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Postharvest Technology of Tropical Horticultural Commodities: Introduction to the Colloquium

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The tropics include all of the earth's area south of the Tropic of Capricorn and north of the Tropic of Cancer. From a broader standpoint, the word "tropics" is used to distinguish those areas with a climate that is normally warm year-round, frost free, and seldom lower than 15C. A wide range of horticultural crops that cannot be produced elsewhere is grown in the tropics.

The basic principles of agriculture are universal, but their application under tropical vs. temperate conditions is markedly different. Climatic, soil, economic, and social conditions are among the many factors that influence the choice of agricultural development. Harvesting techniques and facilities for packing, processing, marketing, and transporting commodities also affects agricultural practice. All these factors, as well as their interactions, must be considered if postharvest quality and condition of commodities are to be optimum.

The timing of this colloquium on postharvest technology of tropical horticultural commodities is appropriate. The market for tropical fruits and vegetables has expanded with increasing ethnic populations within nontropical countries and as individuals have become more interested in their potential health, food preparation, and variety in their diets. Advances in transportation also have helped to increase the availability of potted plants and exotic cut flowers.

The participants in this colloquium present information on the impact of preharvest factors, handling, transportation, and stress from low temperatures and insect disinfestation treatments on tropical horticultural commodities. The information should give guidance to and provoke thought among scientists in these or related areas of research.

Handling of Florida-grown and Imported Tropical Fruits and Vegetables

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South Florida has become an important trading and distribution center for tropical fruits and vegetables in the United States. Production of tropical crops in South Florida increases each year, both in volume and number of species. The presence there of a viable young industry producing dozens of tropical commodities, coupled with South Florida's proximity to Central and South America and the Caribbean, have made the area attractive to foreign and domestic producers. The seaports of Miami, Fort Lauderdale, and West Palm Beach provide reliable service for importers, while several international airports in the area meet the needs of shippers moving highly perishable products. Shipping, handling, and selling imported fruits and vegetables keeps fruit companies on Florida's southern tip busy in the off-season. The imported products are a welcome addition to the large group of fruits and vegetables produced locally. In the case of mangos, fruit are imported throughout the fall and winter from the tropics, but not in the summer when local fruit is available.

Phytosanitary regulations are a vital consideration for trading companies bringing tropical fruits and vegetables to the United States. Quarantine restrictions can render some trading schemes unattractive or at least compel producers in foreign countries to form various associations that allow for a unified voice when dealing with the U.S. government. Many of the U.S. Dept. of Agriculture regulations stipulate that the foreign producer must take the lead role in efforts to bring products here, although companies in South Florida are encouraged to assist their foreign trading partners whenever possible.

Losses during handling and marketing these new products are often high. Long transit times from production areas, unfamiliarity with the commodity on the part of handlers and marketing firms, and the lack of adequate equipment or technology to accommodate the fruits and vegetables contribute to postharvest losses that at times exceed 50% of a given shipment. Interaction between postharvest biologists in the research community and the private sector can allow vast improvements in tropical fruit and vegetable handling systems. All too often a U.S. consumer's first introduction to a bright red, Peruvian mango purchased in New York during the winter is disappointing because the fruit, when cut in the home, is tasteless and rubbery from being harvested prematurely to accommodate the long marketing chain. A mango produced in Peru's northern desert may take 20 days or more to reach a retail market if shipped by sea. While 20 days may represent the outside limit of a mango's postharvest life, many shipments have been successful with the proper sanitation and temperature management. Refrigerated transport containers, fitted with equipment for controlling the storage atmosphere, are being tested to control mango ripening and decay during long sea voyages. All parties involved should cooperate to improve handling systems, thus improving product quality and encouraging customer acceptance of these new tropical commodities.

SOUTH FLORIDA'S PRODUCTION

Production of fresh-market avocados and limes formed the basis for the tropical fruit industry in South Florida. These two fruits still lead all others in production volume, but each has its own set of postharvest problems that limit storage and marketing. The popularity of mango has exploded recently, with dramatic increases in U.S. imports and renewed excitement among South Florida growers leading the way to a more competitive, professional industry. The increased production of carambola, lychee, longan, passionfruit, atemoya, kumquat, pummelo, guava, and various other fruits grown on South Florida farms has made an impact on tropical fruit availability throughout the United States. In this section, production trends that relate to a particular fruit's status in the industry will be discussed along with information about current and potential handling methods.

Avocado (*Persea americana* Mill.)

The varieties grown in Florida are numerous and widely variable. Early varieties are usually of West Indian origin, whereas midseason and late varieties are hybrids of West Indian and Guatemalan parentage having intermediate characters. Early varieties usually are light in color, ripen rapidly, and have a low oil content. Varieties that mature early in Florida's season are less popular with consumers, tending also to be more chilling sensitive. Florida producers grow numerous varieties to maintain a long harvest season. They realize that early season fruit must be handled carefully to protect fast-ripening avocados from bruising and chilling injury. Later in the season, fruit are held at lower temperatures, 5C compared with 7 to 13C for early fruit, and stored longer (Hatton and Campbell, 1965). The introduction of hydrocooling in avocado packinghouses in the 1970s provided a method for rapidly and consistently removing field heat, which allows longer storage and safer transport of avocados throughout the season.

'Tahiti' lime [*Citrus aurantifolia* (L.) Swingle]

This fruit, although having a thick rind and low respiratory rate, is difficult to handle. The fact that limes are chilling sensitive, yellow rapidly, and prone to serious physiological disorders make them worthy of further study. Styler end breakdown (SEB), a disorder promoted by high fruit turgor and high temperatures, develops when juice vesicles rupture in a fruit, releasing juice that kills albedo and flavedo cells, starting at the styler end, and quickly causes the fruit to spoil (Campbell, 1979; Phillips and Goldweber, 1981). The problem must be continuously managed by Florida producers to avoid harvesting in times when turgor pressure is high in the tree and fruit. The practicality of harvesting only when trees have low turgor is questionable when faced with the rainy, hot, South Florida summers occurring when limes are most abundant. Large companies use pressure testers in the field to avoid SEB by measuring fruit turgor, a practice researchers suggested after determining that fruit can be safely harvested when more than ≈ 18 N force is required to rupture oil glands on the fruit surface. Even though the method is simple and the results immediate, many growers are reluctant to adopt the technique—fearing lost labor hours and increased costs. In the packinghouse, fruit are often held for 24 h before packing to allow SEB development so that affected fruit can be detected during grading. Oleocellosis is a less important disorder, also influenced by fruit turgor, that occurs throughout the season in response to rough handling. Fruit with oleocellosis have areas on the flavedo where cells have collapsed and turned brown, which makes the fruit unattractive but usually does not lead to decay.

Yellowing of harvested limes is a tremendous problem to producers and retailers. Many receivers reject shipments that are "too yellow." Low-temperature storage cannot be used to slow yellowing because limes are chilling sensitive and should not be stored below 12C. Hypobaric storage, plant growth regulators, and various other methods have been explored to prevent degreening of limes; most methods have had very limited success due to erratic results or commercial impracticality. Postharvest coatings seem to be the simplest and most reliable method to prevent degreening. Coatings decrease the rate of water loss from the fruit and delay senescence of the rind by creating a modified atmosphere. Various commercial waxes and oils will help delay yellowing of limes and maintain a superior fruit appearance.

