe, XXXVIIIg: see colour section between pages 244 and 245). The characteristic darkening of most chilling-injured fruit is most likely due to an internal release and oxidation of the content of oil glands. In CI fruits, oil glands remain intact in contrast to fruit with 'oleocellosis' where the glands are broken and release their content on the fruit surface. An inner darkening of the oil glands without pits or depressions is also a symptom of CI in early harvested Clementine mandarins. In fruit of other less-sensitive cultivars, like oranges, CI is manifested as non-depressed superficial scald on the flavedo (Alferez *et al.,* 2005). In lemon fruits, CI is also manifested as an albedo darkening or as browning of the capillary membranes (Grierson, 1986). Symptoms of CI are usually manifested during chilled storage, but exacerbated after fruit have been brought to room temperature. CI fruit are also more sensitive to decay than non-chilled fruits.

The critical threshold temperature for storage of citrus fruits to avoid CI varies greatly among varieties: 10 to 12°C for grapefruit and lemon, 9 to 10°C for mandarin hybrids that are sensitive to CI (i.e. Fortune, Nova), 5 to 6°C for mandarin hybrids and tangelos, 3 to 4°C for Clementine and Satsuma mandarins, and 2 to 4°C for oranges (Ladaniya, 2008). It appears that sensitivity to developing CI is a genetic feature of fruit of each specific variety. However, environmental factors may modulate the response of the fruit to CI. For example, grapefruit grown in Florida are more susceptible to CI early and later in the season, whereas those harvested at mid-season are more resistant (Purvis *et al.*, 1979). Under Mediterranean conditions, mid-season Fortune mandarins are much more susceptible to CI than early- and late-harvested fruit. Climatic conditions and a prolonged period at low temperature in the field may influence subsequent sensitivity of citrus fruit to developing CI under postharvest cold storage (Gonzalez-Aguilar *et al.*, 2000).

Initial observations on the physiological and molecular bases underlying the response of citrus fruit to CI indicated that CI altered lipid composition and membrane fluidity in grapefruits (Nordby *et al.*, 1987). Changes in the insaturation of lipids were not correlated with the sensitivity/resistance of Fortune mandarin to CI (Mulas *et al.*, 1996). However, molecular studies have revealed that CI activates the expression of genes related to membrane lipid and sterol metabolism, indicating that lipid metabolism plays a key role in the response to chilling. Cold stress also stimulates the expression of genes related to carbohydrate metabolism, stress stimuli, hormone biosynthesis, transcription factors and DNA binding (Sapitnitskaya *et al.*, 2006). Chilling also repressed the expression of genes of cellular metabolism, cell wall formation, pathogen defence, photosynthesis, respiration, and protein, nucleic acid and secondary metabolism. Together, published information indicate that CI induces a general rearrangement of cellular metabolism, causing protective responses to cope with cold stress. Treatments inducing chilling tolerance may also activate different metabolic pathways such as genes related to stress in response to hot-water treatment, whereas curing mainly activates the expression of lipid-membrane modifying enzymes (Sapitnitskaya *et al.*, 2006). Induction of cold tolerance in the peel of citrus fruits stimulates different metabolic pathways by inducing protective responses and also arresting some chilling-induced mechanisms (Sanchez-Ballesta *et al.*, 2003; Sapitnitskaya *et al.*, 2006).

Oxidative stress may also be involved in chilling-induced damage in citrus fruits (Purvis, 1985b). Genetic tolerance of mandarin fruit to CI and also heat-induced tolerance in sensitive mandarin fruit are associated with an enhanced activity of enzymes of the antioxidant system (Sala 1998; Sala and Lafuente, 1999). In addition, an inhibition of catalase activity abolished the tolerance to cold induced by curing (Sala and Lafuente, 2000). Thus, oxidative stress appears to be a primary mechanism of the damage induced by exposure of citrus fruit to cold temperatures, with the participation of catalase as an essential enzyme in the detoxification process leading to cold tolerance (Sala and Lafuente, 2000). CI also implies the participation of PAL and phenylpropanoid metabolism. PAL may

protect flavedo cells against chilling stress and it is induced by ethylene dependent and independent signals (Lafuente *et al.*, 2001; Sanchez-Ballesta, *et al.*, 2000, 2003). One of the common responses of citrus fruit to chilling is the increase of ethylene production (McCollum and McDonald, 1991). Chilling stimulated the expression of ethylene biosynthetic genes in chilled Fortune mandarin fruit, which were preferentially accumulated in the chilling-damaged tissue (Zacarías *et al.*, 2003). Interestingly, application of exogenous ethylene during exposure to chilling reduced symptoms of CI in Fortune mandarin. On the other hand, a previous treatment with 1-MCP, the competitive inhibitor of ethylene action, before storage at 1°C accelerated CI (Lafuente *et al.*, 2001). Therefore, it may be concluded that ethylene is part of the defence responses of Fortune fruit to cope with cold stress, and the naturally low levels of ethylene evolving from the fruit are required to maintain fruit performance during postharvest life (Porat *et al.*, 1999).

Rind staining or *rind breakdown* are terms used for a range of postharvest physiological disorders that may not be related with each other (Plate XXXVIIIa, XXXVIIIb: see colour section between pages 244 and 245). Postharvest peel *pitting* is also used to refer to a fruit disorder occurring at non-chilling temperature that can be seen as collapsed and dried depressions in the fruit rind that may progressively become brown and darken. These disorders have been reported in different countries worldwide affecting fruits of Marsh grapefruit, navel oranges, Fallglo mandarins and Shamouti oranges (Lafuente and Zacarías, 2006). In Clementine mandarins grown in South Africa, a different physiological disorder has been described and was also referred to as rind breakdown (Van Rensburg *et al.*, 2004). This blemish is characterized as a collapse of the oil glands randomly distributed as round spots over the surface of the fruit.

Typical peel pitting in grapefruit and Fallglo mandarins develops as clusters of collapsed oil glands that may expand to form scattered areas of collapsed tissue. In Florida grapefruit, the disorder is initiated in wax-coated fruit within the first week of storage. Earlier studies suggested that alterations of internal gas concentrations by less permeable shellac-based waxes were the cause of pitting (Petracek *et al.*, 1995, 1998). In Shamouti oranges, however, modified atmosphere packaging, which also altered internal gas concentration, reduced incidence of the damage (Porat *et al.*, 2004). Cumulative evidences indicate that alterations in peel water status are a critical factor in the incidence of rind staining. Fluctuations in air relative humidity during storage at non-chilling temperatures and, thus, sudden changes in VPD between fruit and the environment have been demonstrated to cause rind staining in navel oranges (Alferez *et al.*, 2003), Marsh grapefruit (Alferez and Burns, 2004) and Fallglo tangerine (Alferez *et al.*, 2005). The disorder was induced in non-waxed fruits, suggesting that waxing itself did not promote peel pitting unless previous dehydration had occurred (Alferez and Burns, 2004; Alferez *et al.,* 2005). It is likely that waxing dehydrated fruit impaired normal water exchange and altered the turgor potential of both flavedo and albedo, and may create a suction force from the dehydrated albedo that would cause collapse of external epidermal cells (Alferez *et al.* 2010). The more severe

the dehydration of fruit, either in the field or after harvest but before storage at high relative humidity, the more prone is the fruit to developing postharvest rind staining. A dehydration threshold of around 3% has been proposed in grapefruit and tangelo fruit, after which staining may develop if the fruit is then transferred to a high relative humidity environment (Alferez *et al.*, 2005).

Successful control of peel pitting in fruits of susceptible cultivars is difficult, as preharvest conditions affect peel water status and dehydration and the rootstock greatly influences subsequent susceptibility to development of postharvest pitting (Agustí *et al.*, 2003). Transfer of dehydrated fruits to a more humid environment was shown to increase respiration rate and ethylene production, probably as a result of the damage and injuries done to flavedo and albedo cells (Alquezar *et al.*, 2010). Lipid metabolism plays a critical role in the development of the disorder. In fact, Alferez *et al.* (2008) showed increased phospholipase activity and enhanced expression of several phospholipase genes in affected grapefruit and, interestingly, inhibitors of phospholipase A2 reduced peel-pitting symptoms.

In addition, ethylene is also reported to reduce and 1-MCP to enhance postharvest peel pitting in navel oranges (Lafuente and Sala, 2002). This protective response of ethylene stimulates a defence response in the fruit such as the antioxidant enzymatic system (Sala and Lafuente, 2004) and phenolic metabolism (Cajuste and Lafuente, 2007).

Rind breakdown in Clementine mandarins (Plate XXXVIIId: see colour section between pages 244 and 245) is a postharvest problem for South African fruits. This disorder is particularly important for Nules mandarin compared to other varieties and develops three to four weeks after storage (Van Rensburg *et al.*, 2004). Pre-harvest factors appear to be responsible for the disorder, and incidence is higher in less-colored fruits and also in fruit with lower potassium content. Postharvest factors such as ethylene and high storage temperature aggravated incidence of the disorder (Cronje, 2007).

Oleocellosis is also referred to as oil-spotting. The blemish is caused by the rupture of oil glands and the release of their content, which produces a phytotoxic effect and necrosis in epidermal cells. Mild injury results in light yellow spots that become sunken and turn dark in color as the damage develops. Damaged areas are more susceptible to decay (Knight *et al.*, 2002). The disorder is usually caused by fruit dropping and rough handling and packing. Climatic conditions at harvest time such as wet and foggy mornings, or excessive irrigation or rainfall, cause an increase in peel turgor, and greatly aggravate incidence of this disorder. Variations in the development of the disorder depend not only on the pressure required to break the oil gland in each area of the fruit or among fruits but also on the capability of the affected area to tolerate the released oil (Lafuente and Zacarías, 2006). Harvesting the fruits in the afternoon instead of the morning and delaying their handling and transport to the following day may reduce peel turgidity and incidence of the disorder. To ensure safe picking, a pressure tester has been designed to determine the threshold of the oil gland rupture (Falivene, 2004).

Petaca is a common rind disorder in lemon. Symptoms are characterized by deep depressions in the rind and darkening of the oil glands (Plate XXXVIIIf: see colour

section between pages 244 and 245). In affected areas, albedo collapses and oil is released from flavedo and damages the adjacent tissue. The first symptoms develop three to five days after harvest and are fully developed after ten to 14 days (Cronje, 2007). Potential causes of the disorder are not yet clear but nutritional deficiencies and imbalances have been postulated (Kuhalidy and Nayyal, 1974; Cronje, 2007). Excessive handling in the packinghouse and use of polyethylene-based wax instead of carnauba wax increase the incidence of the disorder. Petaca also develops in conditions of high humidity during storage. To test lemons for petaca, it has been suggested that samples are harvested and stored in polyethylene bags at ambient temperature and then inspected for spot development. Delaying harvest during humid and foggy days reduces petaca. Delaying ethylene application and waxing about two to three days after harvest may decrease incidence of the disorder (Cronje, 2007).

