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Papaya Fruit Quality Management during the Postharvest Supply Chain

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Introduction

Papaya (*Carica papaya* L.) is one of the major dessert fruit crops cultivated in the tropical and subtropical regions of the world. The early and continuous bearing habit makes papaya a popular fruit crop. Papaya belongs to the family Caricaceae and originated from south of Mexico and Nicaragua\(^1\) or from Costa Rica.\(^2\) Ripe papaya is eaten fresh, but also used in juices, nectars, purees, jams, jelly, or dried fruit.\(^3\) Green papayas are prepared as salads, cooked vegetables, or as chutneys and preserves. Papaya is produced commercially in more than 37 countries, with major cultivation in India, Brazil, Mexico, Nigeria, Indonesia, Ethiopia, Congo, Columbia, Guatemala, Thailand, Peru, and the Philippines.\(^4\) World production of papaya totals 10.5 million metric tons.\(^4\) Important exporting countries are Mexico, Brazil, and Belize, whereas European countries and the United States are the main importers of papaya.

The papaya fruit is a fleshy berry, varying in size from 15 to 50 cm in length and from 10 to 20 cm in width, and weighing up to 9 kg.\(^5\) The fleshy, edible pulp becomes aromatic,
yellowish orange, or different shades of salmon or red. Ripe fruit will develop a light or
depth yellow-orange skin color. Mature fruit contain numerous grayish black, ovoid seeds
enclosed in a sarcotesta, and attached to the flesh by soft, white, fibrous placental tissue.(5)
Papaya varieties have been developed by selection for desired phenotypes such as fruit
shape, size, taste, flesh color, firmness, disease resistance, fruit column compaction, preco-
cious fruiting, and yield.(6) The fruit produced from female flowers are spherical to ovoid
in shape, large and heavy, and include cultivars “Tainung 1” from Brazil, “Red Lady,” and
“Maradol.” Although all these varieties produce female and hermaphroditic plants, the Solo
group hermaphroditic flowers produce long, cylindrical or pyriform, small fruit (Fig. 1).(7)
Solo-type cultivars grown in Hawaii include “Kapoho,” “Sunrise,” “Rainbow,” “Sunup,”
and “Laie Gold.” The varieties “Rainbow,” “Sunup,” and “Laie Gold” are genetically
modified with resistance to the papaya ring spot virus.

Papayas are a rich source of vitamins A and C, and a good source of the minerals
magnesium (Mg), potassium (K), boron (B), and copper (Cu). (8–10) Consumption of one
medium papaya (edible portion 350 g) exceeds the Dietary Reference Intakes (DRIs) for
vitamins A and C established by the U.S. Food and Nutrition Board for adult minimum
daily requirements.(10–13) The major papaya carotenoids are lycopene, β-carotene, and
β-cryptoxanthin.(10,14–16) Papayas ranked fourth in total carotenoid content and vitamin
A activity among 39 fruit types,(17) and consumption of papayas high in antioxidant
carotenoids may potentially reduce the incidence of cancer and degenerative diseases.(18)
Consumer acceptance is higher for papayas free from external damage and decay, and uniform in size, shape, and color. Exported papayas are usually small- or medium-sized fruit with yellow or red flesh color.\(^{19–21}\) Generally, hermaphrodite (pear-shaped) or female (round) fruit are accepted by consumers. Internal quality attributes include uniform and intense flesh color, freedom from damage, and adequate soluble solids contents (SSC), depending on cultivar and consumer preferences. Papaya flavor quality also depends on variety, maturity stage at harvest, postharvest handling methods and treatments, and the incidence of mechanical damage or chilling injury, which can affect fruit flavor as observed in other tropical and subtropical fruits.

Papaya fruit is perishable, with a maximum postharvest life of 4 weeks.\(^{22}\) Unfortunately, marketing losses can be high for fresh papaya, with 46% postharvest loss for papaya in developing countries such as Sri Lanka.\(^{23}\) Production practices adopted during the farm to fork chain such as harvesting, field handling, sorting, grading, postharvest treatments, packing, storage, and transportation have a great impact on maintaining the optimum organoleptic, nutritional, and functional quality attributes of the papaya fruit. The objective of this review is to summarize the available research-based information for reducing papaya postharvest losses during the supply chain and retaining overall fruit quality via adoption of suitable postharvest technologies.

### Nutritional Composition of Papaya Fruit

Fresh papaya fruit provide 179–208 kJ of energy, 0.47–0.83 g protein, 0.5–2.1 g fiber, and 0.1–0.3 g fat per 100 g fresh weight (FW).\(^{9,24–26}\) Total sugar concentrations range from 7.5 to 13.7 g/100 g FW, with sucrose, glucose, and fructose as the main papaya sugars.\(^{27,28,29}\) At the early stage of fruit development glucose is the predominant sugar. However, sucrose content increases during ripening, and ranges from 2 to 6 g/100 g FW in ripe fruit.\(^{27,28}\) Sugars accumulate in the papaya flesh between 100 and 140 days after anthesis, coincident with a 10-fold increase in acid invertase activity.\(^{28}\) The edible flesh of ripe papaya also has significant levels of folate and the minerals K, Mg, Cu, and B.\(^{8,10,25,28}\) Papayas (100 g) provide 3–7% of the DRI for K, 6–8% of the DRI for Mg, and 9% of the DRI for Cu.\(^{8,11,10,30}\) The nutritive value of fully ripe papayas is similar for fruit ripened on-tree or off-tree, and for transgenic and nontransgenic lines.\(^{26,31}\)

The papaya’s most important nutritional value comes from vitamin C (ascorbic acid) and the provitamin A carotenoids β-carotene and β-cryptoxanthin. The attractive flesh color is due to the presence of carotenoids, β-Carotene, β-cryptoxanthin, β-carotene-5-6-epoxide, lycopene, and ζ-carotene are present in red-fleshed papaya fruit, whereas the yellow-fleshed papaya contains β-carotene, β-cryptoxanthin, and ζ-carotene.\(^{31,32}\) β-Cryptoxanthin is present as free and esterified forms, and together with β-carotene constitute the vitamin A precursors in fully ripe fruit.\(^{10,14,31}\)

The mean vitamin A content for 60 papaya samples grown in Hawaii was 44.1 μg retinol activity equivalents (RAE)/100 g FW and ranged from 18.7 to 74.0 μg RAE/100 g FW, depending on cultivar, ripeness, location, and season.\(^{10}\) Other sources report average vitamin A values from 30.1 to 64.1 μg RAE/100 g FW.\(^{17,27,24,31}\) Red-fleshed cultivars (“Pococi,” “Maradol,” “Sunrise,” “SunUp”) have further nutritional benefits due to high levels of lycopene (1.4–3.7 mg/100 g FW), a strong antioxidant that protects cells from reactive oxygen species.\(^{10,16,31,33}\) Lycopene content increased 10-fold during ripening of “Maradol” fruit to 3.5 mg/100 g in fully ripe fruit.\(^{16}\) Total carotenoid content was highest in ripe, red-fleshed papaya cultivars (3.0–6.2 mg/100 g FW) due to the abundance of
lycopene.\textsuperscript{(10,16,31)} In contrast, total carotenoid content averaged 0.8–1.1 mg/100 g FW for yellow-fleshed, Solo-type cultivars.\textsuperscript{(10)}