Mango (*Mangifera indica* L.)

Handling methods for this tropical fruit are geared toward controlling ripening and fungal diseases. Anthracnose, caused by

Colletotrichum gloeosporioides (Penz.) Sacc., is the most important disease of mango fruit in Florida. Diseased mangos are removed in the packinghouse during the grading process; however, the pin-point anthracnose lesions are difficult to detect on unripe fruit. These small fungal spots will enlarge during ripening and rapidly rot a fruit. For this reason, anthracnose decay is seldom a problem until after fruit are shipped and placed in stores or in a consumer's home. Ripe mangos with anthracnose decay have large, smooth, black spots that eventually coalesce, covering most of the fruit surface. Postharvest control measures retard anthracnose development on fruit that were previously infected in the field.

The other major postharvest disease is stem-end rot, caused by *Diplodia natalensis* P. Evans. Stem-end rot is particularly troublesome in immature and early season fruit. On prematurely harvested mangos, stem-end rot often begins before fruit ripening and progresses quickly. The stem area of an infected fruit turns light brown, soft, and water-soaked. Hot-water dips are effective in controlling anthracnose and, to a lesser degree, stem-end rot (Smoot and Segall, 1963; Spalding and Reeder, 1972). Treated mangos are submerged in water maintained at 53 to 55°C for 3 to 5 min, depending on the variety and maturity stage. Research on the combination of fungicides and hot water has been promising. South Florida companies are working with the appropriate agencies to register the fungicide 1-[2-(2,4-dichlorophenyl)-2-(2-propenyloxy)ethyl]-1*H*-imidazole (imazalil) for use in hot-water tanks; the work, however, is not yet complete.

Mango ripening is controlled using temperature management and exposure to ethylene. Ripening is promoted in early season fruit, contrasted with later in the season, when fruit ripening is purposely delayed to facilitate storage and transport. Ethylene (10–20 ppm) is applied early in the season to mature, unripe fruit, held at 21°C and high humidity, to promote uniform ripening and superior color development. Various time–temperature regimes are used, depending on the variety and its maturity stage. All ethylene gassing is stopped late in the season, when fruit are stored at 10 to 12°C after hot-water treatment and packing.

A new handling practice has recently gained popularity in South Florida. One large mango packer is packing tree-ripened fruit, which in the past were removed as culls. They are handled carefully, placed in decorative paper cups, and sold in single-layer boxes as a new product line. The special mangos are harvested separately in plastic crates and packed by hand on a small packing line. These full-color mangos are very attractive and flavorful, but will bruise easily, are prone to decay, and must be sold quickly. The ripe mangos will tolerate cooler temperatures and are transported at 8 to 10°C. “Tree-ripes” are sold throughout Florida, but they are also put on direct trucks to customers as far away as New York, where many people prefer the ripe fruit.

Carambola (*Averrhoa carambola* L.)

No fruit typifies the growth of South Florida's tropical fruit industry better than carambola. An industry-wide volume just 5 years ago of 70 t or less increased to ≈2000 t in 1991. Handling methods have changed to suit increased volume and storage requirements. The optimum storage temperature for carambola harvested at color break is 5°C, a low temperature for a tropical fruit but convenient for handlers because carambolas can be combined with avocado shipments (Campbell et al., 1987). Carambola fruit have a low respiratory rate and are not adversely affected by ethylene, nor are they a copious ethylene producer (Campbell et al., 1989). The primary storage disorders in carambola are texture changes and browning on the fin margins due to water loss. Bruising, which leads to browning and decay, is another major concern. Carambola fruit can be stored for several weeks if packed carefully and protected from desiccation. Wrapping fruit in waxed tissue and, more recently, coatings have been used for preventing water loss. Despite the dramatic increase in production, carambolas are still harvested in plastic field crates and packed directly from the crates into a carton designed for storage or shipping. More automated methods for sizing, grading, and packing this tender commodity have eluded producers. Washers and hydrocoolers, which accommodate the harvest crates, are now being

used along with coating applicators that dip and drain the fruit in the same crates. Automated carambola packing has involved more rapid delivery of the harvest container, packing supplies, and corrugated cartons to the packers, combined with efficient removal of cull fruit. Rapidly hydrocooling fruit to 5°C is anticipated to reduce problems with desiccation.

A cooperative effort a few years ago between the U.S. Dept. of Agriculture (USDA), a private carambola packer, and the states of Florida and California resulted in the development of a cold treatment (15 days at 1.1°C) that provides quarantine security against Caribbean fruit fly (*Anastrepha suspensa* Loew), a pest endemic in South Florida but not found in California. The USDA-developed treatment was adopted by the Florida Dept. of Agriculture and accepted by California's plant quarantine division for use on shipments of carambola fruit. Later, the Arizona authorities accepted the 15-day quarantine treatment. As with all quarantine methods, companies using the treatment must carefully monitor temperature, record data, and handle fruit to prevent misuse and potential reinfestation. The treatment has been successful for the South Florida industry—shipments of treated fruit sometimes have exceeded 380 t since the program's inception. Quality problems associated with treated fruit have been few; occasionally, shriveling and fruit browning occur due to desiccation or chilling injury, especially in early season fruit.

Lychee (*Litchi chinensis* Sonn.) and longan (*Dimocarpus longan* Lour.)

Lychee and longan production in South Florida is increasing, with producers forecasting a strong U.S. market that will become increasingly competitive due to the large plantings of young trees that have not yet achieved peak production. Handling methods for lychee, and the closely related longan, are designed to prevent desiccation and protect the fruit from crushing. Fruit in South Florida are rarely kept more than 24 h before shipment because oxidative browning of the pericarp (skin) can develop overnight in unprotected fruit. Storing fruit at 5 to 7°C in boxes lined with vented polyethylene bags will greatly retard browning (Hatton et al., 1966), but shippers must be careful when shipping this fruit by air. Fruit that have been cooled previously and placed in bags will often rot during or after air transport because of condensation within the bags. Many lychee buyers do not have adequate cooling facilities or the means to properly handle the fruit. Many producers leave the fruit in large bunches (panicles), ship only by air, and never cool the fruit. Large companies that sell to retail grocery chains remove the fruit from the panicles and cool them before packing, use boxes with vented liners, and transport them by truck at 5°C. Longans are packed similarly, except that they are left in small bunches containing a few to about 12 fruit. Work related to fruit sanitation and postharvest treatments to retard browning is being undertaken. Handling methods used in Australia—fruit dips in hot water plus benomyl—reduce decay, but these fungicide treatments are not permitted in the United States.