Stem-end rind breakdown (SERB) is also known as peel aging and occurs mainly in oranges. It is characterized by collapse and darkening of the peel around the stem-end of the fruit (Plate XXXVIIIc: see colour section). Its symptoms resemble those of rind staining, but it is localized in a discrete area around the calyx-end of the fruit. Symptoms can be detected during the first week after harvest. SERB appears to be related to nutritional imbalance and excessive water loss between harvest and waxing. Delay in fruit packaging and holding fruit under low humidity and high temperature or use of excessive brushing favor water loss and enhance SERB. The rootstock has also been reported as a contributing factor, but the incidence is highly variable (Ritenour *et al.*, 2004). The particular localization of the disorder may be explained by differences in stomata number, wax cuticle thickness and water potential in the flavedo area surrounding the calyx (Albrigo, 1972). Fruits with thicker peel and from arid areas are more resistant to development of SERB than those with thinner peel or from humid environments. To reduce SERB it is recommended to minimize the time between harvest and waxing, cool the fruit immediately after harvest, avoid direct exposure to sunlight and any conditions that would cause fruit desiccation. Avoiding use of hard brushes and ensuring good coverage of the fruit peel with appropriate wax will reduce the incidence of SERB.

Blossom-end clearing mainly affects grapefruit and is characterized by a translucent and wet appearance at the blossom end of the fruit. Fruit with a thinner skin is more prone to the disorder. Affected fruit exhibits an open core with the fractured juice vesicles sometimes leaking to create a wet spot. Symptoms of the disorder can be detected a few days after handling and brushing. The primary cause of the blemish is rough handling. Operations such as dumping fruit in containers too roughly and pressurized bagging and packing can aggravate the incidence of blossom-end clearing.

Stylar-end breakdown is similar to blossom-end clearing. The blemish is initiated at the blossom-end of the fruit and gradually spreads to other fruit areas. Rupture of juice vesicles and release of their content, giving rise to a water-soaked albedo, are the characteristic symptoms of this blemish that mostly affects Tahiti limes. Inappropriate handling and dropping the fruit on its stylar-end are the cause of the disorder. Careful handling and storing the fruit at high humidity may reduce its incidence.

Zebra skin is a disorder typical of mandarins and tangerines occurring mainly in the flavedo of early-harvested fruit. Small, light-colored and thin-skinned fruit are more prone to developing zebra skin. The cells of the affected area become dark and necrotic and are mostly located at the centre of the fruit segments. Fruit degreened with ethylene is more sensitive whilst brushing and rough handling of fruit in the packing line aggravate the symptoms. Preharvest water stress followed by rain or excessive irrigation causes sudden changes in turgidity that can cause zebra skin. Delaying harvest after rain and allowing fruit to acquire adequate color helps to prevent the condition. Careful handling and brushing are also recommended to reduce zebra skin.

21.7 Pathological disorders

Diseases caused by various pathogens are responsible for substantial economic losses during the whole pre- and postharvest life of citrus fruits. Infection and contamination may occur at different points of the supply chain: in the field, after harvest in the packinghouse, during transport and at the point of sale. Citrus fruit are suitable hosts for many pathogenic agents such as fungi, viruses, bacteria and other microorganisms (Eckert and Eaks, 1989). Most postharvest pathogens invade fruits through wounds and when natural defence is weak. Because citrus fruit has a pH lower than 4, it is a good medium for fungal infection and growth.

21.7.1 Fungal diseases

Fungal diseases are the main pathological disorder and the major cause of postharvest losses in most citrus fruits. The most common postharvest fungal diseases and their corresponding causal agents are listed in Table 21.6. The incidence of each particular fungus is very variable and highly dependent on climate, growing conditions, handling, storage conditions and transport. There are various origins of fungal diseases.

Table 21.6 Main postharvest fungal diseases and their causal agents in citrus fruits

Disease	Causal pathogen	Infection site
Stem-end rot	*Diplodia gregaria*	Flower, young fruit
Stem-end rot	*Phomopsis citri*	Flower, young fruit
Black rot	*Alternaria citri*	Flower, young fruit
Botrytis rot	*Botrytis cinerea*	Flower, young fruit
Brown rot	*Phytophthora citrophthora*	Fruit surface
Brown spot	*Alternaria citri/alternata*	Fruit surface
Anthracnose	*Colletrotrichum gloeosporioides*	Fruit surface
Green mold	*Penicillium digitatum*	Fruit injury
Blue mold	*Penicillium italicum*	Fruit injury
Sour rot	*Geotrichum candidum*	Fruit injury
Aspergillus rot	*Aspergillus niger*	Fruit injury

Decay from field infection

Stem-end rot. The disease is caused by the fungus *Alternaria citri* or *Alternaria alternata*. Decay development is slow and may become a problem after prolonged storage. Fungi establish as a quiescent infection on the button or the stylar-end of the fruit and gradually progress over the fruit surface and develop a black-colored core inside the fruit. The infection has not been successfully controlled by field fungicides. *Alternaria* is insensitive to most common postharvest fungicides such as TBZ or imazalil. The use of imazalil in combination with 2,4-D will delay calyx abscission and fruit senescence and will also provide some control.

Brown rot. This disease is caused by two species of Phytophthora, *P. citrophthora* and *P. parasitica*. These fungi belong to the same pathogenic group that may cause infection of the whole citrus tree. Spores present in the soil are splashed onto the fruit and the tree by irrigation water or rain. Infected fruit may not be visible through inspection in the packinghouse since the disease develops slowly and spreads during transport and storage. The initial infection develops as a light brown discoloration of the rind that progressively forms a white mycelium. Infected fruit has a rancid odor distinguishable from other diseases. Preharvest cultural practices (such as careful irrigation, pruning tree skirts, good soil management and weed control) and application of potassium phosphates or fungicides such as Aliette will reduce the severity of the infection. Postharvest fungicides are not effective but low temperature storage reduces development and spread of the infection.

Diplodia. This disease is caused by the fungus *Diplodia natalensis* and is a major problem in warm, humid environments typical of Florida and other similar climatic zones. Spores develop in dead wood and colonize the fruit during the warm, rainy season. The disease is not apparent in fruit attached to the tree but develops after harvest and especially after ethylene degreening. Good cultural practices and postharvest application of TBZ or imazalil in the drencher and TBZ in the packing line are effective in controlling the disease, especially if application is done before fruit degreening with ethylene. In addition, storage in cool temperatures delays the development of the infection.

Phomopsis. The fungus *Phomopsis citri* is responsible for this disease. Initial symptoms of the infection are indistinguishable from those of Diplodia. Spores are transported by rainfall to immature fruit and are quiescent until after harvest. The fungus invades the stem-end of the fruit and affected areas become dark-brown and clearly distinguishablefrom healthy areas. Lesions spread through the core of the fruit and the fungus may form a mycelium at the surface under humid conditions. Pruning and removal of dead wood may help reduce field incidence of Phomopsis. Fungicide application at the post-bloom stage reduces the amount of inoculum but does not eradicate it. Postharvest application of TBZ and imazalil and storage of fruit in cool temperatures are required for efficient control.

Anthracnose rot. This disease is caused by *Colletotrichum gloeosporioides*, which is able to penetrate intact fruit. The infection is stimulated by ethylene degreening in early season fruit. Spores are quiescent in immature fruit with ethylene causing them to germinate. Green fruits are more susceptible than

mature, well colored fruit. Mandarins and tangerines are most susceptible. Anthracnose may produce sunken dry lesions. The rind becomes brown and softens as decay develops. Infection does not spread to adjacent healthy fruit. Postharvest treatment with TBZ can control the disease.

Decay from postharvest infection

Penicillium decay. Decay by the fungi *Penicillium digitatum* (green mold; Plate XXXIXa: see colour section between pages 244 and 245) and *Penicillium italicum* (blue mold; Plate XXXIXb: see colour section) are the most widely distributed postharvest pathogens of Citrus fruits worldwide. Incidence of blue mold is much higher than that of green mold, and under particular circumstances, losses by these fungi can reach up to 80% and 30% of the total postharvest pathogen-related wastage, respectively. Blue mold is more tolerant to cold storage but green mold invades fruit more rapidly and predominates under normal postharvest conditions. Spores of both fungi are airborne and large amounts are produced on the surface of infected fruit. They will contaminate packingline equipment and storage rooms, and may accumulate in water, drencher and soap tanks. Infected fruit produce large amounts of ethylene that promote senescence and change of peel color. Spores produced by infected fruit contaminate the surface of healthy fruit and the cycle is repeated in the packinghouse and in storage rooms. Good sanitary conditions and cleaning practices should be observed to reduce risks of contamination and ensure hygienic fruit retail sales.

Initial symptoms of infection are similar for both molds. Affected areas appear as watery spots with white mycelium produced at the centre. *P. digitatum* develops olive-colored spores while those of *P. italicum* are of blue color. The infected area enlarges, resulting in a massive sporulation zone of green or blue color, surrounded by a small narrow band of white mycelium. For successful postharvest control, careful fruit harvest and handling procedures should be undertaken that will also reduce the risk of contamination of healthy fruit. Strict hygienic conditions should also prevail in the whole packinghouse, storage rooms and the circulating air. Pallets, boxes, brushes, drenchers and soak tanks should be cleaned and sanitized daily. Chemical control of Penicillium decay is essentially by postharvest application of fungicides in the drencher immediately after harvest and in the packingline. TBZ and Imazalil at concentrations of 1000 ppm are applied as water solution in the drencher. In the packingline, combinations of two fungicides provide successful control: SOPP (sodium-*o*-phenylphenate) at 1%, and TBZ and/or Imazalil at 1000 to 2000 ppm in wax solutions (10 to 12% total solids). Storage at low temperature reduces the development of green and blue molds. Excessive and frequent use of the same chemical treatments may induce fungal resistance to common postharvest fungicides. To avoid these problems, treatments should combine two chemically unrelated fungicides with periodical changes of fungicides.

Sour rot. This decay is caused by the fungus *Geotrichum candidum*, which is a common soil-borne pathogen. Spores enter the fruit through wounds that may extend to the albedo. Mature fruits are more prone to this decay than immature

fruits. Incidence of sour rot increases in fruit harvested early in the morning or following irrigation or rainfall. Initial symptoms of sour rot are similar to those of green and blue molds with light-brown water-soaked areas. At high relative humidity the lesion may be covered by a creamy colored mycelium. The fungus finally degrades the fruit into a slimy and watery mass. Incidence of sour rot can be reduced by harvesting fruit carefully and under conditions of low moisture to minimize injuries, and by preventing fruit coming into contact with the soil. Harvest and packingline equipment should be thoroughly sanitized to prevent inoculum accumulation and contamination. Temperatures below 10°C suppress decay development, but growth of the fungus is restored when fruit is transferred to higher temperatures. Application of SOPP (2%) is effective in controlling the disease postharvest.

Aspergillus niger and *Rhizopus oryzae* are parasitic fungi that invade citrus fruit through small wounds. High temperature and relative humidity favor development of these fungi. At temperatures below 15°C Aspergillus growth is severely affected while Rhizopus grows well at these temperatures. Postharvest incidence of these fungi is normally very low.