The concentrations of carotenoids and vitamin C were reported to correlate highly with antioxidant capacity ($R^2 = 0.988–0.995$).\textsuperscript{(16)} Vitamin C (ascorbic acid) is a potent, water-soluble antioxidant present in ripe papayas at concentrations ranging from 45 to 66 mg/100 g FW.\textsuperscript{(10,17,24–26)} Vitamin C content can increase with maturity and ripening, decline during storage, and also vary according to climate, harvest season, soil type, and production practices.\textsuperscript{(10,16,26,34,35)}

**Postharvest Quality Loss**

The major causes for postharvest quality losses along the marketing chain are due to mechanical injury that occurs during harvesting, field handling or transportation, overripe fruit, desiccated fruit, postharvest diseases (anthracnose, stem-end rots, *Rhizopus* rot), chilling injury from improper storage temperature, pest damage, and physiological disorders. These factors affect the appearance, texture, flavor, and nutritional value of the fruit. For example, loss of firmness and chilling injury were the main limitations to retail quality for “Red Lady” papayas subjected to fluctuating temperatures (too cold or warm) during simulated shipping and handling.\textsuperscript{(36)} However, decay, mechanical damage, and softening were the primary postharvest defects of papayas shipped from Hawaii to the mainland United States.\textsuperscript{(35)} In some cases, more than one defect is found in a carton or on an individual fruit.\textsuperscript{(37)}

**Harvesting Maturity and Quality Attributes**

Maturity at harvest is a very important determinant of storage life and final fruit quality. Harvesting fruit at improper maturity can lead to uneven ripening and overripe fruit. It is recommended to harvest papayas after the skin color changes from dark green to light green, because the fruit accumulate sugars during the final stage of development.\textsuperscript{(38)} However, the sugar content does not increase after picking and this will affect fruit flavor. The development of a yellow tinge or streak at the blossom end (color break) is an important criterion to determine suitable harvest maturity.\textsuperscript{(39)} Papayas for commercial trade are harvested when the peel color is between color break and one-quarter yellow, depending on the distance to markets.\textsuperscript{(9)} At this stage the flesh is hard but will continue to ripen after harvest, and the fruit will withstand the rigors of postharvest handling and transport. Skin and flesh color development, textural and compositional (organic acids) changes, and synthesis of volatile aroma compounds occur during ripening after harvest, concomitant with the climacteric period.\textsuperscript{(40)} Fruit harvested before color break will fail to complete ripening, will have lower total soluble solids content, and will not reach a desirable taste. Fruit harvested at an advanced yellow stage are highly susceptible to bruising, decay, and water loss, resulting in quality deterioration. Therefore, suitable maturity indices for harvesting are very important to minimize quantitative and qualitative losses. Papaya fruit are climacteric, with respiration rates at 20 °C for fruit at the color break and ripe stages of 9–18 and 70–90 mg CO$_2$·kg$^{-1}$·h$^{-1}$, respectively. Ethylene rates ranged from 7 to 10 μg·kg$^{-1}$·h$^{-1}$ in ripening fruit.\textsuperscript{(41)}

Consumers are more likely to purchase bright, colorful papayas.\textsuperscript{(42)} The attractive color of papaya is due to carotenoids.\textsuperscript{(33)} During ripening, the external yellow skin color develops from the blossom end, whereas the internal flesh coloring and softening develops from the endocarp outward.\textsuperscript{(37)} “Maradol” papayas showed higher carotenoid content (2-fold)
than those reported for “Formosa” and “Sunrise” papaya, which could be due to location, sunlight exposure, and production practices, as well as cultivar differences. There was a predominant increase in lycopene and β-cryptoxanthin esters in red-fleshed fruit of “Pococi” during ripening, whereas carotenoid precursors (phytoene, phytofluene, and ζ-carotene) were detected in trace amounts. Lycopene and carotenoids are synthesized via the isoprenoid pathway from two molecules of geranylgeranyl pyrophosphate to form phytoene, phytofluene, and ζ-carotene, which are intermediate products in the biosynthesis of β-carotene and xanthophylls. Papaya flesh color is controlled by a single gene, with yellow color dominant over red. In yellow-fleshed cultivars, lycopene is rapidly synthesized into β-carotene and xanthophylls by lycopene β-cyclases and carotene hydrolases. However, lycopene accumulates in red-fleshed fruit because the lycopene β-cyclase gene has a functional mutation. In yellow-fleshed cultivars, β-carotene and free and esterified β-cryptoxanthins accumulated during ripening, but lycopene was present in only trace amounts. Similar observations were reported in F1 hybrids and inbred lines grown in Costa Rica. The observed differences in lycopene contents in yellow- and red-fleshed papayas were also due to chromoplast morphology and ultrastructure. The red-fleshed papaya contained crystalloid structures linked with accumulation of lycopene. An exponential correlation was reported between the color changes of papaya mesocarp and the total carotenoid, lycopene and vitamin A contents.

The soluble solids content tends to increase during fruit ripening and softening, and varies from 6% to 19% depending on cultivar. However, the soluble solids content of mature fruit should be at least 11.5% to meet market grade. Titratable acidity was reported to increase as fruit ripened to about 75% yellow skin color, and decrease thereafter. Similar observations were reported in “Golden” (“Sunrise” or Solo-type) and “Pococi” papayas. However, in “Pluk Mai Lie” papayas, the titratable acidity did not differ significantly throughout the ripening process and the malic acid content was reported to decrease during papaya ripening. Sweet taste is an important quality parameter for fruit. Taste is generally associated with sucrose, glucose, and fructose contents, which are used as a ripening index to determine the stage of ripeness and for quality standards of papaya. It was suggested that the sweet taste in papaya is related to a loss of fruit firmness and textural changes, and this was supported by an observed correlation between mastication time and sweet taste perception. During ripening-related changes in skin and flesh color, the total soluble solids was noted to increase in the pulp, whereas the flesh softened from a degradation of cell wall components and an accumulation of lower-molecular-weight carbohydrates. Therefore, skin color, carotenoid content, total soluble solids (TSS), and flesh firmness can be considered as suitable parameters to determine a ripening index for papaya. The Solo-type papayas, “Sunrise” and “Kapoho,” showed desirable quality attributes in terms of soluble solids content, flesh color, and small fruit size. During ripening, ethylene (C2H4) initiates the increase in carotenoid content in the skin and flesh and many of the biochemical changes associated with fruit flavor, aroma, and texture. Fruit softening is due to depolymerization of pectin in the cell walls, in which high-molecular-weight insoluble pectin is converted into soluble polyuronides. This ripening-induced softening is catalyzed by the enzymes polygalacturonase (PG), pectin methylesterase (PME), β-galactosidase, and cellulase. A direct relationship was reported between polygalacturonase and xylanase activity and fruit softening. The increased xylanase activity solubilized hemicelluloses in the cell wall and resulted in decreased fruit firmness at the 40–60% yellow ripe stage, indicating that degradation of hemicellulose, as well as pectin, may play a significant role in papaya fruit softening.
Fruit texture is commercially important, as it directly dictates papaya shelf life, quality, and consumer acceptance. For example, bruised papayas soften and deteriorate quickly. Bruising causes compression of cell layers and the loss of elasticity of the cell wall, leading to the rupture and release of cell contents into the intercellular spaces. Enzymatic degradation of the cell wall polysaccharides also occurs in the affected tissues and results in fruit softening. Mechanical wounding has been shown to induce the activity of 1-aminocyclopropane-1-carboxylic acid synthase, which catalyses production of 1-aminocyclopropane-1-carboxylic acid, the immediate precursor for C2H4. Therefore, mechanical damage during harvesting, storage, and transportation needs to be avoided to maintain papaya quality. High-quality papayas are firm and fresh in appearance, and will soften and ripen uniformly before consumption.