Passionfruit (*Passiflora edulis* Sims)

The production of passionfruit is one of the newest endeavors in the South Florida industry. Few handling methods have been developed locally to accommodate the 40 to 50 t of fruit produced for the fresh-fruit market. Diseases are the largest obstacle to increased production. No postharvest fungicides are available to combat the numerous pathogens that cause fruit rots. It is not surprising that several pathogens causing postharvest rots have been identified when one considers that the fruit are collected from the ground, after natural abscission. Fruit are typically washed in chlorinated water, graded to remove diseased fruit, and packed in plastic cell-trays that are put inside cartons. Producers have gained a special-use label for one preharvest fungicide and hope to develop better methods for treating fruit after harvest. Good results were obtained when mature fruit were clipped from the vines (before natural abscission) and treated with ethylene to promote ripening. The treatment, although effective in providing fruit with less disease and a better postharvest life, was very labor intensive for harvesters.

Atemoya (*Annona cherimola* x *Annona squamosa*) and guava (*Psidium guajava* L.)

Ripening control is the goal of atemoya and guava producers in South Florida who want to expand the current market for these fast-ripening fruits. Both of these climacteric tropical fruits are chilling sensitive and have high respiratory rates. Atemoyas are generally cooled to 12C immediately after harvest, packed in single-layer flats, and sold by count, not net weight. Guavas, in contrast, are cooled and then packed in cartons holding 4.5 kg. Much can be done to improve the current handling practices for these two fruits; guavas, for example, respond very favorably when encased in a semipermeable coating to retard ripening. Atemoya fruit are more difficult to manage. To develop a good flavor and texture when soft, atemoyas must be harvested late in their development. When harvested in this manner, however, fruit will ripen in 1 to 4 days; little can be done to retard the ripening rate. Atemoya fruit tend to split around the stem as they soften, making them prone to fungal invasion. Fruit in South Florida have not responded well to modified-atmosphere packaging and quickly ferment even in the most permeable packages. Forced-air cooling and hydrocooling appear to be promising methods to remove heat quickly from these fruit to facilitate storage and transport. Consumer demand for these two fruits is good, and production will increase if successful handling methods can be developed.

Other tropical fruits

More than a dozen other tropical fruits are commercially produced in South Florida; some have a great potential for expanded production. The species mentioned so far are the primary fruits grown in the area. Other fruits are likely to gain importance as some of today's popular items lose favor. Mamey sapote [*Pouteria sapota* (Jacq.) H.E. Moore & Stearn] deserves mention, as it is a fruit with relatively high production (>20 t) and good potential in specialty markets. It was not mentioned previously because production has actually decreased in response to freezes in South Florida and weak demand. It is a chilling-sensitive fruit but can be stored and shipped successfully by truck to northern markets. Kumquat (*Fortunella* sp.) and pummelo [*Citrus grandis* (L.) Osb.] are two other crops with expanding production. Handling methods for them have been taken from the wealth of knowledge available in the state for fresh-market citrus.

Modified-atmosphere storage techniques have shown promise in delaying fruit ripening in many tropical species for extended storage or simply to allow shipping riper fruit to retailers (Kader et al., 1989). Many retailers are expressing an interest in selling fruit that is ripe, or nearly so, to satisfy customers' need for ready-to-eat and more flavorful fruit. Producers are responding to this interest but are discovering the added complexities involved when handling riper fruit. Many produce handlers are unaware of the primary differences in ripe vs. unripe fruit in regards to respiratory rates and production of vital heat, ethylene, and CO₂.

Fruit companies in the area do much of their own marketing and market research. Handling practices for the crops are either devised by the companies or through an important cooperative system with state and federal research agencies. Members of the South Florida industry, out of commitment and necessity, have developed handling methods for many tropical fruits previously unknown in the United States.

Tropical vegetables

Tropical vegetable production in South Florida is dominated by small companies that use vastly different methods for washing, cooling, and packing produce. Cassava, (yuca, *Manihot esculenta* Crantz), malanga [dasheen, *Xanthosoma sagittifolium* (L.) Schott], and boniato [*Ipomoea batatas* (L.) Lam.] production changes in magnitude depending on the previous year's weather and market prices. A year of high production and low prices dissuades many growers from replanting. Generally, cassava and malanga are washed by hand or in brush-washers and then packed in cartons holding 23 kg. Chlorination, if used, is usually inadequate in washers, contributing to serious decay problems. Air driers, similar to those used for potatoes, can improve

product quality by rapidly drying the products after digging and washing. Boniato, a tropical sweetpotato grown in the area, is not cured because buyers think this adversely affects the product's texture. As a result, postharvest rots are sometimes severe. Sweetpotatoes are dug, washed, and packed in burlap bags. They are sometimes repacked in cartons for grocery-chain customers to facilitate stacking and further handling. These starchy crops are stored at moderate temperatures, 10 to 15C. Although most companies do not control the relative humidity within storages, storage in a dry atmosphere reduces postharvest rots.

Another group of tropical vegetables, collectively referred to locally as "Asian vegetables," are grown in the area and sold nearby, with some production being shipped to markets in other states. Several types of cucurbits and legumes dominate this group, along with a few spices. These products, in general, do not enter the large-volume commercial market and therefore will not be discussed in more detail.

IMPORTED TROPICAL FRUITS AND VEGETABLES

The most successful produce companies in South Florida have learned that valid technical support for their growers is essential. Harvesting guides for pickers, complete with color photos, have been used to prevent the harvest of immature carambola fruit in South Florida. Growers greatly appreciate the support and repay the company with their loyalty and commitment to quality improvement.

This same technical support is used to advise foreign producers entering the U.S. market. Many relationships exist where the U.S. firm has no involvement with the importing company, other than to take delivery of the product and provide payment. Technology transfer to foreign producers, however, can prevent many potential problems and make for a lasting trade relationship with fewer problems. Knowledge of import regulations, postharvest treatments, and packing and shipping methods are provided to the importer and tailored to suit local conditions.

Mango

Many countries in Central and South America and the Caribbean have been recently approved to ship hot-water-treated mangos to the United States. The interest expressed by several nations in the area to start treating and shipping fruit has set into motion a remarkable increase in new orchards, often without the support of a treatment facility. Countries with existing mango orchards and established packing companies obviously have a distinct advantage. They simply add the United States as a customer along with the European market. Competition has already increased markedly between Brazil, Ecuador, Peru, and Venezuela, the prominent producers sending fruit to the United States during our winter months. Mexico, one of the world's leading mango producers, ships fruit to the United States during the same summer period as Florida's season, while Haiti has been prohibited entry by the United States for political reasons.

Hot-water treatments, designed to safeguard against several fruit fly species, vary according to mango variety and fruit mass, but all involve complete submersion of the fruit in water maintained at 46.1C for ≥1 h. Information concerning specific treatments in a given area can be easily obtained from the USDA. New treatment schedules are being developed for large mangos from some areas. Treatment installations must pass inspections by U.S. officials who also must be present at all times fruit are being treated. The importing country is required to support a new import venture with appropriate representation by their government officials, technical support, and record keeping. Funding, which may come from private sources, must be supplied to the USDA to cover operating costs for the U.S. inspectors and the program.