21.7.2 Postharvest-decay control

Use of fungicides

Fungicides are the most efficient and widely used treatments for control of postharvest decay. As mentioned above, some treatments are applied to citrus trees from fruit set to a few weeks before harvest to control some of these fungi. After harvest, chlorinated water is generally used to clean and disinfect fruit upon arrival to the packinghouse. Chlorine has both a fungicidal and bactericidal action. Sodium or calcium hypochlorite (with 50 to 200 ppm active chlorine) is used in dump tanks or at washing/brushing and after rinsing with water to provide satisfactory disinfestation. Three postharvest citrus fungicides are currently used, and their residue tolerance limits are listed in Table 21.7.

Benzimidazoles: This family includes thiabendazole (TBZ), which is used in the drencher as well as in the packingline. It is effective against stem-end rot and

Table 21.7 Residue tolerance (in ppm) for approved fungicides in the USA, the European Union, Japan and Codex Alimentarius

	Country			
Fungicide	USA	European Union	Japan	Codex
Imazalil	10	5	5	5
SOPP	10	12	10	10
Thiabendazole (TBZ)	10	5	10	10

Penicillium but does not provide control against *Alternaria, Rhizopus* or *Geotrichum*. It is usually applied at concentrations of 1000 ppm in water solution or 2000 ppm in water-based wax.

Imidazoles. This family includes imazalil and prochloraz. Imazalil is the most effective fungicide against green and blue molds, including benzimidazole-resistant strains. This fungicide has some activity against *Diplodia*, has reduced control against *Alternaria*, but is ineffective against *Phytophthora* and sour rot. Imazalil is used at concentrations of 1000 ppm as water suspension or at 2000 ppm in wax formulations.

SOPP (Sodium-o-phenylphenate). This fungicide is effective for the control of Penicillium and provides some efficacy against *Geotrichum, Phomopsis* and *Diploidia*. SOPP may be applied in the drencher, in soak tanks or in foam-applicating machines (at concentrations of 1.5 to 2%) or in wax (at 1%). The duration of application is important for best effectiveness of SOPP treatments, since application for less than two minutes may be inefficient but longer exposure may cause peel damage. Fruits treated with SOPP should be rinsed with clear tap water. Currently, fruit disinfestation in the packinghouse is done using SOPP followed by treatment with TBZ or imazalil.

There is a general concern worldwide about the use of synthetic fungicides to control postharvest decay and legislation has progressively eliminated some compounds and reduced the residue tolerance limit of authorized chemicals in favor of production of the so-called 'organic' or 'ecologically-grown' citrus fruit in which use of fungicides is totally prohibited. Continuous use of the common fungicides has resulted in the development of fungicide-resistant strains in most postharvest fungi, especially *Penicillium*, which is a major problem for the industry.

Alternative control methods

Searching for new alternatives to synthetic fungicides has been an area of intensive interest and several alternative methods, which can be used alone or in combination have been developed with successful results. These methods can be summarized as follows.

GRAS compounds. Chemicals recognized as GRAS (generally regarded as safe) provide an alternative to traditional fungicides and can be used as part of good manufacturing practice with no toxic residues or health hazards. Sodium carbonate and sodium bicarbonate have proven to be effective in the control of green and blue molds and they have been commercially used in California (Palou *et al.*, 2001b, 2002). Addition of these compounds to fungicide solutions may increase their fungicidal effect, which can be further enhanced by heating. As a result combinations of these factors may reduce the rate of fungicide application (Smilanick *et al.*, 2005). However, bicarbonate treatments have some problems: a) fruits should be rinsed after treatment to remove residues on fruit surface and b) disposal of sodium bicarbonate solutions is a problem in the packinghouses. Potassium sorbate has also been used in combination with fungicides, biocontrol agents and heating and was demonstrated to provide a very efficient control of

Penicillium and sour rot (Smilanick *et al.*, 2008; Montesinos *et al.*, 2009). The efficacy of the treatments is highly dependent on the heating temperature, the length of the treatment, and fruit susceptibility to decay. Incorporation of potassium sorbate in fungicide solutions permits reduction in use of synthetic fungicides but has some environmental constrains similar to bicarbonates. In general, it is effective on oranges, mandarins, lemons and other citrus species, and successful results have been obtained under commercial conditions, demonstrating that it may be effectively used in integrated disease management strategies.

Hot air/water treatment. Heat treatments have long been recognized as promising methods for decay control. Successful heat treatments can be applied as hot humid air, hot water dip or short hot water brushing. Applying hot humid air for a few days is also referred to as curing (one to three days at 30 to 37°C). It alleviates chilling damage and reduces fungal infection in fruit of many citrus species (Schirra *et al.*, 2000b). However, the cost of heating large volumes of air in the storage rooms limits commercial application of curing.

In contrast, water-dip treatments at 50 to 53°C for a few minutes have proven to be as effective as curing and are much less expensive (Schirra *et al.*, 2000b). Hot water dips are thought to eliminate incipient infections by removing spores from wounds and acting directly on their viability. It has also been demonstrated that hot water activates a number of fruit defence responses related to stopping fungal infection and to improving fruit natural defensive barriers (Sapitnitskaya *et al.*, 2006). In general, hot water treatments may be applied for a few seconds at high temperatures (55 to 60°C) or for a few minutes at somewhat lower temperatures (40 to 55°C). The induced resistance to decay appears to be related to the amount of heat provided. However, fruit from different species and varieties and the stage of ripening are critical factors for the efficacy of the treatments. In some experiments, decay due to Penicillium may be reduced by two minutes' exposure to temperatures of 53 to 56°C, but is increased at higher temperatures (60°C) (Schirra *et al.*, 2000a). High temperatures may induce fruit senescence and hence increase fungal infection, and, in more mature fruit hot water may induce peel damage. Hot water treatment also increases fungicide uptake and, thus, fungicide concentrations can be considerably reduced (Schirra *et al.*, 2000a). More recently, a hot water rinsing and brushing system has been developed that is also highly effective in inducing cold- and fungal-resistance. In tangerines, grapefruits and Shamouti oranges it has been demonstrated that hot-water brush for 20 seconds at temperatures between 56 and 62°C reduced decay without causing heat damage on the fruit surface (Porat *et al.*, 2000).

Biological control. Biological control of pre- and postharvest diseases using microbial agents is considered a promising alternative to chemical fungicides. Biological agents can be used alone or in combination with other agents for more efficient and non-hazardous control. A series of microbiological agents has been selected and evaluated as bioagents against fungal pathogens of citrus fruits, and some of them are patented (Janisiewicz and Korsten, 2002). Control of green mold with antagonistic yeasts such as *Debaromyces hanseii* (Chalutz and Wilson, 1990), *Pichia guilliermondi* (Droby *et al.*, 1993), *Candida famata* (Arras *et al.*,

1996) and *Candida oleofila* (Droby *et al.*, 1998) has been reported. Several bacteria like *Pseudomonas* spp (Smilanick and Dennis-Arrue, 1992) *and Pantoea agglomerans* (Teixido *et al.,* 2001) have also been reported to provide effective pathogen control. Three yeasts (Candida, Crypyococcus and Metschnikowia) under the trademarks of ASPIRE and Yield-Plus and two bacteria strains (of *Pseudomonas syringae*) under the name of BIOSAVE-110 are currently available as commercial biocontrol agents.

The efficacy of the biocontrol agents against postharvest fungal pathogens of citrus is usually high but it is much less than the control obtained with chemical fungicides. Combining several non-chemical treatments has been demonstrated to be highly efficient and increases the protection provided by a single treatment. Under experimental and semi-commercial conditions, *Pantoea agglomerans* in combination with a sodium bicarbonate solution heated to 40 to 45°C was very efficient in controlling *P. digitatum* infections in Clementine and Valencia late fruits stored under ambient or low temperature (Palou *et al.*, 2008; Torres *et al.*, 2007). Biocontrol microorganisms can also be used in combination with calcium chloride (Teixido *et al.*, 2001) or other physical methods like curing (Plaza *et al.*, 2004) or heat (Huang *et al.*, 1995). The mode of action of these microbial antagonists to control postharvest fungi is probably a result of competition for space and nutrients (Janisiewicz and Korsten, 2002).

21.7.3 Bacterial and virus-like diseases

Diseases of citrus fruits caused by bacteria, viruses and virus-like organisms during postharvest storage and management are mostly of minor relevance. Fruit infected by these microorganisms are from affected plants that may develop particular symptoms. The main pathogenic bacteria infecting citrus fruits are *Pseudomona syringae*, which causes widespread black pitting of fruit and *Xanthomonas campestris*, the causal agent of citrus canker, one of the most destructive diseases in citrus. Lesions of 3 to 5 mm spread along the fruit surface that may induce abscission or fruit deformation if infection occurs early in development. Lesions do not penetrate the albedo and do not affect internal fruit segments. Citrus greening, also known as Huang Long Bing, is has recently become a very serious disease in many citrus-growing countries. Infected fruit are invariably small in size and pale yellow in color. Internal fruit quality is also compromised and juice is sour and acid. Infected fruit are lopsided with a curved central core and a yellow stain beneath the calyx button. Symptoms may differ between species, time of infection and maturity, but greening-infected fruit develop a characteristic misshape and lopsided appearance (Plate XXXIXc: see colour section between pages 244 and 245).

Viruses and viroids are also important diseases of citrus. Tristeza and exocortis are two of the main infections affecting tree health and fruit production and quality. Fruits from affected trees are usually fewer in number, irregular in size, and with a pale yellow color. Some fruits may show a characteristic acorn shape. The rind of the acorn-shaped fruit appears normal near the stem end but becomes thinner and smoother at the stylar end. Grapefruits frequently have a blue color in

the albedo at the thin part of the rind. Because most of the citrus-growing countries have active and efficient certification and pest-management and eradication programs, citrus fruit affected by bacterial and virus diseases are not usually harvested and handled and thus incidence of fruit affected by these infections in the market is negligible.

21.8 Insect and pests' mites and their control

A wide range of pests is found in the main citrus producing areas. These pests can often cause severe damage and heavy losses in fruit quantity and quality of different varieties of citrus. These are either endemic pests or have been accidentally introduced. Only a few examples of the most important pests and mites will be discussed in this section.

21.8.1 Fruit flies

Fruit flies are the most dangerous pests of economic importance for citrus. They exist in most of the citrus-producing geographical areas worldwide. Moreno *et al.* (2000) reported the existence of over 4000 fruit fly species in the world. The main species often reported are Mediterranean fruit fly (*Ceratitis capitata* Wied.), Mexican fruit fly (*Anastrepha ludens* Loew), Caribbean fruit fly (*Anastrepha suspensa* Loew), and Queensland fruit fly (*Dacus dorsalis* Hendel). Most of these pests attack ripe or maturing fruit. Adult females oviposit in a puncture made in the peel of a mature fruit and the hatched larvae feed upon the fruit tissue (Christenson and Foote, 1960). Infested fruit should be removed either in the field or at the packinghouse to avoid decay development postharvest, which usually starts at the point of puncture of the fruit (Plate XXXIXd: see colour section between pages 244 and 245). In general, most of these fruit flies do not infect acidic fruit or those at an early stage of their development when their acid content is high. The outbreak of the infestation occurs in the Mediterranean countries in late summer to early autumn for early varieties of Clementine, mandarin and navel orange and during the spring period for late varieties of orange and mandarin. These flies are considered as quarantine pests in the areas where they are not present. Therefore, phytosanitary quarantine measures and protocols have been established and enforced by authorized regulatory agencies in many countries.