Ripening is also associated with biosynthesis of aroma volatiles, but fruit picked while still green will never attain their full aroma. Papaya volatiles consist of a complex mixture of compounds including esters, with terpenes as the most important volatile constituents. Ester volatile production (ethyl butanoate, ethyl hexanoate, ethyl octanoate, methyl benzoate, ethyl acetate) was low at immature and color break stages and then increased with the onset of ethylene production, showing a dramatic rise coincident with ripening and the loss of fruit firmness. Esters are formed by combining alcohols with acyl-coenzyme A (CoA) derivatives of fatty acids by the action of alcohol acyltransferase. Ethylene induces ester volatile production in climacteric fruits in particular via control of alcohol acyltransferases. Alcohols are another important group of volatile compounds found in papaya and these compounds act as substrates for ester production. The levels of methanol, butanol, and hexanol in papaya fruit increased steadily throughout ripening. Ripening-related processes, such as changes in cell wall composition, might also contribute intermediates to ester biogenesis. Terpenoids, the most abundant volatile components in papaya, are synthesized through the acetate–mevalonate pathway in the cytoplasm. The mevalonate pathway leads to the production of sesquiterpenes and triterpenes (sterols), whereas monoterpenes, diterpenes, tetraterpenes (carotenoids), and polyterpenes are formed by the nonmevalonate pathway in the plastids.

The amount of each volatile component varies according to cultivar and production location. Linalool, benzyl isothiocyanate, and terpene hydrocarbons are major volatile components in Solo papaya. "Sri Lankan" papayas also contain glucosinolate products in their volatile components with methyl esters, mainly methyl butanoate. Papaya fruit aroma determines the consumer acceptance and market preference for specific cultivars. Consumers from the European Union and the United States typically do not appreciate the heavy musk odor from methyl butanoate in some South Asian cultivars. The variety "Maradol Roja" contains higher concentrations of butanol, 3-methylbutanol, benzylalcohol, and α-terpineol at the fully ripe stage. Flavor is an important quality trait that also affects consumer acceptance to a great extent. Flavor is mainly composed of sweetness, sourness, and aroma that correspond to sugars, acids, and volatile compounds. During the development of sweetness in papaya, there are changes in the profiles of phenolic compounds that contribute to flavor, but the titratable acidity offers a low contribution to papaya flavor. Although flavor is determined primarily by genetic factors, it can be affected by preharvest conditions, postharvest handling, packing operations, and storage.

**Harvesting, Cleaning, and Grading**

Papayas are generally hand harvested during the coolest part of the day by twisting the fruit until the peduncle snaps off the plant, or cutting the peduncle with a sharp knife. Generally,
harvest needs to be during the morning, because as the fruit temperature increases, it becomes more susceptible to bruising injury. Harvesting poles fixed with special baskets or rubber cups also are used to harvest papayas, and the fruit are allowed to fall into a collecting basket, tray, bucket, or bag. In some orchards, mechanical harvest aids with platforms are used to reach fruit high on the plant columns. Care should be taken to prevent latex staining of the fruit surface. Latex staining occurs as a result of fruit skin damage. Latex exuding from the cut stem end can cause staining of the fruit surface. Latex contains two proteolytic enzymes, papain and chymopapain. The stem must be trimmed equally with the shoulder of the fruit to prevent puncturing adjacent fruit.

Mechanical injuries (cuts, abrasion damage, or bruising) can be ideal sites for postharvest pathogens such as Phomopsis and Rhizopus spp. to gain entry to the fruit tissue. Skin abrasions result in areas or islands in the peel that will remain green and sunken when the fruit is fully ripe. Furthermore, abrasion and impact injuries can lead to a loss of pulp firmness and desiccation. Papayas are collected in smooth surfaced, ventilated, padded plastic crates or in clean collection bags. Thereafter, fruit are transferred into large bins without scratching the skin, which would release latex and stain the skin. Fruit are sorted in the field according to color stages and defects. After harvest, the fruit should be protected in a shaded area until transport to the packing house. The postharvest handling chain of papaya is illustrated in Fig. 2.

Generally, papayas are not washed for domestic markets. However, in South Africa, fruit are washed to remove latex and to improve the appearance of the fruit for market. Sodium hypochlorite solution is used in the wash water as a sanitizing agent. Grading is an essential step before marketing, and is done according to fruit size, shape, and external color. Fruit that are destined for export need to be free of bruises, latex burn, skin blemishes,

![Figure 2. Postharvest supply chain flow for papaya.](image-url)
insect damage, physical injury, shriveling, surface scars, and diseases. Hawaii Fancy or Hawaii Grade AA standards for papayas require that total defects cannot constitute more than 10% of any lot, with no more than 5% defects causing damage, and not more than 1% with decay or breakdown.(47)

Temperature and Relative Humidity Management

Low-temperature storage extends papaya postharvest life while maintaining quality attributes such as texture, aroma, flavor, and nutritional composition during the supply chain. Low temperature has a direct effect on the respiration rate of fresh papaya, which is an indication of the rate of perishability. For every 10 °C increase in temperature the respiration rate approximately doubles and primary metabolic substrates (sugars and organic acids) are depleted at a faster rate. Storage life varies inversely with respiration rate, therefore, papaya shelf life is shortened at higher temperatures. Low-temperature storage slows the climacteric increase in CO₂ and C₂H₄ production that occurs with ripening. Multiple enzymes involved in the synthesis of ethylene, carbohydrates, organic acids, carotenoids, and volatile compounds are inhibited at lower temperatures, and consequently, ripening-related changes in color, flavor, texture, and aroma are delayed. Therefore, papayas should be stored at 10 °C to extend shelf life. An increase in temperature above 10 °C will accelerate fruit ripening and softening, whereas fruit stored below 10 °C may develop chilling injury (CI). Postharvest storage life of papaya also depends on the maturity stage at harvest. Fruit harvested at the color break stage and held at 25–28 °C will ripen to 60–70% yellow skin color within 4–6 days, but can be stored 14–21 days at 10 °C with adequate postharvest disease control measures. Market life is very short at advanced stages of maturity (e.g., 5–6 days for three-quarters ripe fruit).(48)