Because hot-water treatment is a common thread connecting all imported mangos, it is the central feature of a handling system. Harvesting, cooling, packaging, and container loading must accommodate the demands imposed by the phytosanitary regulations. Fruit cannot be cooled below 21C immediately after treatment, and, similarly, no treatment can commence unless fruit are 21C or warmer. To prevent reinfestation, fruit are packed and containers loaded only in

areas protected by screening. Mangos will not tolerate long hot-water treatment unless they are fully developed. The treatment will scald fruit that is picked too early. The fruit may begin to show symptoms within hours, or may appear undamaged at first, only to shrivel and rot as much as 1 week later. Fruit harvested close to ripeness and then treated, however, will probably not survive a sea voyage lasting 1 to 2 weeks. Generally, fruit are harvested when fully expanded, having flesh that is one-half yellow or more, but still firm. Fruit that is air-shipped obviously can be picked at a later maturity stage. Most fruit produced in Ecuador and Peru is sized, graded, and packed by hand without the aid of packing lines. Some packinghouses in Brazil have automated packing lines to handle fruit after treatment. Not all producers have cooling facilities for their mangos, relying instead on inadequately refrigerated trailers for cooling, or simply the prompt export of their product to prevent fruit ripening. The standard export carton holds 4.5 kg of fruit and is designed to be hand-folded instead of machine-glued or stapled. Mango shipments from Central and South America have arrived in the United States with mixed quality. Scalded and shriveled skin, internal damage, and over-ripeness are the prominent problems in imported mangos. Producers are learning to minimize these problems with careful attention to fruit maturity and temperature management during packing and transport.

Papaya (*Carica papaya* L.)

South Florida companies import high-quality, red-fleshed papayas from the Caribbean and Central America. Jamaica, Belize, and Costa Rica are the primary producers of the solo papayas, with 'Sunrise' being the principal variety. The fruit are packed in single-layer boxes that are sold by count. Most companies wrap fruit individually in paper, but a few use foam sleeves that cover each papaya in the box. Most shipments from Jamaica are sent by air freight, but sea shipments are becoming more popular. Most fruit from Belize is sent in sea containers maintained at 10 to 12°C. Most shipments have been received in good condition. The papayas grown in Belize are handled by a single company that hand-packs all fruit in a small packinghouse without automated machinery. The fruit are washed by hand, packed, and loaded into sea containers for the 4-day voyage. Some Jamaican producers use automatic sizers and conveyors for grading and packing. Postharvest decays are the principal problem in the papaya shipments, sometimes affecting 25% or more of the fruit. Some producers treat fruit with 2-(4-thiazolyl) benzimidazole (thiabendazole) to reduce decay. Other major quality problems include fruit that arrive ripe and soft due to delays during transport, or fruit that simply ripen too fast during periods of exceptionally hot, rainy weather.

Other tropical fruits, such as key limes [*Citrus aurantifolia* (Christm.) Swingle] from Guatemala and specialty bananas (*Musa* spp.) from Colombia, are traded in smaller volumes; yet they form a valuable part of a company's product line. Each crop mentioned in this paper was, at one time, a low-volume specialty fruit.

Tropical vegetables

Central American countries have been shipping tropical vegetables to South Florida for many seasons, but the volume of this trade has increased recently. Chayote [*Sechium edule* (Jacq.) Sw.], yuca, malanga, and eddo [*Colocasia esculenta* (L.) Schott] are shipped in entire trailer loads for distribution in the United States. Chayote, a light-green, pear-shaped squash, sometimes called vegetable pear or trellis squash in the United States, is shipped in the largest volume. It is tender and must be handled carefully to avoid bruising and abrasion. The squash are wrapped individually in tissue paper or placed in plastic bags; however, the bags are considered inferior because they allow water to

accumulate, thus increasing decay problems. Chayote squash are generally sold in 24-count cartons that weigh ≈6 kg. The most common storage temperature for chayote is 5 to 7°C. Several pathogens cause stem-end rot of chayote, representing the most serious disease problem. A disorder, characterized by water-soaked blisters on the chayote's surface, sometimes affects a large percentage of a given shipment. This curious disorder usually occurs during periods of rainy weather and is made worse by handling the squash roughly.

Calabaza (*Curcubita pepo* L.), a tropical pumpkin, is shipped in large net bags holding ≈23 kg. The pumpkins are harvested by hand, washed, packed in bags, and shipped in bulk containers to the United States. Bacterial decays are prevalent when pumpkins develop during rainy weather. Infection occurs in the field, and often a large percentage of the pumpkins are rotted when unloaded at the U.S. destination. Careful sanitation and handling the fruit gently reduce decay, but few producers are willing to invest in better handling methods because calabaza is not a high-value commodity.

Yuca, malanga, and eddo are starchy vegetables that are handled in nearly the same manner after harvest. They are simply removed from the soil, washed, and then packed in cartons holding 23 kg. Modifying handling methods can improve product sanitation, drying, and cooling. Fungal decays and sprouting are the most serious quality problems associated with these commodities. Rapidly drying the washed products would reduce decay problems and discourage sprouting. Heated drying tunnels have been installed in a few locations for this purpose. Coating freshly harvested yuca roots with paraffin after washing greatly preserves their market quality by reducing a disorder known as vascular streaking. This coating system involves melting blocks of pure paraffin in electrically heated tanks into which washed and dried roots are dipped by hand. The wax seal must be complete to ensure the proper protection of the root. Properly coated roots will have a smooth coating that is completely clear. A whitish, cloudy coating indicates that the roots were too wet or the wax too cold during dipping. Postharvest treatments focusing on sanitation are the most important concern in tropical vegetable packinghouses.

In this paper, I have attempted to describe the handling practices used for several important tropical commodities in the U.S. market. Most of these crops are new to North American consumers and produce handlers. Trade in these products seems certain to increase in the future as U.S. consumers become better acquainted with tropical fruits and vegetables.

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Postharvest Technology of Imported and Trans-shipped Tropical Floricultural Commodities

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World trade in floricultural products is expanding, due in large part to diminished technological and political barriers, improvements in infrastructure, and the recognition by many developing countries that floricultural products can be an important source of foreign currency. Along with this increase in international trade comes the demand for improved quality and quality control. However, what constitutes quality of these highly perishable commodities is poorly defined. External appearance is a poor measure of eventual quality at the consumer level. Thus, predictive tests and quantitative measures of internal quality are needed.

WORLD TRADE IN FLORICULTURAL PRODUCTS

The total intercontinental trade in floricultural products exceeds 1.250 million U.S. dollars (Heinrichs and Siegmund, 1992). Cut flowers account for most of it (Table 1). The remainder consists of foliage greens, bulbs, nursery stock, and live plants. Flowers are a luxury product. There are only three major world markets: North America, Japan, and Europe. Because of the predominantly temperate and Mediterranean climates in these markets, they depend largely on imports from the tropics and the southern hemisphere for their supply of exotic and out-of-season products. Still, intercontinental trade of floricultural products is small compared to a total consumption of 25 billion U.S. dollars in these markets. Overseas suppliers to these countries are mostly on the nearest continent. Colombia is the main foreign supplier of the North American market, with an import value of >200 million U.S. dollars (Table 1). The contribution of other Central and South American countries and Mexico is much less. A similar situation exists in Japan, which also imports most cut flowers from its southern neighbors. In volume, imports from Thailand into Japan are larger than those from Europe (Gunneröd, 1991). Increased air traffic between Japan and Australia and New Zealand has given these southern hemisphere countries an opportunity to increase their flower exports.