Preventative measures include mass trapping using lures and baits with insecticides, which has become the main way of limiting the development of the infestation. The release of sterile males of the Mediterranean fruit fly, a measure also known as the Sterile Insect Technique (SIT), is developing in Central America and the Mediterranean area (e.g. Spain, Madeira Island (Portugal), Israel, Jordan and Morocco) and in many other countries. In situations where the infestation is low, chemical sprays are localized, generally targeting the south-eastern quadrant of the trees and taking one row out of every three to four rows of trees, depending on tree density. When the infestation is general and the population of the fly is large, full-coverage tree spraying with insecticides is the common practice to

drastically reduce the population. The main insecticides used against Medfly are Malathion (+ Protein hydrolyzate when the spray is localized), Spinosad and Deltamethrin (pyrethroids).

Other methods against the fruit fly are applied postharvest to combat the presence of larvae in the fruit. They include, among others, cold treatments at temperatures between 1.4 and 2.2°C for an exposure period of about two to three weeks depending on the variety and the size of the fruit. Heat treatment by immersion of fruits in hot water for disinfesting fruit was also reported to be efficient (Shellie, 1999). Other measures include irradiation of fruit by gamma rays with doses depending on different species (Ladaniya, 2008).

21.8.2 Scales

Many of these phytophagous arthropods are reported in the main citrus-producing areas. The most serious arthropod pests that cause heavy losses in production are California red scale, *Aonidiella aurantii* Mask, yellow scale (*Aonidiella citrina* Coq.), black scale (*Saissetia oleae* Oliv.), cottony cushion scale (*Icerya purchasi* Mask.), and purple scale (*Lepidosaphes beckii* Newm.). The outbreak of scales is associated with mild climatic conditions, especially high relative humidity in the air and overcast skies. California red scale is one of the most dangerous pests on citrus around the Mediterranean basin. It causes damage to all tree organs including fruit. Although there is no effective method available to eradicate the pest, scale control is mainly based on mineral oil and pesticide sprays in the field. Spraying with methidathion, chloropyrifos and pyriproxyfen has proven efficacy in reducing the incidence of the pest. Another alternative is biological control using the parasite *Aphytis melinus* de Bach. This method is now commonly used in citrus orchards in many countries. *Aphytis melinus* and *Aphytis lingnanensis* are used with success against *Aonidiella aurantii* and *Chrysomphalus dictyospermi* (Abassi, 1977).

21.8.3 Mites

Mites can damage citrus leaves as well as fruits. Thus, a reduction in production occurs. Several species of mites are found in various countries. These include, among others, citrus red mite (*Panonychus citri* McGregor), broad mite (*Polyphagotarsonemus latus* Banks), Pacific spider mite (*Tetranychus pacificus*, McGregor), citrus bud mite (*Eriophyes sheldoni* Ewing), citrus rust mite (*Phyllocoptruta oleivora* Ashmead), Texas citrus mite (*Eotetranychus banksi* Pitchar and Baker) and spider mite (*Eotetranychus orientalis*), among several others that have been reported in the major citrus production areas (Luck *et al.* 1982). Sprays with chemicals are the most common method to reduce the infestation.

21.8.4 Thrips

Thrips (*Scirtothrips citri* Moulton) can be a problem in many citrus-growing areas. The pest can damage different parts of the tree and significantly increase

flower abscission. Scarring due to thrips is often first observed at the stem-end of the fruit. In infested orchards, large portions of the fruit can be affected, which in turn significantly reduces fruit packout. The damaged areas of fruit present a silver-like color. Methods of control of thrips consist of application of systemic insecticides during flowering. Organophosphorus and carbamates among other insecticidal active ingredients are used in citrus orchards.

21.8.5 Snails

Snails can damage leaves and fruit. Snails are active during the wet season or after a heavy irrigation of the citrus groves. Snails are inactive in winter and they hide in the soil. Good monitoring of their presence and of their activity is of great importance to reduce their negative impact on fruit quality and yield. Other precautions include pruning the tree skirt so that fruit will not come in contact with the ground or weeds and use of snail baits when snails are most active. Application of insecticides on tree stems and branches or the entire tree can reduce the snail population. Elimination of weeds in the orchard should also be practiced to reduce chances of population build-up and channels for transfer of the snails from the ground to the trees using the weeds as a bridge. Natural enemies of snails also include rats, snakes, lizards and birds.

21.8.6 Aphids

Several species of aphids are commonly found on citrus. The most dangerous are *Aphis gossypii* Glover and *Toxoptera citricidus* Kirk. The two aphids can transmit the Tristeza virus, which is a major concern in countries where it is not yet present and where trees are grafted on susceptible rootstocks such as sour orange. This disease causes the death of infected trees. It is important to use appropriate rootstocks that ensure a certain tolerance or resistance of the variety/rootstock combination. The control of aphids is not an easy task, as they have multiple hosts besides citrus. Pesticides such as Abamectin and Acetamiprid are applied on trees to control the pest.

21.8.7 Leafminer (*Phyllocnistis citrella* Staint.)

The larva of the Leafminer moth causes burrowing damage in young and newly developed leaves. It attacks most of the citrus varieties, causing distorted leaves and silver-like trails. As the larva feeds and develops inside the leaf it leaves a trail of excrements inside the tunnels it has created. Under favorable weather conditions *P. citrella* completes its cycle within two to three weeks. The moth causes heavy damage to nursery trees and young leaves from summer and autumn flushes of fully-grown trees. Fruits can also be damaged, thus affecting the aesthetic quality of fruit. Younger trees (less than five years of age) should be spayed regularly with insecticides to protect new leaves from insect attacks. Biological control has been tried in many citrus growing areas where the leafminer has settled but with very limited success.

21.8.8 Other insects

Other pests of economic importance in citrus producing regions include mealy bugs, whiteflies, ants, leafhoppers, etc. Most of the common techniques to control their infestation are based on monitoring, biological control with other parasites and spraying chemicals in the field when needed, but all in an integrated approach.

21.9 Postharvest handling practices

21.9.1 Harvest operations

Fruit destined for fresh consumption should be handled with care at harvest and in all postharvest operations. If the fruit is handled with the necessary care, it will guarantee the success of a whole season. The method of harvesting, the extent of injury to fruit during the operation, the physiological status of trees during harvest (particularly in relation to fruit turgor), weather conditions during harvest and during the period that fruit remains in the field after harvest greatly determine the extent of loss of quality due to weight loss and decay during the fruit's postharvest life.

Although research has been going on for many years to develop mechanical harvesting of fresh fruit, most of the fruit destined to fresh markets is still harvested manually. Details of mechanical harvesting are described by Brown (2006) and Ladaniya (2008). Brown (2006) describes machines used for mechanical harvesting or used to facilitate movement of crew within the orchard during hand picking.

In several regions of the world, fruit picking is done manually using a stick to hit the fruit or the branch to which it is attached so that the fruit falls directly on the ground (Fig. 21.2a) or into a cloth or a plastic cover so that it does not come in contact with the ground. Fruit that remains on the tree is then harvested by pulling off the fruit using a stick with a scythe or a hook attached to its end. Fruit harvested this way often has a long stem (Fig. 21.2b) and may also have peel injuries. If the fruit comes into contact with the soil, these injuries may pick up spores of fungal diseases that may cause postharvest decay or bacterial organisms that may be harmful to humans such as those that may be brought into the field with animal manure used as fertilizer.

In countries like Morocco, Spain, the USA (California) and others, fruit destined for fresh market is harvested using clippers that are specially designed for the citrus type to be harvested. In many other countries, fruit is harvested either by simply pulling on the fruit or using the snap method (grasping individual fruits in the hand and twisting them and then pulling) (Fig. 21.2c). Clipping the supporting stem as close to calyx as possible is the common method in modern citriculture destined for fresh fruit production, although it is time-consuming and costly. Clipping avoids having a long stem that would then injure adjacent fruits postharvest in the picking bag, field bin or box and in packaged boxes. Injured fruit will be more exposed to loss of weight by transpiration and to decay, the extent of decay being proportional to the amount and severity of injury (Eckert