The maintenance of high relative humidity (RH) also is important because papayas are susceptible to shriveling. Therefore, it is recommended to store the fruit at 90–95% RH to prevent weight loss and skin desiccation. Weight loss is directly related to water loss, which takes place through the stomata, stem scar, and cuticle.(72) The amount of water loss depends on cuticle thickness, which varies with cultivar and maturity stage. Papayas become unacceptable for sale after reaching 8% weight loss for the small-fruited Solo types and 4–6% weight loss for large-fruited “Red Lady.”(36,72) However, high RH may promote decay development, especially if moisture condenses on the fruit (sweating) over long periods of time when temperatures fluctuate during transportation. Therefore, for efficient marketing of papayas, the participants in the supply chain need to understand and maintain optimum temperature and RH to retain overall fruit quality.

Alleviating Chilling Injury (CI)

Chilling injury occurs when papayas are stored at temperatures below a critical threshold. CI is associated with changes in chemical composition of the membranes, in particular the fatty acid composition. The temperature affects the degree of membrane changes from a gel phase to a liquid crystalline phase. As a result of this transition, the cell membranes lose integrity and cell compartmentation is weakened.(73) The CI is also accompanied by lipid degradation due to the activity of lipoxygenase, for which linoleic acid and linolenic acid serve as common substrates.(74) The degradation of such polyunsaturated fatty acids yields peroxide ions and malondialdehyde, the product of oxidation injury. Discoloration of the skin or flesh may result from CI, and is caused by browning reactions mediated by
peroxidases and polyphenol oxidase. The severity of CI depends on exposure time, cultivar, and maturity stage. Papaya fruit at the color break stage can be stored at 7 °C up to 14 days without CI and the fruit ripens normally at ambient temperature, whereas the mature green fruit reveal CI symptoms.

Symptoms of CI appear after transferring the chilled fruit to ambient temperatures (25–28 °C) during marketing. Typical CI symptoms include the development of sunken spots or pitting on the skin, discoloration, uneven ripening, inferior fruit flavor, and increased susceptibility to postharvest pathogens. During chilling damage, sugars and organic acids are depleted as a result of increased respiration rates. Malaysian cultivars Bentong and Taiping developed CI after storage for 7 days at 15 °C. A prestorage heat treatment at 45 °C for 6 h was reported to reduce chilling injury symptoms for “Sunrise” papayas stored at 5 °C, by delaying the decline of superoxide dismutase and catalase activities, and suppressing an increase of peroxidase activity.

Superoxide dismutase is an enzyme that converts the radical anion superoxide (O$_2^-$) to H$_2$O$_2$ and O$_2$. The accumulation of H$_2$O$_2$ reactive oxygen species can result in the peroxidation of membrane lipids. The catalase enzyme catalyzes the dismutation of H$_2$O$_2$ to H$_2$O and O$_2$. Peroxidase facilitates the oxidation of unsaturated fatty acids by singlet oxygen and formation of malondialdehyde. The membrane damage caused by CI can induce the activity of the ethylene-forming enzyme that converts 1-aminocyclopropane-1-carboxylic acid into C$_2$H$_4$. Therefore, the use of ethylene absorbers inside packages of papayas controlled chilling injury after 20 days storage at 7 °C. CI symptoms also were diminished in “Sunrise” papaya with methyl jasmonate (10$^{-4}$ M) treatments and modified atmosphere packaging (MAP) under cold storage. The inhibitory effect of MAP on chilling injury may be related to reduced water loss and the effects of low O$_2$ and high CO$_2$ concentrations on C$_2$H$_4$ biosynthesis and sensitivity. Methyl jasmonate was reported to reduce CI via a mechanism that involves an increase in abscisic acid and polyamine levels.

**Ripening and the Use of Ethylene Inhibitors**

The presence of ethylene during postharvest storage and transportation accelerates ripening, resulting in soft, overripe fruit that can lead to substantial losses. The detrimental effects of ethylene on fruit quality can be minimized by inhibiting ethylene biosynthesis or by removing ethylene surrounding the fruit in storage. The ethylene inhibitor, 1-methylcyclopropene (1-MCP), is a nontoxic chemical that delays ripening by blocking ethylene action in plant cells, and thereby maintains postharvest quality of fresh produce. Applications of 1-MCP have been investigated for Solo-type papayas and shown that the 1-MCP treatment increased the number of days taken to ripen by ~15.5 days for papaya compared with untreated fruit. With some climacteric fruit, such as papaya, 1-MCP can prevent uniform ripening due to exogenous ethylene exposure or rapid fruit softening because of poor postharvest handling. The commercial product (Smartfresh) was registered for use on papayas and 12 other fruit types in the United States and is currently being registered for papaya in South Africa (Rohm and Hass, South Africa).

Papayas treated with 1-MCP showed less PME activity and lower contents of soluble pectin, and delayed fruit softening. 1-MCP may reduce cellular disintegration resulting from oxidative stress by enhancing some antioxidant enzyme activities (superoxide dismutase, ascorbate peroxidase, and catalase) and preventing ethylene-associated degradation of cell wall components that lead to tissue softening. Treatment with 1-MCP at 100 μL·L$^{-1}$ resulted in a longer shelf life for cultivar Kapoho, with less severity of diseased fruit. However, in other studies, 1-MCP treatment delayed ripening in fruit harvested at commercial maturity, but increased the incidence of postharvest fungal diseases after ripening.
When papayas at the 25–30% yellow stage were pretreated with 1-MCP (100 μL) and dipped in a biocontrol agent (*Bacillus amyloliquefaciens* PPCB004), disease incidence and severity were lower and overall fruit quality higher than for untreated or 1-MCP-treated fruit. Therefore, 1-MCP treatment can enhance uniform ripening and extend shelf life and may provide a commercial solution to ensure fruit quality if postharvest diseases are managed. In developing countries, postharvest treatments that extend storage life are especially important where cold chain infrastructure is not well established. In those circumstances, application of 1-MCP may provide a suitable alternative to extend the postharvest life of papaya at ambient temperature (25 °C).

Treatment durations (4–24 h) with 1-MCP did not affect ripening parameters. Rather, the ripening pattern was reported to vary according to the color stage of the treated fruit. Fruit treated during color break stage were reported to soften completely, but developed an elastic or rubbery flesh texture. The “rubbery” condition was noted when the fruit were treated with 50–1000 μL·L⁻¹ 1-MCP. In contrast, fruit treated at 25% yellow skin ripened normally, and when treated at 10% yellow skin, the fruit failed to soften. Fruit treated with 1-MCP at maturity less than 25% yellow skin failed to ripen completely, had a reduced respiratory peak, and delayed ethylene production. Fruit treated at over 30% yellow color stage had slightly delayed ripening and skin color development, but softened normally.