Nevertheless, significant imports come from even more distant production areas. The Netherlands has been a large supplier of seasonal products, such as tulips, to the American market. The share of these cross-Atlantic imports has declined recently because of the diversification of the Colombian flower industry and the continued increase in local production (Hack and Heybroek, 1992). The Netherlands supplies specialty products to Japan as well. The import of Colombian products on the Japanese market is small, but is growing steadily. The import of Colombian products into Europe has shown the largest increase and is expected to continue to increase.

Europe accounts for almost 50% of world imports of cut flowers. More than half of the flowers imported into Holland come from overseas (Table 2). Germany imports only a small portion of its cut flowers from overseas, but because of its enormous total consumption, it is still the second major importer. As distance from the Dutch distribution system increases, the volume of direct overseas imports increases. Israel is the major exporter of cut flowers to Europe. The United States is an important supplier of foliage greens (Produktschap voor Siergewassen, 1992). Tropical countries that are major exporters to Europe include Colombia, Costa Rica, Kenya, the Canary Islands, and Thailand. Many of the imports from these tropical countries are actually temperate or Mediterranean-type products. Roses and carnations are by far the largest volume products and are imported in the winter months (Hack and Tap, 1990).

The amount of exotic products imported into Europe is comparatively small: <200 million U.S. dollars. The actual value depends on what one considers to be an exotic product—a distinction made difficult by seasonal and protected cultivation. Because of the difficulty of getting European data, the imports discussed later are limited

to imports into the Netherlands, which serves as a gateway for most of the specialty products imported into Europe. Exotic products are a very diverse group; most are cut flowers used in the more expensive mixed bouquets, and diversity, therefore, is important. Some of the more important ones are *Limonium latifolium* (Sm.) Kuntze, *Chamelaucium uncinatum* Schauer, *Solidaster*, *Liatris*, orchids, and *Protea*. Only about 5% to 30% of these crops is grown in Dutch greenhouses (Association of Dutch Flower Auctions, 1993). *Limonium latifolium* accounts for an auction value of 25 million U.S. dollars. *Liatris* is much less important, with a value of ≈7 million U.S. dollars. Proteas are less important on the European market. Most of the imported orchids come from Thailand, but imported orchids account for only a small part of the total.

The imports of flowers native to the tropics, such as *Alpinia purpurata* (Vieill.) Schum. (red ginger), *Heliconia* spp., *Gomphrena globosa* L., *Stephanotis floribunda* (R. Br.) Brongn., and *Strelitzia reginae* Banks esc. Dryand., are small. *Amaranthus* spp., *Anthurium andraeanum* Linden, *Celosia argentea* L., *Zantedeschia aethiopica* (L.) Spreng., and many other tropical flowers are actually grown more in greenhouses than imported. Even though cut flowers have the lowest transport cost per unit, they are not the only exotic commodities imported into the European market. Singapore supplies potted orchids and plants. Costa Rica is a large supplier of tropical foliage and unrooted cuttings, such as yucca (*Yucca elephantipes* Regel) stems.

DETERMINANTS OF INTERNATIONAL TRADE

The perishability of floricultural commodities puts high demands on all aspects of intercontinental trade. Some of the more important determinants are market structure and organization, government regulations, infrastructure, and information exchange.

Good market structure and organization are essential. Too many links (brokers, shippers, receivers, retailers, etc.) lengthen the time in the marketing chain, because often each link sells the products from stock. Even with a system of central auctions, a product will have

Table 1. Overseas trade of cut flowers in 1990 and 1991 based on import values.²

Origin	Destination					
	USA and Canada		Japan		Western Europe	
	1990	1991	1990	1991	1990	1991
	millions of U.S. dollars					
Colombia	192	202	3	6	73	113
Rest of America	34	42	4	5	17	24
Thailand	3	5	25	29	27	32
Rest of Asia	2	3	37	53 ³	6	8
Israel	---	---	---	---	121	130
Rest of West Asia and Northwest Africa	---	---	---	---	41	44
Kenya	---	---	---	---	38	47
Rest of sub-Saharan Africa	---	---	---	---	30	35
Netherlands	65	51	44	52	na	na ^w
Rest of Europe	5	4	1	1	na	na
Total overseas imports	302	307	115	146	356	434 ^v

²Compiled from Heinrichs and Siegmund (1991, 1992).

³Predominantly and about equally from Taiwan, New Zealand, Singapore, and Australia.

⁴Not available, but, with the exception of export from Israel to the United States, considered to be small.

^wNot applicable.

^vIncluding export from Turkey to Great Britain.

Table 2. Value of floricultural products imported into western European countries in 1990 and 1991.²

Importing country	Imports (millions U.S. dollars)				Percent total from overseas		Share (%) of overseas imports	
	Total Floricultural products ³	Cut flowers	From overseas Floricultural products	Cut flowers	Floricultural products	Cut flowers	Floricultural products	Cut flowers
Netherlands	436	169	244	122	56	72	33	29
Germany	2150	1144	183	89	9	8	25	21
Great Britain	549	268	84	70	15	26	11	17
Italy	438	113	47	28	11	25	6	7
Switzerland	296	130	35	24	12	19	5	6
Austria	178	76	25	16	14	21	3	4
France	746	301	30	18	4	6	4	4
Other countries	866	260	87	71	10	27	12	17
Total (1991)	5659	2460	734	421	13	17	100	100
Total (1990)	5003	2115	615	343	12	16		
Increase, 1990-91 (%)	13	16	19	23				

²Western Europe = countries of the European Community and European Free Trade Association.

³Cut flowers, bulbs, foliage green, potted plants, and nursery stock. Compiled from Heinrichs and Siegmund (1991, 1992).

changed hands four times before it gets to the consumer. At least one more link is added to the chain if the product is first imported. Delivery of unsold products to the destination market can decrease the marketing time. For example, flowers from Israel are shipped unsold to Dutch auctions, and Colombian flowers are often delivered unsold to Miami. In contrast, products from the Netherlands are only shipped to overseas markets after sale.

Government regulations, such as phytosanitary requirements and tariffs, can greatly affect international trade. Tariffs on Colombian products imported into the European community were lifted after the Colombian authorities agreed to enforce the payment of royalties to, mostly Dutch, plant breeders. Phytosanitary requirements affect the range of products that can be imported and the time it takes those products to pass customs. Japan has strict phytosanitary requirements. As a consequence, 30% of flowers imported into Japan do not pass inspection and have to be fumigated (Gunneröd, 1991). Viruses and soilborne pathogens are feared most: overseas import of cut flowers into the United States and Canada is much larger than the import of live plants (307 vs. 26 million U.S. dollars; Heinrichs and Siegmund, 1991). In contrast, trade in live plants between the United States and Canada exceeds 100 million U.S. dollars. To alleviate losses incurred due to phytosanitary requirements, agricultural inspectors from the import country could inspect and certify the products in the country of origin. This is done for export from the Netherlands to Japan.