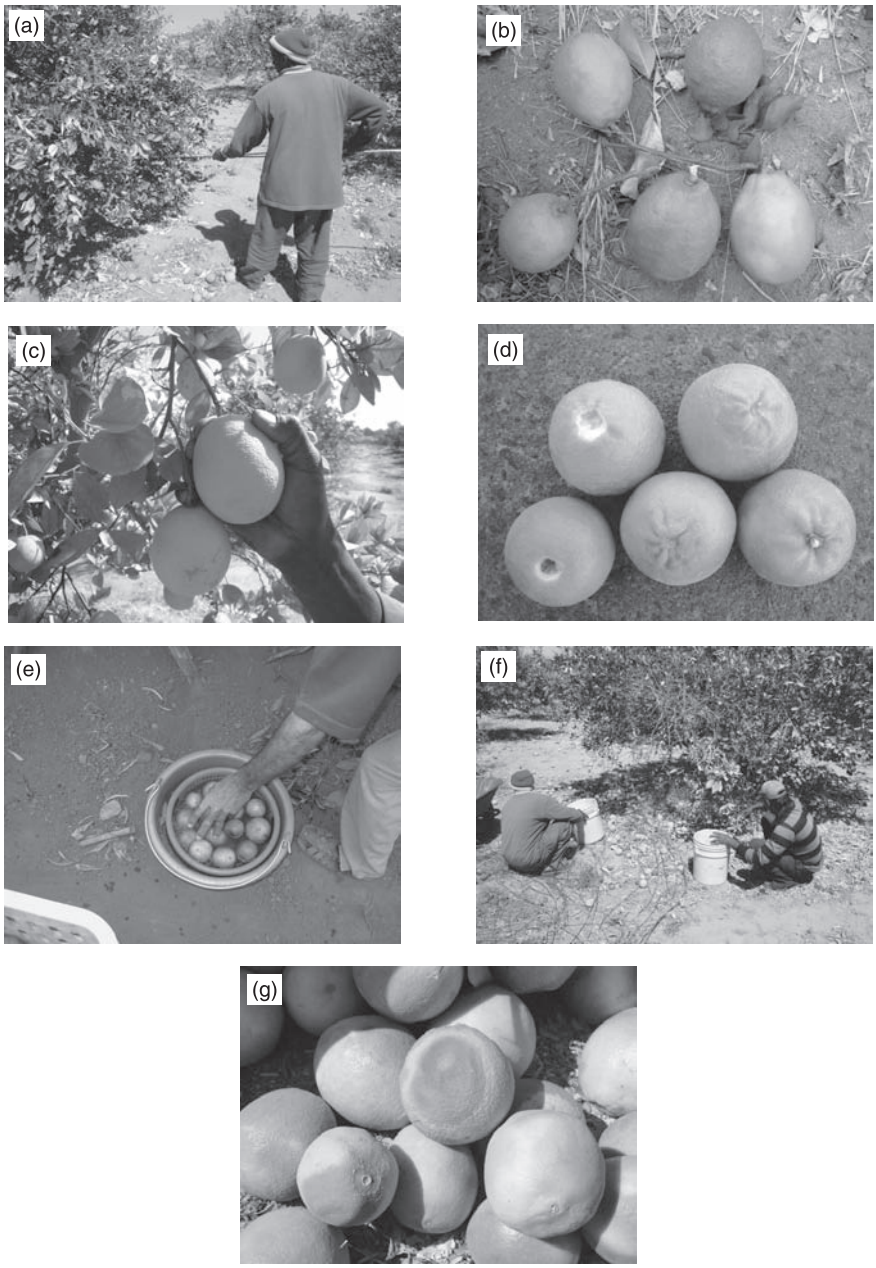

Fig. 21.2 Fruit harvesting: (a) Valencia fruit picking using a stick and letting fruit drop on the ground; (b) Lemon fruit with long stem as a result of harvesting by stick hitting on tree and fruit; (c) Valencia fruit being harvested by pulling on fruit; (d) Fruit with 'button hole' at the stem-end (upper and lower left) or without the calyx (upper right and lower middle) as a result of pulling, and fruit harvested with clippers with green calyx (lower right fruit); (e) Clementine fruit harvested green in water for degreening; (f) Fruit being picked directly from the ground; (g) Washington navel fruit picked from the ground showing symptoms of Phytophthora brown rot and of desiccation.

and Eaks, 1989). Clipping will also ensure that the fruit retains the calyx (Fig. 21.2d). This is a market requirement for premium prices, as the green calyx is a sign of freshness. Presence of this organ on the fruit also reduces weight loss from transpiration through the stem-end of the fruit and avoids penetration of decay organisms into the fruit.

Pulling on the fruit for harvesting will cause what is known as 'plugging', where the calyx and the peduncle and part of the peel remain attached to the tree stem creating a 'button hole' injury at the fruit stem-end (Fig. 21.2d), an opening that will cause fruit weight loss and development of decay organisms.

If fruit has not reached the minimum required size, it can be left on the tree for some time to gain in size or be picked and delivered to a juice factory or sold in local markets if prices are adequate. Fruit left on the tree should be protected from insect damage such as from the Mediterranean fruit fly (*Ceratitis capitata*). Soft fruit such as mandarins can deteriorate rapidly if left on the tree too long after full maturity. This fruit is exposed to potential weather damage such as 'water spot', caused by rain where areas of the skin soak with water and soften faster.

If mature fruit has not reached an appropriate color, it can be degreened. Fruit degreening on the tree is rarely used. Ethephon is the active ingredient used to enhance fruit color on the tree but may also cause excessive leaf drop.

In Morocco, particular care is taken during harvest of Clementines during days of high air humidity, often resulting in accumulation of morning dew on trees, and during days following irrigation (particularly where flood irrigation is used). In these conditions the fruit are turgid and oil cells can easily rupture, resulting in necrosis of adjacent epidermis (a symptom named 'oleocellosis'), which initially causes a blemish and, ultimately, an open invasion site for decay-causing pathogens. All types of citrus are susceptible to 'oleocellosis' but 'easy peelers' are the most susceptible under Mediterranean conditions and losses from it can be quite high. Therefore, early morning picking is unadvisable. Once the harvest starts, fruit is picked into buckets (Fig. 21.2e) half-filled with water plus 2,4-D (at 5 ppm). Picking into water reduces fruit injury and incidence of oleocellosis and 2,4-D maintains the calyx green and delays its abscission, particularly when fruit is degreened postharvest. It has recently become a common practice to drench whole pallets with an aqueous solution of 2,4-D (at 4 to 5 ppm) in the packinghouse.

21.9.2 Degreening

Under subtropical conditions, early maturing varieties do not often develop a specific orange peel color. This is related in general to warm temperatures during the day and an insufficient drop in temperature during the night to allow the development of the carotenoids in the fruit skin. Greenish mature fruit are not accepted by the consumer who associates maturity with an orange color. In tropical areas, the consumer is familiar with the green mature citrus. Under Mediterranean conditions, exporters of citrus fruit are obliged to degreen fruit artificially using ethylene gas in order to meet market requirements and consumer expectations.

Nowadays, the technology of degreening is well developed worldwide and large packinghouses are equipped with automatic injectors of ethylene and a system of ventilation to reduce the build-up of carbon dioxide in the degreening room. To ensure good color development, precise control of temperature (20 to 24°C), relative humidity (90 to 96%), ethylene concentration (3 to 5 ppm), good air circulation and ventilation (rate 1 to 1.5 room volume air change/hr), and carbon dioxide content (less than 1500 ppm) in the room are needed. The duration of the degreening will depend on fruit peel chlorophyll content but should be as short as possible and preferably not exceeding two to three days so that fruit will not be harmed by longer exposure to ethylene at the high temperature required.

Application of ethylene for degreening is based on two biochemical processes, degradation of chlorophyll and accumulation of carotenoids, which co-ordinately induce coloration of the peel (Grierson *et al.*, 1986). Commercial degreening is especially applied to early-season fruit, in which the pulp has reached internal maturity but the peel is still green. Occasionally, fruits of late harvesting cultivars (Valencia late, Hernandina, etc.) require degreening to remove the green color or to induce development of the uniform coloration required by the market. Current research suggests the involvement of complex metabolic pathways, both chlorophyllase-dependent and independent, in the process leading to chlorophyll breakdown (Jacob-Wilk *et al.*, 1999; Shemer *et al.*, 2008). In addition, studies at the molecular level indicate that the hormone chrophyllase is required to sustain the expression of carotenoid biosynthetic genes and that other ethylene-independent factors participate in the induction of the process (Rodrigo and Zacarías, 2007; Matsumoto *et al.*, 2009).

It is noteworthy that maturation of citrus fruit involves very low but constant levels of ethylene (non-climacteric), which are required to maintain the health of citrus fruit during postharvest storage and in response to different stress conditions. This conclusion is based on the fact that, in fruits of different varieties, use of the ethylene action inhibitor 1-methylcyclopropene (1-MCP) on fruits renders them more susceptible to *Penicillium* infection (Porat *et al.*, 1999; Marcos *et al.*, 2005), chilling damage (Lafuente *et al.*, 2001) and peel pitting at non-chilling temperatures (Establés-Ortiz *et al.*, 2009). These results are compatible with the requirement of ethylene for the resistance of citrus fruits to postharvest stress conditions. Ethylene, however, accelerates fruit senescence and spoilage. Prolonged exposure of fruit to ethylene or its exposure to high doses during degreening induces physiological disorders and browning of the fruit peel. Therefore, special care should be taken to limit the duration of the degreening treatment and to avoid pathogen contamination in the storage room and during transport.

21.9.3 Packinghouse practices

Good packinghouse practices are important to protect the fruit and to add to its value. The main operations are:

- Drenching fruit with fungicides against postharvest diseases.
- Systematic labeling of received lots from each grower.
- Dumping fruit either manually or automatically.
- Trash removal to avoid fruit injury and infection.
- Presorting of fruit by removing rotten, damaged and misshapen fruit.
- Removal of small-size fruit.
- Washing fruit with tap water and detergent over rolling brushes to remove external dirt load on fruit peel.
- Rinsing fruit to remove excessive water on fruit surface by passing the fruit under fans and/or in a tunnel where the temperature is about 45 to 48°C.
- Waxing and fungicide treatments to replace the natural wax lost from the fruit peel during washing to avoid/reduce water loss by fruit. Waxing also gives the fruit a shiny and attractive appearance to the consumer. Fungicide treatments such as TBZ (Thiabendazole) and Imazalil protect the fruit from postharvest pathological diseases. They are applied in wax. After waxing, fruit is dried with hot air in a tunnel to allow and facilitate the adherence of wax to the fruit surface.
- Fruit sorting to remove all unwanted fruit that do not meet the requirements of the market. These include misshapen fruit, fruit showing physiological or pathological disorders, fruit with uneven color, fruit with unacceptable blemishes and scarring, etc.
- Grading to allow the distribution of fruit onto homogenous size groups to facilitate packing and meet market requirements and standards. Sizing is achieved using modern electronic sizers which can sort fruit according to color, shape and dimensions.
- Box and carton filling, which is done manually. This is an important operation that must be done with care and by trained workers. Fruit disposition in a definite pattern in box, carton, and crate allows good appearance in a tightly packed unit. This will reduce vibration and thus bruising of fruit during transport and handling.
- Fruit labeling is often only made on the top visible layer of fruit in the package but can also concern each fruit.
- Packed fruit are unitized on a standard pallet for ease of transport and manipulation using forklift trucks. These pallets are also labeled to insure traceability.

21.10 Processing

Processing of citrus fruits mostly involves the production of juice. The consumption of fresh fruit has not increased substantially during recent decades and, therefore, there is an industrial interest worldwide in offering new citrus-derived products on the basis of satisfying consumer demand for highly valuable and healthy products. Freshly squeezed citrus juice with supplemented health-promoting compounds, fresh mandarin juice, fresh-cut citrus fruit salads, mandarin segments,

etc. are examples of new products which will be in high demand in the near future.

21.10.1 Citrus fruit juices

Total world production of Citrus fruit juice (65° Brix) in 2009 was just above 2.2 million metric tons (USDA-FAS, 2010). About 40 to 45% of the total world production of oranges is for fruit processing. Brazil and the USA produce about 48% of the total orange fruit but account for nearly 90% of the world production of orange juice. The citrus industry in Brazil and Florida, USA is mainly dedicated to juice production and, together, they produce about 90% of the total citrus fruit juices of the world. A remarkable difference in the juice industry and market between Brazil and the USA is that whereas in Brazil 90 to 95% of the juice is for export, 95% of the juice produced in the USA is for domestic consumption. In addition to oranges, an important proportion (20 to 25%) of total production of grapefruit and lemon is destined to juice processing. Blood orange juice has several nutritional and health-related advantages due to the biological effects of anthocyanins. Production and juice processing of blood oranges is currently restricted to the south of Italy, but it will have a great potential for export markets in the future (Pao and Fellers, 2003).