The inhibitory effects of 1-MCP on ethylene action and ripening could not be reversed by exposing fruit to a synthetic ethylene-releasing compound (ethephon). Normally, papaya ripening is hastened by ethephon treatment (500–600 μL·L⁻¹ for 30 min), but ethephon treatment after or before 1-MCP treatment failed to soften 1-MCP-treated fruit. This could be due to a strong affinity or competition of 1-MCP for the ethylene binding sites in the cell membrane, effectively blocking ethylene action and fruit ripening. Synthesis of new receptor sites to bind ethylene, or disassociation of 1-MCP from existing receptor sites, would be needed to overcome the inhibitory effect of 1-MCP on ethylene responses.

**Postharvest Decay**

Postharvest diseases reduce fruit quality and result in severe losses. High relative humidity, improper storage temperature, or abusive temperatures can favor the incidence of postharvest diseases on fruit. Fungal pathogens gain entry via the wounds or cuts on the fruit surface. Insect injuries also can act as ideal infection sites for many postharvest disease-causing organisms. Therefore, damaged fruit must be removed from the packing line during the grading process.

Anthracnose, caused by *Colletotrichum gloeosporioides*, is a major postharvest disease of papaya. Field inoculum of *C. gloeosporioides* in the form of conidia originates from dying infected petioles of the lower leaves. The disease is more severe during wet weather. Conidia released by splashing rain are carried by air currents to developing fruit. If moist conditions exist for a few hours, the conidia develop appressoria and infect the fruit. Infections remain latent and symptoms become evident only when the fruit ripens during the postharvest period. *Rhizopus stolonifer* is another pathogen that infects and limits the postharvest life of papaya fruit. The infection takes place during harvest and handling and causes a soft, watery rot. The fungus spreads rapidly to adjacent healthy fruit, causing an extensive nest of decay, especially in storage under favorable conditions. Stem-end rots are caused by *Lasiodiplodia theobromae*, *Mycosphaerella caricae*, and *Phoma caricae-papayae*. These fungi become established during fruit development and remain quiescent under the cuticle. Some fungi enter through mechanical injuries, such as the
broken peduncle while harvesting. The presence of spots and rots can degrade external quality and can lead to market rejections.

Generally, low-temperature (10–12 °C) storage can delay decay development in fresh papayas. However, strict preharvest disease control measures and orchard sanitation practices also must be adapted to prevent postharvest diseases. During harvest and handling, precautions must be taken to avoid using unsanitary harvesting bags, bins, sorting or grading equipment (especially the rollers and brushes), and packing boxes in order to avoid colonization of pathogens or accumulation of inoculum that can infect healthy fruit. Water used for washing can become contaminated with the propagules of postharvest pathogens and needs to be changed on a regular basis. The water temperature also is an important factor in the transfer of inoculum present in the wash water into the fruit. Although storage at 10 °C can inhibit decay, residual protection against postharvest diseases is important after removal from cold storage.

**Postharvest Insect Infestation**

The movement of fresh papaya between countries poses a risk of introducing insect pests to new areas. The Caribbean (*Anastrepha suspensa*), Mexican (*Anastrepha ludens*), Mediterranean (*Ceratitis capitata*), oriental (*Bactrocera dorsalis*), melon (*Bactrocera curcurbitae*), Asian papaya (*Bactrocera papayae*), and papaya (*Toxotrypana curvicauda*) fruit flies are quarantine insects that can limit the marketability of papaya. The presence of surface pests such as scales, mites, aphids, thrips, leafhoppers, or whiteflies also may impede shipments or lead to rejections by port inspectors. Therefore, fresh papaya must receive an approved quarantine treatment before export to prevent the spread of exotic pests. The aim of the quarantine treatment is to kill or sterilize infecting insects to meet phytosanitary requirements. Heat treatments (hot-water immersion, vapor heat, or forced hot air) and irradiation are approved quarantine treatments for fruit flies and surface pests on papayas.

**Postharvest Treatments**

*Effect of Heat Treatments on Decay, Insect Control, and Fruit Quality*

Postharvest heat treatments (water or vapor) are regarded as nonpolluting, safe physical treatments to control disease and insect disinfestations during postharvest storage and marketing of fresh fruit. Immersion of papayas in hot water (48 °C) for 20 min has been a principle treatment to control postharvest diseases such as anthracnose and stem-end rot. The effectiveness of fungicide treatments (thiabendazole, TBZ) were enhanced with hot water. An integrated treatment with hot-water spraying and TBZ reduced the incidence of anthracnose and stem-end rot in papaya. TBZ also appeared to be an effective fungicide capable of controlling chilling injury in cold-stored papaya.

A two-stage hot-water treatment (double dip) was developed for disinfecting papaya of tephritid fruit fly eggs for Hawaiian papayas by immersing one-quarter ripe papaya in 42 °C water for 30 min, followed by 49 °C water for 20 min, and finally hydrocooling with water spray at ambient temperature. Fruit are subjected to the two-stage hot-water treatment within 18 h of harvest. However, the two-stage hot-water treatment did not provide adequate control for insect infestation. The two-stage hot-water treatment kills only eggs and early instar larvae near the fruit surface. Papayas more than one-quarter ripe may have larvae in the center, which might not be killed by the treatment. Viable larvae of
oriental fruit fly were found after treatment in fruit with blossom-end defects. Also, the two-stage hot-water treatment damaged fruit in some cases.

Subsequently, vapor-heat treatment was adopted to kill fruit flies in papaya. Vapor-heat treatment uses moist hot air to kill internal feeding pests and is an alternative to chemical fumigation with methyl bromide. During vapor-heat treatment, the fruit core temperature is raised to 47.2 °C over a period of 6–8 h, thereafter the fruit are cooled to below 30 °C with water. The vapor-heat treatment is sufficient to kill both the fruit fly eggs and larvae. Vapor-heat treatment is commercially practiced in Hawaii for papayas exported to Japan.

Forced hot-air treatment (dry heat) is a modification of vapor-heat treatment to kill Mediterranean fruit fly, melon fly, and oriental fruit fly eggs and larvae in papaya. During this treatment, papayas are heated from 4 to 7 h in order to allow the centers of all the fruit to reach 47.2 °C, with the RH between 45% and 65%. The effectiveness of forced hot-air treatment depends on the size, physiological variability, and thermal conductivity of individual fruit. The fruit treated at 1/8 color stage had good quality after storage. Forced hot-air treatment has been used commercially for Hawaiian papaya exported to the U.S. mainland, from Belize to the United States, and from the Cook Islands, Fiji, Samoa, and Tonga to New Zealand.