The infrastructure and mode of transport is another important determinant of international trade, because it directly affects quality. In terms of speed, transport by airplane seems to be the most logical choice for intercontinental trade. However, temperature control is often poor, both in the airports and on the planes. Transport on either end of the intercontinental leg must connect well. Transport by boat is not yet an option, but it could become an alternative for production and destination areas that are close to the sea and have good port facilities, e.g., trans-Atlantic and inter-Asian trade. The shipping industry has gained experience in containerized, modified-atmosphere transport with other horticultural commodities. Currently, ships sail on time schedules almost as strict as airplanes.

Intracontinental trade is mostly by truck because of its low cost and because the product reaches its final destination without trans-shipment and with minimal handling. Transport by truck has good possibilities for temperature control, but that advantage is not always used fully.

Information exchange has long been neglected. Two-way communication can be lacking, especially with the delivery of unsold products to the destination market. Not being aware of the eventual quality or of the changes in consumer demand can seriously impede long-term export possibilities.

POSTHARVEST HANDLING

Product requirements

Postharvest requirements involve both the criteria that products have to meet and the conditions and treatment that a product demands.

The criteria for floricultural products to withstand postharvest handling successfully are similar for imported and locally grown commodities. Some of the more important criteria follow.

Cut flowers and potted plants should have enough carbohydrate reserves to develop fully. A low sensitivity to and production of ethylene will reduce the effect of many transport-related problems. The right maturity stage at harvest is essential. Immature flowers can lack not only the carbohydrate reserves to come to full bloom, but also the hormonal signaling that guides their development. However, products of higher maturity can be more sensitive to transport damage and ethylene.

The ability to withstand transport is another important criterion. It includes resistance to moderate water stress, darkness (live plants and foliage green), and fungal and bacterial pathogens. For imported commodities, the ability to withstand quarantine treatment can be an additional criterion.

The main difference between imported and nonimported products is the time spent in the marketing chain. Importing requires a much stricter adherence to product demands.

The most important measure that can be taken to meet these demands is temperature control. Low temperatures slow the development and depletion of carbohydrate reserves. They also decrease ethylene production and sensitivity and limit pathogen growth. The chilling sensitivity of tropical products defines the lower limit of the acceptable temperature range.

The second most important measure is cleanliness. Cut flowers demand strict hygiene, starting immediately after harvest with clean containers that contain a suitable bactericide solution. Adverse conditions at any time can allow bacteria to occlude the stem or fungi to infect the bloom.

Adequate water should be available to flowers to avoid prolonged water stress. Therefore, flowers should be turgid before they are shipped and be allowed to rehydrate after unpacking. However, excessively high turgor increases the chance of damage during packing. A small vapor pressure deficit during transport will reduce water loss from the product; this requires a well-designed vapor barrier and good temperature control, because condensation will increase the chance of spoilage.

Rooted plants can have a high susceptibility to water stress as well. An additional requirement for live plants is the need for light immediately after shipment to recover from dark transport.

Packaging can be a major aid in controlling temperature and relative humidity. However, packaging often seems to be designed to prevent mechanical, not physiological, damage.

For a well-chosen variety grown under good conditions, the above measures should suffice. In practice, product and handling conditions are seldom optimal and additional measures, mostly in the form of chemicals applied to the cut flower before packing, are often taken. Therefore, apart from a bactericide, pretreatment solutions often contain one or more of the following: sugar, an anti-ethylene agent (silver thiosulfate or amino-oxyacetic acid), a surfactant to aid in rehydration, and gibberellin to reduce leaf yellowing.

Marketing chain evaluation

A complete marketing chain evaluation was conducted in 1987 and 1988 to determine to what extent good handling practices were implemented and what improvements should be made (Bloemen Marketingbureau Holland, 1988). This extensive study dealt mostly with temperate-climate (Dutch) products. Time, water availability, packaging, and organization affect quality most. The conclusions could be summarized in two general statements: "Potential vase life is reduced by 5 to 10% for each day spent in the marketing chain" and "Postharvest requirements for individual products are seldom met." Simulated transport conditions confirmed this. Rehydration of packed *Bouvardia* was blocked by 20 h of water stress at 17°C (van Meeteren, 1990). This quality loss is obvious, but it also can be hidden and noticeable only when the product is with the consumer. The vase life of packed spray carnations (*Dianthus caryophyllus* L.) kept for 40 h at 20°C is reduced by up to 4 days compared to the same flowers kept at 8°C (M.B.M. Ravesloot and R. van Gorsel, unpublished data). Forty hours of dryness at 20°C represents the intercontinental link in the marketing chain. Another example is *Aster ericoides* L. 'Monte Casino': 40 h at 20°C will reduce the vase life by 3 to 6 days compared to stems kept at 8°C. Two types of flowers of similar visual maturity can reach the customer: either flowers harvested when immature and marketed with inadequate temperature control or flowers harvested when more mature and kept at a constant, lower temperature. Because of insufficient temperature control, the trade often chooses and pays the grower more for the inferior, immature products.

External and internal quality

Many definitions of quality exist. A practical definition is: Quality is the extent to which a product meets the requirements of the customer. The customer being each successive link in the marketing chain, the last link being the consumer. Quality, therefore, means something different to the producer, exporter, retailer, and consumer. The carnation and aster examples show that these requirements can be in conflict. Exporters prefer immature carnations (early bud stage) because these flowers withstand tight packing during shipping better and allow more leeway in time and temperature. The same is true for roses (*Rosa hybrida* L.). Slow-opening roses of low maturity are preferred to the point that many flowers will not open at all.

Therefore, one should look for internal rather than external quality. Two important characteristics of internal quality are that it is invisible at the time of transaction and essential to consumer satisfaction. Because of these characteristics and because repercussions only come much later and do not harm the violator more than the trade as a whole, it is necessary to be able to measure internal quality. Internal quality tests should be effective for both freshly harvested commodities and products at later stages in the marketing chain. Another requirement is that internal quality can be established at the moment of sale.

Tests to measure internal quality

Developing tests to measure internal quality is an important area of research at the Research Station for Floriculture at Aalsmeer. Obviously, there is no one single test to measure internal quality. Some examples of current research are given below. Near infrared reflectance (NIR) and transmittance spectroscopy have been evaluated for predicting the vase life of *Freesia* at the time of auction. Thus far, the precision in predicting vase life is not accurate enough to warrant

commercial application (van der Pluym et al., 1993). Starch content of the first-coloring flower bud of lily (*Lilium*, Asiatic hybrids group) can be used in predicting vase life, provided that it has been treated with silver thiosulfate (G. Slootweg, unpublished data). Bacterial counts in rose stems correlate with their sensitivity to bent neck during summer (G. Slootweg, unpublished data). Spot checks of bacterial counts inside flower stems are used to enforce bactericide pretreatment. A check, by means of enzyme-linked immunosorbent assay, on pretreating *Alstroemeria* with gibberellin was developed elsewhere (Franssen et al., 1992). Developing and implementing these and comparable tests should eventually make it possible to introduce a quality certificate.