The maximum juice yield from citrus fruits is around 45 to 60% of their weight, depending on the variety and climatic and growing conditions. Fruit for industry must be processed rapidly to ensure preservation of nutritional quality and low risks of microbial infestation. For juice production, fruits should be first washed to remove soil particles, leaves, and other debris and may be graded before entrance to the extractor. Two extractor systems are currently used: a) a squeezer and b) a reaming system. The first system is designed to separate juice from the peel by compressing the fruit into an upper and a lower cup and cutter that squeeze the fruit and juice flows through a connecting manifold and tube. Commercial large-scale extractors connected to a centrifugal processing unit may be used. In the reaming system, the fruit is cut in two halves, which are penetrated and rotated by a series or reamers. The juice is separated by a strainer and the remaining residues may be collected to be further processed for oil extraction or other purposes. In the USA, regulation in relation with Hazard Analysis and Critical Control Points (HACCP) is applied to the juice industry to ensure safe and hygienic procedures. Juice obtained by both systems has a high content of pulp and must be clarified by centrifugation. More recently, ultracentrifugation is used to separate serum from the pulp, which may then be thermally treated before remixing to obtain a more flavored juice (Lanza, 2003). The final juice may be processed in different ways to be marketed as different products.

Freshly squeezed juice

This juice type is not thermally processed and may be commercialized as natural juice. After aseptically packaging it, juice must be stored and retailed at 1 to 4°C with a short shelf life of a few days.

Not-from-concentrate juice
This juice receives minimal thermal treatment, and is processed and stored frozen under aseptic conditions. Most of the juices are a blend from different origins and extraction procedures, and are combined before processing for retail sales.

Frozen concentrate juice
This product is suitable for storage and shipment, since volume is reduced more than six times compared to fresh juice. Citrus juices are largely supplied in this manner and the final juice may be a blend of different qualities or varieties. Thermal accelerated short-time evaporators are currently used to concentrate the juice very quickly, thus ensuring preservation of the quality. Lemon-concentrated juice is mostly used as an ingredient in beverages, rather than as pure juice. During preheating, the juice is pasteurized to inactivate the pectinase, an enzyme that is responsible for cloud formation, and also to inactivate any microorganisms that might be present. The juice is then vacuum-processed until concentrated. Heat has the disadvantages of reducing oxidative processes and negatively affecting flavor components. In blood oranges heat may degrade anthocyanins and carotenoids, thus affecting juice color and its nutritional properties (Fox, 2000).

21.10.2 Other processed products

No new advances have been made in fresh-processed products from citrus fruit other than juice due to the facts that: a) there is little demand from the consumer, b) there are industrial difficulties in removing and processing the peel and aseptically pressing the edible pulp, and c) off-flavors easily develop in processed and stored pulp.

An essential factor for minimal processing of citrus fruits relies in the peeling process of the fruit and this area has recently received intense research work. Traditionally peeling citrus fruit consists of manual or mechanical removal of the skin for further chemical degradation of the albedo and segment membranes. These methods generated large amounts of water and pollutants. Enzymatic peeling is an alternative method that could reduce the use of water and the degree of contamination in the production of peeled citrus fruits. These methods are based on infusion, under vacuum conditions, of cell wall degradation enzymes that cause disintegration of pectic substances of the albedo (Petrel *et al.*, 2008). Different combinations of large amounts of pectinlyase, pectin esterase, cellulase and polygalacturonase have been examined, and several commercial trademark enzymatic preparations (example: Peelzin® II) have been generated (Ismail *et al.*, 2005; Petrel *et al.*, 2005). To improve the efficacy of the enzymatic activity on albedo degradation, a scalding treatment at 100°C for two to four minutes has shown very valuable results. Hot water dip until the albedo temperature reaches 40°C provides conditions for an efficient enzymatic peeling. To facilitate the penetration of the enzyme into the peel, it is necessary to perform cuts in the peel surface and to perform vacuum infiltration. Different systems have been assayed but temperatures of 35 to 40°C, a pH of 3.5 to 4.5 and optimum ratios of the different enzymes are appropriate

conditions for efficient enzymatic peeling (Petrel *et al.*, 2007; 2008). Preparation of segments of mandarins (Satsuma and Clementine varieties may be suitable for this purpose) or slices of orange fruit packed in modified atmosphere packages are alternative minimally-processed citrus products with a great future potential to increase citrus consumption and appreciation.

21.11 Safety issues and quality assurance

21.11.1 Safety and security issues and market requirements

Safety and quality of the final food product is currently becoming a major issue in the citrus sector as in the whole fruit and vegetable production sector. Consumer awareness is high regarding the problems of contamination in the food industry and it is the responsibility of producers and retailers of fresh produce as well as those in the processing industry to establish procedures and means to ensure that the delivered product is produced and manufactured using well defined procedures in order to protect the consumer from food-borne diseases and unwanted contamination.

After the food crises of the early 1990s in Europe, new and more restrictive laws and regulations were developed. The aim is that each producer, handler, exporter and distributor, should be able to implement a quality and safety management system that will ensure a safe final product to the consumer. A traceability system should also be implemented from the farm to the consumer.

At the farm level, misuse of pesticides may lead to an increase in pesticide residues in the fruit and to the pollution of the soil and water. These chemicals are known to be, at least in part, potential hazards for human health. Some are proven to be carcinogenic. Regulations and laws that govern the use of pesticides have established maximum residue limits (MRLs) for each crop, together with rules about the timing and frequency of pesticide application, which growers, packers and exporters must follow.

21.11.2 Quality management systems and certifications implemented in the field

It is often said that quality starts at the farm. In fact agricultural operations and practices from selecting plant material, choosing the site of production and applying certain cultural practices to the plant material have a direct effect on quality of the produce. Examples include inputs such as the fertilizers used to insure adequate production and pesticides used against pests and diseases. Fruit handling at different points of the supply chain from harvest to the final destination also influences the quality of harvested crop. For these reasons, several quality management systems have been developed for production sites. Accredited certifiers will certify any system. In this section, we will briefly highlight some of the most commonly encountered systems in citrus orchards.

GlobalGAP standard

For growers and producers of citrus fruit, GlobalGAP is becoming a reference standard for integrated farm assurance, which can easily be implemented by all parties involved in the supply chain. The standard has incorporated parts of HACCP as means of food safety management at the primary food sector. Integrated farm assurance includes adopting integrated pest management (IPM) and integrated crop management (ICP). In most of the regions where citrus is produced, growers are very active in implementing the guidelines of the standard. Besides being a good tool for minimizing the risks of contamination, it is also a good way to optimize production inputs, preserve natural resources such as water and, thus, increase the profit margin to the grower.

The aim of this section is not to detail the requirements of GlobalGAP and how it should be implemented but to enumerate some control points and compliance criteria (CPCC), corresponding to the checklist of the standard for farms that produce fruits such as citrus. More details and additional information can be found at www.globalgap.org. The following are the main CPCC of the standard:

- Traceability using appropriate methods for tracing inputs to crop production and the produce at every point of the supply chain from the farm where it is produced to the point where it is consumed.
- Record-keeping and internal self-assessment of different operations during production. They include all inputs, cultural practices adopted and workers' training and health and welfare programs.
- Site history and management to maintain the quality and fertility of soils.
- Applying fertilizer based on plant requirements; type of application and frequency should be adequate to avoid waste of fertilizers and contamination of water sources and the environment; fertilizers should be stored away from produce and other chemicals such as pesticides.
- Supplying irrigation water using appropriate and most effective methods to reduce overuse; only water of appropriate quality from renewable sources should be used; wastewater should not be used unless it is treated and free from any source of contamination to the crop.
- Crop protection with an emphasis on applying IPM rather than straight use of chemicals with record-keeping of all chemicals applied; training of workers responsible for spraying and providing them with all the necessary equipment and protective clothing; respect for pre-harvest interval; ventilation and safely-locking room for pesticide storage; regular control of quality of pesticide application.
- Harvesting the crop should be done by workers trained on good hygiene practices to avoid contamination of the crop from various potential sources.
- Postharvest operations include storage of the crop in an appropriate space to avoid any source of contamination; postharvest sprays should use approved chemicals only.
- Workers' health, safety and welfare programs should be implemented including risk assessment, keeping records of the training of workers, hazard site

identification, existence of first-aid kits, protective clothing/equipment, and worker welfare.
- Existence of a well-designed waste and pollution management plan for recycling and re-use of waste and pollutants generated on the farm.
- Development of an action plan for environment preservation with an assessment of the impact of farming on the environment and biodiversity.
- Complaints should be handled efficiently and their resolution procedures should be recorded.

Nature's Choice standard

This is a private standard developed by Tesco, UK in 1991. Nature's Choice has much in common with GlobalGAP but with more emphasis on environmental issues. It contains over 238 control points covering rational use of plant protection products, rational use of fertilizers and organic matter, the prevention of pollution, the protection of workers' health, the efficient use of energy, water and other natural resources, recycling and the re-use of plant byproducts and waste conservation and the improvement of wildlife and landscape. By 2006, all the suppliers of Tesco worldwide had to implement and comply with the requirement of the Nature's Choice code of practice (www.tescofarming.com).

Organic standard

This is an environmentally oriented production system. It has expanded very rapidly in many parts of the world as environmentally friendly practices for producing healthy products have been developed. The main points of this standard consist of adopting techniques and practices that conserve and build soil fertility with little negative impact on biodiversity and agro-ecosystems. These practices include, among others, crop rotation, green manure application, cover cropping, the use of livestock manure, and the use of composts and of mineral-rich rock powders. In organic production systems, it is important to prevent contamination of organic produce with conventional produce. The use of synthetic fertilizers and pesticides is prohibited. Organic plots should be located away from conventional agriculture to prevent accidental pesticide drift from conventional production sites. Transport, handling, packing and storage of organic produce should be done separately from those for conventional products. Equipment used for the two systems should also be separate.

21.11.3 Quality management systems and certifications implemented in packinghouses

In packinghouses, several systems are implemented worldwide depending on the objectives of each manager. Some are food safety management systems and others are quality systems. The following are some characteristics of the main systems adopted in packinghouses of citrus fruit.

Hazard analysis and critical control points

It is a safety management system developed in the USA in the early 1960s and adopted by Codex Alimentarius Commission of the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) of the United Nations, and by the food industry in several countries. HACCP is a prevention-based food safety system. It is a tool to assess hazards and establish control systems that focus on the prevention approach rather than testing and analyzing the final end product. It is based on a systemic method for analyzing the food chain from the farm to the final consumer, determining potential hazards (biological, physical and chemical) at each step and designating critical control points that need to be monitored and controlled in order to eliminate the hazards or to reduce them to acceptable levels so that they will not cause any adverse health effect to the final user.

HACCP is compatible with the implementation of quality management systems such as that of the British Retail Consortium (BRC), International Food Standard (IFS) and International Standard Organization (ISO) series. Therefore, most of these standards incorporated HACCP as a system of choice in the management of food safety.

The seven principles of HACCP system apply to all phases of food chain from primary production to consumer use. These principles are:

1. Conduct a hazard analysis
2. Determine the critical control points (CCPs)
3. Establish critical limits
4. Establish monitoring procedures for the CCPs
5. Establish corrective actions
6. Establish verification procedures
7. Establish record-keeping and documentation procedures.