Heat treatments, whether to manage chilling injury, diseases or insects, may impact the quality of papaya fruit. Heating “Ekotsika” papaya at 38 °C for 6–24 h prior to low-temperature storage was reported to alleviate chilling injury. Internal color, total soluble solids, weight loss, and β-carotene and lycopene concentrations did not change due to heat treatment (dry [50%] hot air [48.5 °C] for 4 h) in “Maradol” papaya, although the interaction between heat treatment and storage temperatures affected sugar concentration. The impact of two-stage hot-water treatment on subsequent ripening depends on harvesting and treating fruit at the correct skin color. The two-stage hot-water quarantine treatment produced uneven ripening at some maturity stages, with surface scalding and unusual fruit softening. Poor flavor, lumpiness, and “hard-core” texture were common quality problems in hot-water-treated papayas. The slower heating of the forced hot-air quarantine treatment produced a preconditioning effect that provided better fruit quality than the rapid heating of the two-stage hot-water immersion treatment.

The forced hot-air treatment for disinfestation of fruit flies did not improve postharvest disease control when compared with fungicide or hot-water treatments. However, the incidence of most papaya postharvest diseases was reduced when the forced hot-air quarantine treatment was combined with TBZ or hot-water immersion at 49 °C for 20 min. Disease incidence was not significantly affected by the sequence of hot-air or hot-water application. However, when hot-water preceded hot-air treatment, pitting and scalding symptoms increased with degreening and the incidence of internal lumpiness (hardened lumps of ripe flesh) increased. High-temperature treatments can alter the pattern of ripening-related changes in papaya, including skin color, respiration and ethylene production, 1-aminocyclopropane-1-carboxylic acid content, ethylene-forming enzyme activity, and internal carotenoid synthesis. Paull suggested that the response of papaya to heat treatments depends on harvest maturity and seasonal changes. Fruit that were harvested during cooler periods were observed to be susceptible to heat injury.

Effect of Biocontrol Agents, Carbonate Salts, and Coatings on Fruit Quality

Fungicide residues present on fruit surfaces may be harmful to consumers. This situation has prompted investigations of potentially safer approaches to disease management.
When developing nonchemical control measures, the effects on fruit quality, ease-of-use, and safety for public health and the environment should be considered. The efficacy of sodium bicarbonate at 2% for control of anthracnose was reported to increase when combined with the biocontrol agent Candida oleophila at 13.5 °C and 95% RH for 14 days, followed by 2 days at simulated marketing conditions (25 °C, 75% RH). The growth of C. gloeosporioides was reduced significantly in the presence of C. oleophila in both inoculated and naturally infected fruit, resulting in 60% marketable fruit. C. oleophila has the ability to utilize a large number of carbohydrates and organic acids as carbon and energy sources and thereby competes with the C. gloeosporioides that causes anthracnose disease in papaya. Incorporation of 2% sodium bicarbonate into a wax coating (carnauba) and in the presence of C. oleophila resulted in a significant reduction of anthracnose incidence and severity in naturally infected fruit and was considered as a partial alternative to fungicides to control anthracnose on papaya during storage. This treatment can be recommended for organic growers, exporters, or health-conscious niche markets. The synthetic wax coating was later replaced with a chitosan application in combination with sodium bicarbonate. Chitosan with ammonium carbonate was more effective at reducing anthracnose incidence and severity than chitosan alone, or chitosan with sodium bicarbonate. The application of biocontrol agents still has challenges for adoption into commercial practice. These include survival of the organism during long-term cold storage, registration of bacterial biocontrol agents that produce antibiotics, public acceptance, and potential development of pathogen resistance to biocontrol agents. Therefore, the integrated use of biocontrol agents with modified atmosphere packaging or with ammonium carbonate may be more practical and effective at controlling postharvest diseases.

Effect of Irradiation Treatments on Decay, Insect Control, and Fruit Quality

Irradiation (gamma, X-ray, or electron beam) at doses up to 1000 Gy has been approved by the U.S. Food and Drug Administration for the preservation and disinfestation of fresh fruits and vegetables. The U.S. Department of Agriculture’s Animal and Plant Health Inspection Service (USDA-APHIS) regulates the use of irradiation as a phytosanitary treatment for commodities entering the United States. USDA-APHIS also regulates interstate movement of fresh horticultural crops from Hawaii, Puerto Rico, and the U.S. Virgin Islands into the mainland. Hawaii is the first place where irradiation was used for quarantine treatment of tropical crops. In 2000, a commercial e-beam (converted X-ray) facility was built on the island of Hawaii and papaya was the first crop treated and exported. Irradiation is an effective quarantine treatment for papayas due to its insecticidal effects on all stages of the fruit fly life cycle at low doses. USDA-APHIS has approved minimum generic irradiation doses of 150 Gy for control of tephritid fruit flies and 400 Gy for all insects except pupa and adult Lepidoptera. The 150-Gy dose is approved for fresh papaya based on its host status for fruit flies. However, in commercial practice, papayas are treated with 400 Gy irradiation to avoid the chance of rejections due to the presence of surface pests.

Papayas at the mature-green or quarter-ripe stage can tolerate up to 1000 Gy irradiation without changing in nutritional or sensory quality or developing surface scald. Irradiation may delay ripening and softening, but its effect depends on the maturity stage of treated papaya fruit. Papayas irradiated at the 25–30% yellow stage with 500–1000 Gy retained firmness for 2 days longer than control fruit. Delayed softening of irradiated fruit (500 Gy) was related to changes in the activity of cell wall degrading enzymes, especially PME. Also, fruit treated at the 30% yellow stage with 250 Gy...
irradiation softened more uniformly than untreated fruit.\cite{40} Fruit with less than 25% yellow color developed skin scald when placed at 10 °C immediately after irradiation, but injury was prevented by delaying cold storage for 12 h.\cite{40}

**Effect of Modified (MA) and Controlled (CA) Atmosphere Storage on Disease and Insect Control**

In MA or CA, gases are removed, altered, or added to create an atmosphere around the fruit that differs from ambient air, usually resulting in lower O\(_2\) and elevated CO\(_2\) concentrations. CA storage has an exact control of the atmospheric composition, whereas MA varies according to fruit respiration rate, package permeability, and storage temperature. Storage atmospheres with moderately low O\(_2\) (2–3\%) and high CO\(_2\) (>5\%) levels were reported to inhibit ethylene production and ripening, reduce the respiration rate, maintain color and flesh firmness, retard decay, prevent chilling injury, and thereby extend the storage life of fresh produce, including papaya.\cite{129} However, gas composition (excessively low O\(_2\) or high CO\(_2\)) outside the fruit’s tolerance range can cause physiological disorders, uneven ripening, increased susceptibility to decay, off-flavors, and loss of product. Successful MA/CA application depends on avoiding mechanical damage and implementing good sanitation practices, temperature management, and humidity control. MA or CA conditions are most suitable during sea transport, which is less expensive but of longer duration than air transport.