EXTENSION NEEDS AND RESEARCH DIRECTIONS

International trade in floricultural products is a growing business. It will only stay a flourishing business if there is a consensus about the need for good quality. Extension efforts should be extended to all parts of the production and marketing chain. They should emphasize temperature control, hygiene, and product knowledge. This goal could be achieved, for example, through short courses where representatives of all links in the marketing chain participate. The conditions are right to show that trading in high-quality products has financial benefits. Extension efforts should also include the promotion of internal quality tests. This implies that extension needs to be supported by research in this area. Research on underlying physiological processes, such as those involved in flower opening, water relations, the influence of growing conditions on postharvest quality, further improvements in postharvest technology, and genotype improvement also are necessary.

These research and extension efforts should remove barriers to international trade. International collaboration is the key to solving these problems.

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Preharvest Factors Influencing Postharvest Quality of Tropical and Subtropical Fruit

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The goal for postharvest physiologists, whether they are working in basic or applied research, is to maximize the postharvest quality of horticultural commodities. Quality relates to several factors that can be commodity specific and mean different things to different people. The consumer may perceive quality as it relates to appearance, flavor, and dollar value. The packinghouse handler, wholesale distributor, and retailer, in contrast, may perceive quality as ease of handling, uniformity of packaging, and freedom from physical and physiological defects as well as pathological breakdown. Although there is much to learn about the mechanisms of a given tropical or subtropical fruit's response to the postharvest environment, past research has provided handlers with the general principles of sound commodity management. These principles include temperature, relative humidity, atmosphere modification, cooling, and judicious use of fungicides and waxes following harvest. These management strategies are of critical importance for tropical products given their long transit conditions and the potential need for postharvest insect disinfestation quarantine treatments.

This paper will examine the role of the preharvest environment and how it may affect the postharvest life of tropical and subtropical fruit. Essentially, preharvest factors can influence both the rate of fruit development and maturation. The preharvest environment can also have a physical impact on fruit quality: for example, wind or insect scarring may reduce the packout percentage. Finally and most important, but much more difficult to quantify, are those effects that influence susceptibility to physiological and pathological breakdown. This review will not dwell on the latter, but recognizes that the influence of preharvest factors on postharvest decay incidence and severity has been well documented.

One must remember that the plant exists in a dynamic environment and therefore can respond to changes to that environment in an interactive fashion. The factors listed in Table 1 are neither all inclusive nor mutually exclusive. Several examples will illustrate the interaction between one or more preharvest factors on postharvest fruit quality.

ENVIRONMENT

Environmental factors include climate (temperature, wind, rainfall), air quality, and positional effects both within a planting and within the tree. Elements such as wind, heavy precipitation, and frost may result in direct loss of the fruit from the postharvest chain due to fruit scarring; increased incidence of plant pathogens associated with high rainfall, especially during flowering (i.e., anthracnose); and loss of fruit related to freeze damage. Temperature during fruit growth and maturation may also influence fruit quality by either hastening or delaying horticultural maturity.

In persimmons (*Diospyros* spp.), warmer temperatures both during early fruit development and just before harvest may influence the accumulation and subsequent turnover of tannins (Kitagawa and Glucina, 1984). Under cool growing conditions, incomplete tannin removal may result in inferior flavor development in nonstringent cultivars such as 'Fuyu'. High temperature during early growth also may influence fruit shape. In Japan, a study conducted under plastic illustrated that pummelos [*Citrus grandis* (L.) Osb.] grown under constant warm conditions tended to have large pear-shaped fruit with thicker peels and lower total soluble solids content (SSC) (Susanto and Nakajima, 1990).

Blackheart or endogenous brown spot (EBS), an important postharvest disorder of pineapple [*Ananas comosus* (L.) Merr.], has been related to both preharvest and postharvest temperature (Smith, 1983). EBS symptoms include small, brown translucent spots that

form at the fruitlet base close to the core; there are no external symptoms. In their study conducted in Queensland, Australia, Smith and Glennie (1987) demonstrated the influence of field temperature and time before maturation (based on shell color). At constant growing conditions <25C, the incidence of this disorder increased at the time of harvest. Varying day/night temperatures (25C/15C) to approximate the heat units of a constant exposure to 20C moderated this effect.

After mild freezes in California, avocado (*Persea americana* Mill.) fruit, although exhibiting no external damage, may become more susceptible to decay, weight loss, and chilling injury following storage. Relative susceptibility can be correlated to pedicel appearance following exposure to temperatures below -1C in the field. This characteristic can be used as a marker of fruit quality at harvest following mild freezes (Arpaia, unpublished data).

In South Africa the incidence of grey pulp or mesocarp discoloration of avocados changes with time within a given growing district (Rowell, 1988). Rowell also documented differences in the amount of mesocarp discoloration related to growing districts, which also influence other quality aspects, such as the volatile oil content of navel orange. Bartholomew and Sinclair (1946) compared the warmer inland growing districts of California to a cooler growing district and found about a 25% reduction in volatile oil content in the cooler site.

Heat accumulation, expressed as heat units, may be a maturity index for 'Caraboa' mango (*Mangifera indica* L.) in the Philippines. One thousand heat units (degree-days above 17.9C) were required for proper fruit maturation. Temperature records from varying growing districts showed that the apparent difference in days to maturity could be explained by the difference in the rate of heat accumulation (Mendoza and Suriyapananont, 1984).

Rindstain of the peel is a major postharvest problem with California navel oranges [*Citrus sinensis* (L.) Osb.]. This disorder is influenced by several preharvest factors, including position on the tree. Fruit harvested from the north side of the tree showed a higher propensity to this disorder (Eaks, 1964). Tree positional effects on citrus fruit quality occur in relation to SSC, the SSC : titratable acidity (TA) ratio (Sites and Reitz, 1949, 1950), and epicuticular wax deposition and metabolism (El Otmami et al., 1989).

A good correlation between light and external fruit pigmentation development, a desirable quality attribute, exists for mango. Internal flesh breakdown (IFB), also known as jelly seed, soft nose, and tip pulp, of mangos is a leading postharvest problem for this fruit. Symptoms vary, but the occurrence is strongly cultivar dependent and may be genetically linked. Evidence also substantiates that large fruit size aggravates the occurrence of breakdown. For instance, 'Alphonso' mango had a 45% incidence of IFB in the largest fruit category compared to an 18% incidence in the smallest (Wainwright and Burbage, 1989).

Environmental conditions also influence susceptibility. In South Africa, Van Lelyveld and Smith (1979) reported that early season 'Sensation' mango had no IFB, whereas the incidence in late-season fruit was 80%. There is a higher incidence of the disorder when fruit are harvested ripe as opposed to harvesting horticulturally mature but

Table 1. Preharvest factors involved in postharvest fruit quality.

Climate/environment
Rootstock/scion
Planting design
Pruning practices
Pest management
Irrigation
Plant growth regulators
Plant nutrition

unripe fruit. Sun exposure after harvest also has been implicated in subsequent IFB development (Wainwright and Burbage, 1989).

Prasad et al. (1971) suggested that black tip, a related disorder in mangos, could be induced by sulfur dioxide emissions from local kilns in India, although they recognized there was substantial variation in cultivar susceptibility. Chandra and Yandagni (1984) reported that foliar sprays of sodium carbonate or borax could reduce tip pulp when the fruit were about the size of a marble.