Quality management system (ISO 9001:2008)

This is one of the ISO 9000 series developed by ISO. It is applicable to any organization, whether working in the food sector or not. ISO 9001 is among the most implemented standards in the packinghouses and it is compatible with other management systems. It is a prerequisite for the implementation of BRC, IFS and ISO 22 000 certifications. The main principles of ISO 9001 are:

- Customer focus of the enterprise
- Leadership
- Involvement of the working force in the production process
- Use process approach
- System approach to management
- Continuous improvement at various points of the production
- Factual approach to decision making
- Mutual and beneficial client–supplier relationship.

The major requirements that need to be met for certification of the system focus on:

- Quality management system
- Management responsibility
- Resource management efficacy
- Product/service realization
- Measurement, analysis and improvement of quality at all points of the production and supply chain.

Environmental standard (ISO 14001)
This standard intends to give more information and requirements of environmental management allowing the enterprise to formulate a policy with the objectives that take into account legislation requirements and information on significant impacts of the production on the environment. It is based on continuous improvement of environmental performance by the management of impacts related to the activities of the production enterprise. It requires the implementation of an environmentally oriented system and insuring the traceability of its application.

The principles of ISO 14001 are based on Deming wheel also known as the cycle 'Plan Do Check Act' (PDCA). The standard is applicable to any organization that is concerned about:

- Implementation/improvement of an environmental management standard;
- Assuring the conformance with an environmental policy;
- Demonstrating the conformance with such a system;
- Ensuring compliance with environmental laws and regulations;
- Seeking certification on the implemented environmental management system;
- Making an internal audit of the system.

British Retail Consortium global standard (BRC)
Developed by the British Retail Consortium in 1998, it is now one of the widely implemented standards in citrus packinghouses. By meeting its standards, the producers demonstrate that they completely comply with industry requirements. For this standard, the fundamental requirements are:

- Implementation of an HACCP system.
- A quality management system with its different elements to be fulfilled including, among others, a quality statement, the development of a manual for quality, an organizational structure, a management commitment, customer focus, resource management, internal audit, documentation of all purchasing, corrective actions, traceability, product withdrawal and recalls, and complaint handling.
- Implementing an environmental standard that covers various aspects related to external and internal environments of the entity. The standard contains: site external environment standards (location, perimeter and grounds); internal environment standards (the characteristics of walls, ceilings, windows, doors, lighting, air ventilation, etc.).
- Product control: The system focuses on product development, layout, product flow, segregation and preparation, handling requirements for specific materials,

metal detection, product packaging, product inspection and analysis, stock rotation and control of non-conforming products.
- Internal audit/self inspection.
- Corrective actions.
- Traceability of different procedures and their applications.
- Control of operations.
- Training of workers and staff.

International Food Standard (IFS)
This standard was developed by distributors and suppliers from Germany, France and Italy. It is now at its fifth edition. Much like BRC, IFS focus is on food safety, HACCP, hygiene, the manufacturing process and environmental standards. The five requirements for certification are:

- Declaration of management responsibility
- A well designed and documented quality management system
- Use of an efficient resource management
- Development of a well designed production process
- Having criteria for measuring progress, analyzing situations and continuous improvement.

ISO 22 000 standard
ISO 22 000 is a food safety management standard. It is considered one of the most complete standards that goes beyond the food safety requirements and recommendations of Codex Alimentarius Commission and HACCP system requirements and principles. Before conducting hazard analysis, ISO 22 000 has introduced an upstream establishment of prerequisite programs. These programs, as defined in the standard, constitute the basic conditions and define the activities that are necessary to maintain a hygienic environment throughout the food chain suitable for production, handling and provision of safe end products, and safe food for human consumption (see www.ISO.org). Implementation of ISO 22 000 is based on five main elements, which include: systemic approach, implementation of prerequisites, HACCP system, traceability and interactive communication. In other terms it requires the implementation of ISO 9001 quality management system, HACCP system and a traceability system.

OHSAS 18 001 standard
The Occupational Health and Safety Assessment Series 18 001 management system (OHSAS 18001) was developed by the British Standards Institute as a standard that will enable any organization to control and manage health and safety risks and improve performance of its workers. The main objective is to reduce the number of accidents in the work place. The standard is compatible with ISO 9001 and ISO 14001. OHSAS 18 001 principles are:

- Policy making and commitment on the part of the management
- Planning for hazard identification, risk assessment and risk control

- Having an OHSAS management program
- A structure and responsibility that is well defined (legal requirements, objectives and programs, organization of personnel)
- Training, awareness and competence development of the workforce (with documentation and records)
- Consultation and communication channels between personnel and the management
- An operational control system
- An emergency preparedness and response plan
- A performance-measuring, monitoring and improvement plan
- Procedures for accident and incidence investigation and for corrective and preventive actions
- Regularly auditing and reviewing the system for its effectiveness.

Social accountability (SA 8000)
This is a voluntary standard that was developed for auditing and certifying labor practices in enterprises and organizations. It is a standard for social welfare and employment practices based on the international human rights norms and the World Labor Organization standards. The principles of SA 8000 code of practice concern child labor, forced labor, health and safety at the workplace, freedom of association and collective bargaining, discrimination, disciplinary practices and measures, working hours, and compensation and labor management systems.

21.12 Best harvest and postharvest practices

21.12.1 Best harvest practices

The stage of maturity at harvest and harvesting operations is very critical for the quality and storage life of citrus fruit and for reducing the risks of postharvest pathological and physiological losses. Citrus fruit is non-climacteric and should be harvested at full internal maturity. Immature fruit are of low quality and are not acceptable to the consumer. They are usually acidic with low sugar content, very susceptible to postharvest disorders such as shriveling, have an imbalanced color of the peel and will not develop full flavor and aroma in comparison to mature fruit. Over-mature fruit lose their acidity and develop insipid flavor; they soften very rapidly and become susceptible to mechanical damage and decay development during the subsequent postharvest operations.

There are several factors that have a direct effect on harvesting and on quality of picked fruit.

Weather conditions at harvest
Weather conditions prevailing during harvest should be taken into consideration as they may affect fruit quality after harvest. Therefore:

- Picking should not start unless the workers can easily access and move in the field. If it rains, picking must be delayed until the terrain is dry enough to perform the operation under adequate and safe conditions.

- Fruits should not be harvested when they are very turgid following a heavy irrigation or rain or when there is dew on the tree. Under these conditions, oil glands are turgescent and susceptible to mechanical disruption at harvest, which will increase the rate of fruit with oleocellosis. When the dew stays on trees for a long period of time, they are more turgid and easily damaged. Therefore, growers tend to pick fruit into buckets half-full with water to avoid fruit damage and reduce oleocellosis. Water is used to wash the oils from disrupted oil glands and avoid its oxidation on fruit peel, which will give rise to discolored areas.
- During days with high temperature and low relative humidity, picking should be done early in the morning or late in the afternoon. Heat increases fruit transpiration and thus fruit weight loss, which will cause shriveling and 'stem-end rind breakdown', a disorder particularly occurring in late varieties of oranges, their maturation and harvest season occurring in late spring to early summer coinciding with hot and relatively dry days.

Quality of harvesting tools and workers' hygiene

All the tools and equipment used for harvesting should be designed to prevent any injuries and bruises to fruit. These equipments include: clippers, plastic crates, buckets, bins, ladders, etc. They should be of appropriate size and kept clean to avoid any contamination to fruit.

All workers should receive specific training related to proper manners of fruit picking and to hygiene procedures for keeping their equipment clean and avoiding any contamination of fruit by microorganisms that may be harmful to the consumer. Contamination may come from direct contact with fruit during harvest (for example from injured hands or sick workers) or from containers, water, or any equipment or tools used for picking or transportation to the packinghouse or to the market. Contamination may also come from contact of fruit with the soil, which may contain harmful bacteria, such as from animal manure used as fertilizer. All workers should be trained in sanitary hygiene procedures to minimize the risk of any potential contamination. They are required to wash their hands with odorless soap and rinse with potable water before returning to picking fruit.

Harvest operation considerations

For the fresh fruit market, picking citrus fruit is manual and requires a large number of pickers. Citrus fruit are harvested by hand either by snapping or clipping the fruit. The snap method is usually used for fruit geared to local consumption or processing as these fruits may be detached by hand following a slight twist and pull-off of the fruit from the stem. In general, snap harvesting increases fruit 'plugging' with part of the stem-end of the fruit removed. It may also lead to fruit with a long stem. For best results for fruits destined for the fresh market, fruit are picked by clipping the supporting stem just above the calyx. It is consequently important to take the following precautions to prevent

contamination and injury to the fruit and to minimize the risk of postharvest decay and losses:

- Workers should not smoke, drink or eat except in designated areas away from the production site. Those who suffer from illness or have open wounds or any other infection risk should not be in contact with fruit.
- The fruit stem is cut as close as possible to the pedicel, leaving only a couple of millimetres' length in the peduncle, so that it will not puncture or injure adjacent fruit during subsequent postharvest operations.
- Only one fruit at a time should be held in the hand during picking to prevent squeezing when several fruit are held together in one hand. Workers should avoid applying any extra pressure with their fingers or nails when picking.
- Nails should be kept short, and wearing jewelry should not be permitted, in order to avoid fruit bruising and peel injury. Protective clothing and equipment used by workers, picking bags and buckets, clippers, etc., should be regularly inspected and replaced when they become a potential source of contamination or present risk of injury to fruit.
- Plastic crates and bins, clothing and clippers should be cleaned before use and after each use. They should be washed with pressurized detergent and rinsed with potable water.
- Fruit from the lower parts of the tree skirt should be harvested first before using ladders and other harvesting aids to reach fruit on upper tree parts. In any case, a fruit that is in direct contact with the soil or that drops during picking must not be picked and sent to fresh consumption as it may be injured and/or contaminated by soil fungi or bacteria (Fig. 21.2f and 21.2g). Workers should not stand on harvesting containers to reach fruit on the tree.
- Appropriate precautions should be taken when transferring picked fruit into harvesting bags or buckets and when emptying these containers onto transport crates or bins to avoid injury and bruises to fruit.
- Harvest and transport containers should not be over-filled (Fig. 21.3a) to prevent damage from pressure exerted on lower fruits in crates or bins for example.
- Harvested fruit should not be placed under direct sun (Fig. 21.3b) but should be stored in the shade in a ventilated area. As there is a risk of contamination with bird excrements or rodent droppings, harvested fruit should not be placed under trees or left too long in the field.
- After harvesting, fruit should be sent as soon as possible to the packinghouse for storage and packing to avoid loss of quality and freshness.

21.12.2 Best packinghouse practices

Packinghouse operations aim at preserving quality and adding value to the crop. A packinghouse should be designed to ensure good quality of the citrus fruit, to reduce injuries and any risk of contamination of the product.

(a) (b)

Fig. 21.3 Fruit packing in the field: (a) Cardboard boxes overfilled with Valencia orange fruit packed; (b) Harvested fruit sitting on the ground in the sun and being packed in the field in Styrofoam boxes (see overfilled boxes).