MA/CA can also be useful for insect control, which may be achieved with high CO\(_2\) or low O\(_2\) concentrations combined with higher temperatures and lower RH, although the effectiveness depends on fruit maturity stage, insect species, and treatment duration.\cite{100} Extreme atmospheres with <1\% O\(_2\) and/or >60\% CO\(_2\) were lethal to several insects.\cite{130} The use of MA or CA for insect disinfection or quarantine treatment is considered a cost-effective alternative to chemical fumigation.\cite{131} MA/CA storage does not leave any chemical residue on the fruit, and does not accelerate ripening or cause fruit injury as compared with heat treatments.\cite{85} However, anaerobic conditions (<1\% O\(_2\)) promote fermentation of the fruit, reducing organoleptic properties. Use of insecticidal MA/CA at room temperature prevents heat injury and requires a lower energy input. However, the advantage of using insecticidal atmospheres at higher temperatures is to achieve insect mortality during a very short period, while preventing the accumulation of fermentation products.\cite{100}

“Sunrise” papaya can tolerate insecticidal atmospheres of low O\(_2\) (0.17–0.35\%) for 3 days at 20 °C without resulting in off-flavors.\cite{132} After 3 days, low O\(_2\) correlates with an increase in the activities of pyruvate decarboxylase and lactate dehydrogenase, but not alcohol dehydrogenase, in fruit tissue. Therefore, low O\(_2\) atmospheres (0.17–0.35\%) are recommended to control insects that can be killed within 2 days at 20 °C without sacrificing fruit quality and consumer acceptance.\cite{132} Longer duration can induce off-flavor development and fruit decay and affect consumer acceptance of CA/MA-stored papayas.\cite{132}

The MA can be achieved passively when respiring fruit are packaged in polymeric films with restricted permeability to CO\(_2\) and O\(_2\). Modified atmosphere packaging (MAP) has been shown to delay color development and reduce water loss of papayas before fungal decay limited shelf life.\cite{133} The modified atmospheres (4–5\% CO\(_2\) and 2–3\% O\(_2\)) created inside low-density polyethylene (LDPE; 0.04 mm thickness) bags was suggested as a possible way to transport “Eksoṭika” papaya to distant markets in refrigerated sea containers at 10–12 °C for 14 days.\cite{134} On arrival, the fruit were reported to be fresh, with minor
changes in skin color, reduced disease incidence, and the ability to ripen normally within 3–4 days at ambient temperature.\(^{(134)}\)

The postharvest quality of papaya was enhanced by combining methyl jasmonate treatments with MAP.\(^{(82)}\) Treatment of “Sunrise” papaya with methyl jasmonate vapors for 16 h at 20°C inhibited fungal decay, chilling injury, and loss of fruit firmness. Methyl jasmonate was reported to reduce chilling injury via a mechanism that involves an increase in abscisic acid and polyamine levels.\(^{(84)}\) The inhibition of fungal decay and loss of fruit firmness after exposure to methyl jasmonate vapors was due mainly to an induced defense mechanism observed in the fruit tissue during subsequent storage at 10°C for 14–32 days, followed by 4 days shelf life at 20°C.\(^{(82)}\) Methyl jasmonate treatment enabled the fruit to retain higher organic acids, and the MAP prevented water loss, further softening, and yellowing. The MA (3–5% O\(_2\) and 6–9% CO\(_2\)) created inside the LDPE package did not induce any off-flavor development during storage at 10°C.\(^{(82)}\)

Combination treatments of hot-water dipping and MAP also have been evaluated for extending the storage life of papayas.\(^{(23)}\) Papayas (cv. Rathna) subjected to hot-water dipping (49°C) for 20 min followed by spraying with 5% ethanol (for surface disinfection of the fruit) and packaging in LDPE with KMnO\(_4\) (an ethylene absorber) had an extended postharvest life up to 12 days.\(^{(23)}\) The C\(_2\)H\(_4\) plays a major role in papaya ripening, and the KMnO\(_4\) oxidizes ethylene to form CO\(_2\), H\(_2\)O, and MnO\(_2\) and thus delays ripening.\(^{(135)}\) Due to its high toxicity, KMnO\(_4\) cannot be used in direct contact with fresh produce and, therefore, it is used commercially in combination with different inert substrates in sachets, films, or filters. Packaging papayas (cv. Golden) in LDPE (0.25 mm thickness) with ethylene absorber sachets (Always Fresh\(^\text{®}\)) was effective at controlling chilling injury after storage at 7°C.\(^{(81)}\) MAP using polyethylene bags with ethylene absorbent was reported for “Eksotika” papaya exported from Malaysia.\(^{(136)}\) Furthermore, “Sunrise” papaya stored under modified atmospheres (LDPE; 0.025 mm thick) containing commercial Retarder\(^\text{®}\) (KMnO\(_4\) based; at dose of 8 g/kg fruit) for 9 days at 25°C slowed fruit ripening and retained fruit firmness with less intensity of color changes.\(^{(137)}\)

**Fresh-Cut Papaya**

Fresh-cut fruit are highly perishable, but the convenience, uniqueness, and nutritional quality of fresh-cut papayas have driven market opportunities via grocery stores, restaurants, and institutional venues. There are few reports on the quality of fresh-cut papayas, but in general, processing of fruit results in loss of color, texture, flavor, and nutrients. Tissue wounding elicits many of the biochemical changes that shorten shelf life. Wound ethylene was detected within 4 h of cutting and deseeding papayas.\(^{(72)}\) Microbial growth also can proliferate on cut surfaces and reduce shelf life. For fresh-cut papayas, tissue softening and translucency appear to limit shelf life before other quality attributes diminish.\(^{(27,138,139)}\)

Fresh-cut papaya should be prepared from fruit with 60–80% yellow surface color.\(^{(27,72,89)}\) Fruit with <55% yellow color have a low amount of edible flesh and are difficult to deseed, whereas fruit at full yellow color are too soft to handle.\(^{(72)}\) Unlike whole fruit, fresh-cut papayas do not suffer chilling injury when stored at 4–5°C, and the flesh does not brown from oxidation.\(^{(138,139)}\) The cultivar, “Maradol,” had a 10-day shelf life when cubes were stored at 5°C, making it more suitable for fresh-cut processing than Solo-type cultivars with a 2-day shelf life at 4°C.\(^{(27,139)}\) Calcium lactate (1%) treatments were marginally effective at enhancing firmness, but the solutions caused translucency, a major quality defect.\(^{(27)}\) However, pretreating Solo-type fruit (cv. Sunrise) with 1-MCP (2.5 μL·L\(^{-1}\)) improved firmness and extended shelf life by 3–4 days for fresh-cut slices stored at 5°C.\(^{(89)}\)
Microbial growth does not typically cause spoilage of fresh-cut papayas during storage at 4 °C.\(^{138}\) Immersion of whole fruit in chlorinated water (100–200 μL·L\(^{-1}\)) prior to peeling and cutting led to low microbial counts of aerobic organisms and nearly undetectable coliforms, Enterobacteriaceae, and molds.\(^{27,89}\) However, certain papaya cultivars are susceptible to internal yellowing disease, caused by *Enterobacter cloacae* and *Enterobacter sakazakii*.\(^{140,141}\) Internal yellowing is not discernible on the fruit exterior, but high populations of *E. cloacae* (8.57 × 10⁷ colony-forming units [cfu]/g FW) were recovered from the flesh of naturally infected “Kapoho” papayas.\(^{141}\) The ability of *E. cloacae* and *E. sakazakii* to cause infections in humans and the occurrence of these bacteria in food crops such as papaya could pose a food safety risk. The use of cultivars that are resistant to internal yellowing (“Sunrise,” “SunUp,” “Rainbow”) would help ensure that safe, fresh-cut papaya products are marketed.\(^{27,140,141}\)

### Implementing Quality Assurance Practices in the Papaya Supply Chain

Although consumers typically purchase fruit based on desirable appearance, freshness, taste, and size, concern regarding the microbial food safety of fresh produce is increasing. The safety of fresh produce in largely importing developed countries, such as the United Kingdom and the United States, are managed via policies and regulations. During the supply chain, fresh produce can be contaminated with foodborne pathogens. A *Salmonella* outbreak associated with the consumption of papaya was reported in Australia \(^{142}\) and more recently Mexico. The U.S. Food and Drug Administration (FDA) issued a countrywide import alert of Mexican-grown papayas into the United States after *Salmonella agona* was found in 33 samples out of a total of 211 (15.6% positive rate).\(^{143}\) As a result, imported papayas can be detained at the border until third-party laboratory analysis verifies that the product does not contain *Salmonella*.

The microbial risks associated with fresh produce can be greatly minimized with proper agricultural and postharvest practices.\(^{144}\) For example, the *Salmonella* contamination that occurred in Australia was due to the use of untreated river water to wash the fruit with fungicide before the papayas were packaged and transported to distribution centers.\(^{142}\) In the Australian papaya-associated outbreak, the researchers suggest that the *Salmonella* could have become internalized into papayas when they were immersed in water.\(^{142}\) This emphasizes the importance of using clean, potable water in dipping tanks. According to the USDA, the water used for fruit processing needs to be filtered, flocculated, and chlorinated to a concentration not to exceed 200 ppm, and must be checked regularly for microbial contamination.\(^{145}\) Furthermore, inadequate sanitation in packing houses, deficiencies in worker hygiene, and the use of animal manure for fertilizer also were identified as potential sources of foodborne pathogens.\(^{144}\) Insufficient cleaning practices can lead to the formation of biofilms on the surface of equipment and dipping tanks, compromising the safety of the fresh fruit.

The implementation of best production and handling practices will improve the currently adopted quality assurance system to control microbiological risks on fresh produce.\(^{144}\) Also, many developed importing countries request zero pesticide residue levels. At a minimum, any heavy metal and pesticide residues on fresh produce must be less than the permitted levels according to the Codex Alimentarius standard for papayas,\(^{144}\) and papayas must be handled according to the recommendations of the International Code of Hygienic Practice for Fresh Fruits and Vegetables and other relevant Codex texts.\(^{146,147}\) However, the presence of pesticide residues were reported in papaya fruit obtained from five market locations in Ghana.\(^{148}\) According to the report, 50% of the papaya fruit...
contained high pesticide residues. Based on this information, rigorous monitoring programs are needed to enforce food policies and consumer laws to ensure food safety. Furthermore, strict control on the use of pesticides must be implemented at the preharvest and postharvest stages, especially for pesticides such as organophosphates, carbamates, and pyrethroids, as they are used in many developing countries.

Papaya production methods and environment, harvest procedures, postharvest operations (sorting, grading, packing, and heat or quarantine treatments), and temperature management during storage, transportation, and marketing are factors involved in maintaining papaya fruit quality during the supply chain. Effective coordination between the grower, harvest crew, packing house management, transportation and import agents, wholesale buyers, and retailers is important to maintain an efficient quality management system. It is advisable that suppliers or growers comply with Good Agricultural Practices (GAPs) during the production, harvest, and packing of papayas. Fresh-cut processors must implement Good Manufacturing Practices (GMPs) and adopt food safety programs such as Hazard Analysis and Critical Control Points (HACCP).

The packing houses that export fresh produce to the international market need to obtain a certification for international practice and standards such as HACCP and EurepGap certifications. The occurrence of hazards in the supply chain can be minimized with correct product handling by implementing HACCP. The EurepGap primarily aims to maintain consumer confidence in fruit quality and safety through record keeping and traceability designed for farm-level certification. The ISO 22005 (International Organization for Standardization) outlines the principles and basic requirements for the design and implementation of a food traceability system.

Quality standards for export grade fruit are more stringent than for domestic markets. For example, under the Codex standard for papaya, fruit marketed as Class I must be of good quality, with no more than slight skin defects that do not exceed 10% of the total surface area, and only slight defects in shape, provided that these do not affect the appearance, quality, shelf life, or presentation of the papayas in the package. No more than 10% of fruit number or weight can exceed the requirements of the class. The minimum export grade for Hawaii-grown papayas is Hawaii No. 1 or Hawaii Grade A, with no more than a 10% tolerance for slight defects and not more than 1% of the fruit may be affected by decay or breakdown. Meeting these standards requires careful integration and control of preharvest and postharvest practices and conditions.

Conclusions

Papaya-exporting countries must implement stringent quality assurance systems and postharvest management practices during the export chain to ensure fruit quality at the international markets. Temperature fluctuations during marine or air transport of papayas can increase postharvest losses due to decay, softening, and poor fruit quality. Fungicide thiabendazole (TBZ) is used for postharvest application in combination with hot-water treatment to control postharvest decay in papaya packing houses. However, over-reliance on fungicides can increase pathogen resistance to these fungicides. Strict orchard and packing house hygiene can reduce the incidence and severity of postharvest diseases. Heat treatments and combinations of biocontrol agents also can provide good control of postharvest diseases. A suitable sanitizing treatment must be adopted by papaya growers and packers to prevent the incidence of a foodborne pathogen outbreak, and fresh papaya must be washed with water that meets drinking quality standards.
Fruit softening commonly impacts papaya quality during the export chain, but can be controlled by using technologies such as MAP and ethylene absorbers to delay ripening. Furthermore, MAP in combination with 10 °C storage temperature can reduce weight loss and retard ripening during long distance transportation. The application of 1-MCP to delay papaya ripening is limited to a very narrow window of fruit maturity (25–30% yellow skin) and requires further investigations for commercial use. In developing countries where the cold chain infrastructure is not well established, 1-MCP may provide a suitable alternative to extend the shelf life of papaya at ambient temperatures, especially when considering the amount of postharvest losses due to rapid ripening and fruit softening.

Papaya shows good potential for the fresh-cut industry. Fruit at the 75% ripe stage are suitable for fresh cut and can be stored at 5 °C with 5–10 days shelf life. The tissue softening associated with fresh-cut papaya can be minimized with 1-MCP treatment prior to the cutting process.

Consumer demand for papayas could be increased substantially with targeted marketing of high-quality product. However, for repeat purchases, consumers would expect a consistently superior papaya in the marketplace. This requires that the supply chain is optimized and coordinated to meet the multiple challenges to delivering attractive, nutritious papayas to consumers.

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