Site selection and equipment needed for different operations in a packinghouse
To take best advantage of the packinghouse, there are several factors to consider for its location and size:

- The site of construction should be in the vicinity of the production area for ease of supply and to avoid long-distance transport of harvested product. It should have all the necessary infrastructure and facilities including additional land for future expansion. It should be easily accessible from production sites by good roads, have access to potable water, electricity and communication, and be connected to solid and liquid waste disposal systems. The site should not be close to any source of contamination by undesirable odors or dust, and should not be constructed above a contaminated ground or in an area exposed to adverse conditions such as strong winds, erosion or flood. It should be located in a vicinity where sufficient labor is available.
- Equipment at the packinghouse should be up to date and should include:
  - A reception area where fruit are received, weighed and clearly marked with respect to the origin, the variety, the day of reception, the quantity received, etc. for tracing purposes.
  - Drenching equipment for fungicide application: necessary for protecting the fruit from postharvest decay organisms. Different treatments are applied depending on destination whether it is degreening, temporary storage or long storage duration.
  - Temporary holding area before packing: should be well ventilated and preferably with appropriate temperature and humidity to avoid excess weight loss from adverse conditions such as heat.
  - Full packingline equipment: should include manual or automatic dumping system on conveyer, pre-sorting to remove rotten fruits or those with very

apparent disorders, a pre-sizing cylinder to eliminate under-size fruits, followed by washing with detergent and brushing before rinsing with potable water and then drying to remove excess moisture on fruit surface. Other operations include waxing with food-grade synthetic resins and postharvest fungicide application to protect fruit from decay pathogens. Sorting is done to remove undesirable fruit with blemishes, misshape, unwanted color, or those presenting other apparent alterations. Grading equipment either by size, weight or color should be available. The operation allows separation of fruit according to fruit size and color: for example, for degreening, lots of fruit having similar green color intensity. Packaging tables should be clean with a smooth surface. Palletized packed fruit are then held in a cool temporary holding area before shipping or storage in cold room facilities.

– Other equipment of the packinghouse includes manual or automatic trolleys and fork-lift trucks to transport pallets within the building. They should be in good condition and regularly inspected for optimum results.

Considerations for sanitary procedures

Each packinghouse should be constructed in a way that risk of contamination of fruit is minimized. The following considerations (from the Food Safety Enhancement Program of the Canadian Food Inspection Agency) should be taken into consideration:

- The facility should be protected by a wall designed to prevent entry of animals and vermin.
- Walls, floors, and ceilings should be made with materials easy to wash, clean and sanitize.
- The floor should have a slight slope to ease elimination of liquids from washing and cleaning the facility.
- All windows should be protected with a mesh to prevent entry of birds, insects and vermin.
- Light bulbs should be covered so that, in case of breakage, the glass will not contaminate the fruit or injure the workers.
- Sewage water should be controlled to avoid mixing with potable water.
- A sufficient number of toilets should be constructed in relation to the number of workers (males and females).
- Sanitary facilities should always be kept clean and records of cleaning should be kept regularly.
- All the sanitary facilities should have cold and hot water, soap, a hand dryer and a sanitizer.
- Packinghouse facilities should regularly be disinfected and fumigated to reduce build-up of spores of pathogens.

21.12.3 Best storage and transport practices

The postharvest life span of harvested citrus fruit can be terminated with the development of decay, excessive weight loss, the appearance of physiological

disorders, over-maturity and loss of firmness and of internal quality (essentially aroma and flavor). Fruit storage duration depends on the site of production, variety and rootstock, climatic conditions prevailing before and during harvest, cultural management and postharvest practices.

Maturity and harvesting

Fruit destined for prolonged storage should be at optimum maturity. Immature or over-mature fruit are not suitable for prolonged storage periods. For each variety, the best timing of harvest must be determined according to production zone and environmental conditions. Fruit with thin skin may exhibit more decay and disorders compared to fruit with normal peel thickness. Thin peel is often observed in light soils and in areas with mild climatic conditions. Fruit from dry areas show more storage capability and will tolerate longer periods of storage. Care taken during fruit harvesting is very critical for fruit storage. Rough picking and handling will increase peel bruises and injuries, which will then expose the fruit to pathogen attacks and postharvest disorders. The quality of harvesting tools and equipment should be appropriate in order to minimize risk of injury and contamination of fruit.

Postharvest pre-storage treatments

After harvest, fruit should be transported immediately to storage facilities. Fruit must be pretreated with fungicides against postharvest pathogens. The treatment is often done by drenching or immersion of whole pallets in a basin containing the fungicide whose composition depends on the targeted pathogen. Thiabendazole (TBZ) and Imazalil are used against Penicillium molds, guazatine is used against sour rot caused by *Geotrichum candidum* and phosetyl alluminum against brown rot due to *Phytophthora*. Cold treatment for quarantine purposes is another treatment required by some countries such as the USA for control of fruit flies like *Ceratitis capitata* (see other sections of this chapter). Temperature and duration of exposure must be compatible with cultivar sensitivity to low temperatures.

Storage conditions

Storage conditions of citrus fruit vary with the variety and storage duration. To take most advantage of cold storage the following measures should be taken into account:

- Rooms should be disinfected, washed and cleaned before fruit storage, rooms should be cooled to the desired temperature.
- Storage temperature should be as low as possible to reduce fruit metabolic activity without causing chilling injury of fruit. For different cultivars the following temperatures are often applied; clementines (3.5 to 5°C); mid-season mandarin varieties (5 to 7°C). For varieties sensitive to chilling injury such as Fortuna mandarin and grapefruit, they should be stored at above 10°C. Most of the oranges can be stored between 3.5 and 5°C.
- Relative humidity in the storage room must be set between 90 and 95% in order to reduce fruit weight loss and shriveling.

- Fruit should be treated against postharvest diseases before storage and the room should be fumigated with compounds such as ozone or Imazalil.
- Avoid admitting fruit of a high temperature to cold storage. Removal of field heat is necessary if fruit temperature is above 20°C.
- For prolonged storage, keep only one variety in each room.
- Always keep 20% volume of the room empty for good air circulation.
- Height of stacked pallets should be below the evaporators and ventilators.
- Packages should be appropriate and should withstand the high relative humidity of the storage room.
- Placement of pallets should allow good air circulation in the room.
- Rooms should never be left open for a long period of time to avoid loss of humidity and an increase in storage temperature.
- Quality of stored fruit should be checked regularly.
- Records of all of the postharvest operations and any corrective measures taken should be kept up-to-date.

Transport practices

Transport of fruit to the market must be performed under very satisfactory conditions. For many producing countries, fruit are exported to different parts of the world and transit time may take several weeks. Shipping fruit from South Africa, Chile or California, for instance, may take four to six weeks from the time of packing to the time it reaches distribution centers in Europe or the Far East. During this long transit time, citrus fruit and especially mandarin types may show weight loss, chilling injury, anaerobic damage of fruit skin due to low permeable wax coating used, 'stem end rind breakdown' caused by excessive water loss, decay development by postharvest pathogens, damage from mishandling of pallets during loading and unloading of ships and from pallet movement particularly in bad sea conditions, etc. To reduce these losses and maintain fruit quality, transit conditions must be at their optimum in terms of temperature, relative humidity, fruit protection and implementation of Good Transport Practices. These practices must include amongst others:

– Good sanitation of ships, refrigerated trucks and containers. A systematic program must be developed for each type of transport in order to reduce the build-up of pathogens inside it.
– For long-term transit, fruits must be treated carefully by fungicide to protect them against any pathogen invasion.
– Packaging must be suitable for containing fruit and avoiding fruit movement within the box. Packages must withstand pallet stacking and be resistant to moisture, and pallets must be straight and reinforced to prevent their collapsing, which in turn will damage fruit from heavy weight. Packages should have sufficient openings to allow good ventilation and air circulation.
– Precooling of fruit to appropriate temperature must be carried out as soon as fruit are packed particularly if the transport facility does not have the capacity to bring the temperature of fruit down to the desired level within a

satisfactory period after loading. This temperature must be kept constant until destination.
- The best transit temperature that reduces fruit respiration and metabolic activity of the fruit must be set for each specific variety, and should not cause chilling injury to fruit. When different varieties are transported together, the appropriate/safest temperature should be that for the variety that is most sensitive to cold. In general, transport temperature of citrus fruit varies from 4 to 7°C for both mandarins and oranges.
- Relative humidity in transit transport should be kept as high as possible (around 92 to 95%) to prevent water loss from fruit and development of physiological disorders such as shriveling and stem end rind breakdown.

21.13 Conclusions

Citrus production has surpassed 100 million tons and certain market saturation starts to occur, particularly with regard to the production of oranges. Consumers seek fruit that is easy to handle and peel, without seeds but with adequate size and juice content, balanced sugar:acid ratio, and attractive bright color. Current production trends indicate that variety profile is shifting towards 'easy peelers'. This is particularly true with the fact that the two hemispheres are complementary and that development of transport technology allows for long-distance shipping and storage for long periods of time. Research will thus continue seeking improvements in the varieties with the aim of prolonging the period of production in the 'easy peeling' group via creation of new early and late cultivars through breeding and other technologies such as induced mutations and ploidy manipulation. Fruit of these varieties should be regarded as providing health- and wellness-related compounds and should have good firmness, juiciness, taste, color, size and be seedless, easy to peel and resistant to postharvest pathogens and to physiological disorders.

Research should also continue tackling aspects related to packaging to create attractive material and packages that would increase citrus fruit consumption. In addition, investigation should continue to create new ways of presentation of fruit, particularly for orange fruit, to facilitate handling by the consumer and, thus, increase demand.

Consumer awareness regarding health and safety has made significant and rapid changes in fruit handling and in the whole production and supply chain. These changes aim at ensuring a supply of good-quality, safe and healthy products to the consumer in the marketplace. These include bookkeeping of all practices and operations done to the crop at each point of the supply chain, implementing a traceability system and good production, harvesting, packinghouse, transport and storage practices, and also implementing quality and management systems that are certified as appropriate and optimal for the citrus sector. Efforts will continue in this field to ensure sustainability of citrus production and supply to guarantee a safe environment and adequate and clean natural resources for the generations to come.

21.14 References

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Plate XXXVIII Physiological disorders of fruit. (a), (b) Rind staining of Navelate oranges; (c) Stem-end rind breakdown on Valencia orange; (d) Rind breakdown in Clementine; (e) Chilling injury in Fortune mandarin; (f) Petaca in lemon fruit; (g) Chilling injury in Marsh grapefruit.

(a)

(b)

(c)

(d)

Plate XXXIX Fruit with disease symptoms. (a) Washington navel with blue mold (*Penicillium italicum*); (b) Fruit with green mold (*Penicillium digitatum*); (c) Reduced size and misshapen asymmetric fruit as a result of Huanglongbing disease on Valencia late; (d) Valencia fruit showing decay development postharvest starting at the point of puncture of the fruit by Mediterranean fruit fly.

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