Two physiological disorders of durian (*Durio zibethinus* Murr.), dry hard pulp and watery pulp, have been attributed to environmental conditions (Lim, 1990). Watery pulp is characterized by watery, dull-tasting flesh surrounding the seed and is closely associated with fruit that matures and ripens during the rainy season.

ROOTSTOCK/SCION

Bitters and Scora (1970) demonstrated that citrus rootstock could influence both the yield and composition of the volatile peel oil. They documented that there was $\approx 40\%$ difference in the yield of volatile oil between the two extreme rootstocks in the study. They also observed that the D-limonene content of the oil varied with rootstock. Kesterson et al. (1974) reported that lemon [*Citrus limon* (L.) Burm. f.] selection significantly affected peel oil yield ($\approx 25\%$ difference between two extreme scions). Labanauskas (1969) reported that fruit size, juice content, and ascorbic acid content of 'Valencia' orange was higher when the fruit was grown on sweet orange rather than rough lemon rootstock. He also reported significant rootstock effects on the macro- and micronutrient levels in citrus fruit.

Rootstock also affects the incidence of navel orange rindstain. Eaks and Jones (1959) reported the incidence of this disorder ranged from 64% in navel oranges on Rubidoux sour orange rootstock to 20% on Duncan grapefruit rootstock. Eaks and Arpaia (unpublished data) also have observed variability between navel orange strains in terms of their ability to withstand Mediterranean fruit fly disinfestation cold treatments during quarantine. Strain differences were moderated by preharvest application of gibberellin (GA_3). Kremer-Köhne and Köhne (1992) illustrated the influence of 'Fuerte' vs. 'Hass' avocado on susceptibility to chilling injury. They observed that 'Hass' had a higher percentage of fruit free from physiological disorders following storage than did 'Fuerte'.

PLANTING DESIGN AND PRUNING

Pruning practices may influence fruit maturation by allowing more light to reach the interior fruit. In navel orange, Boswell et al. (1982) demonstrated that tree spacing influenced the rate of fruit maturation as determined by SSC : TA ratio and color development. A critical consideration for tropical and subtropical fruits is also the timing of pruning. If pruning or girdling occurs at a time that promotes vegetative growth at the expense of fruit growth, a Ca imbalance and reduction in overall fruit size may occur. Whiley et al. (1992) reported higher fruit Ca levels during the first 8 weeks of 'Hass' avocado fruit growth when the spring vegetative flush was controlled with the growth regulator β -[(4-chlorophenyl)methyl]- α -(1,1-dimethyl)-1H-1,2,4-triazole-1-ethanol (paclobutrazol). Cutting and Bower (1992) demonstrated, under the subtropical growing conditions of South Africa, that avocado fruit borne on trees where vegetative growth was controlled by pruning had higher Ca, Mg, K, and P levels at harvest.

PEST MANAGEMENT

Pest management practices may result in direct fruit loss from scarring and in indirect losses from changes in fruit composition. Eaks and Dawson (1979) documented the influence of weed management practices on Valencia orange chlorophyll loss and carotenoid development. Fruit on trees maintained on bare ground showed a significantly lower amount of chlorophyll and higher amounts of carotenoids in its peel at all times. This finding can be related to the known effect of ground cover on lowering the soil temperature in the grove.

Lim and Khoo (1990) reported that direct loss of guava (*Psidium guajava* L.) fruit quality can be attributed to pesticide application.

They reported scorching of guavas resulting from the herbicide 1,1'-dimethyl-4,4'-bipyridinium (paraquat). In some cultivars, Cu sprays for decay control can induce russet formation on the fruit surface. Fruit at all stages of development are susceptible. They also reported that russetting may influence the storage quality of the fruit. Beck et al. (1991) demonstrated that applying phosphorothioic acid *O,O*-diethyl *O*-(3,5,6-trichloro-2-pyridinyl)ester (chlorpyrifos), an organophosphate, at the time of carpel initiation could affect grapefruit (*Citrus paradisi* Macfad.) morphology by stimulating chimeral-type ridges on the fruit.

Thrips scarring, caused by second instar feeding of the citrus thrips on young, developing navel orange fruit, is a major concern for growers and is the number one pest controlled in navel orange in California (Arpaia and Morse, 1991). The occurrence of thrips scarring on the fruit results in direct fruit loss as a result of downgrading at the packinghouse. Arpaia and Morse (1991) examined the impact of using less pesticides on subsequent fruit quality affected by varying levels of citrus thrips scarring. They found that fruit with moderate or severe scarring had higher levels of SSC, lower TA, higher SSC : TA ratios, and greater weight loss. In a subsequent study (Arpaia and Morse, unpublished data), they found that the more heavily scarred fruit reached the legal minimum 8 SSC : 1 TA ratio sooner than fruit with no or slight scarring. This differential was maintained through the sampling period.

In the Philippines, mangos are often bagged to reduce the amount of damage from leafhoppers. Ortega (1983) compared the effectiveness of various coverings to control pests. He found that fruit bag material also influenced fruit quality, an indirect loss due to a pest management practice. Covering fruit with paper ≈ 55 days from flowering resulted in less anthracnose and stem-end rots. Conversely, fruit covered with polyethylene resulted in more decay and increased fruit softening. This softening was attributed to higher fruit temperature and relative humidity in the polyethylene bag.

IRRIGATION

Irrigation effects on postharvest fruit quality are difficult to quantify. However, George (1987) documented that 'Apen' banana (*Musa × paradisiaca* L.) subjected to water stress during growth had a significantly shorter storage life. He also reported that GA_3 application can increase storage life only when bananas are maintained under high relative humidity during storage. Bower (1988) found that preharvest water stress influenced polyphenol oxidase (PPO) levels in ripe avocado fruit after 30 days in storage at 5.5°C. PPO has been associated with mesocarp discoloration in avocados. He also found that preharvest water stress influences the fruit's ability to withstand low O_2 and high CO_2 . Fruit from stressed trees exhibited more physiological disorders following storage and ripening than fruit from nonstressed trees.

SSC and percent juice content at harvest of navel orange trees were affected by varying irrigation regimes. Fruit harvested from well-irrigated trees tended to have higher SSC and higher juice content. Irrigation practices also had a seasonal effect on the fruit's relative tolerance to an insect disinfestation quarantine cold treatment (Arpaia and Eaks, 1990).

PLANT GROWTH REGULATORS

Several researchers have reported the impact of exogenously applied plant growth regulators on postharvest fruit quality. External pigmentation of litchi (*Litchi sinensis* Sonn.) is an important determinant of fruit quality. Deep-red pigmentation is desirable in litchi cultivars. External quality within a cultivar can be influenced by growing region, light level, and overall nutrition (Underhill and Wong, 1990).

Jaiswal et al. (1987) studied the effect of kinetin and cycloheximide on anthocyanin development in 'Kasba' litchi. Both materials were applied ≈ 3 days before full color development. Total anthocyanin content of the litchi rind was significantly lowered by both materials and was concentration dependent. They also report that kinetin delayed chlorophyll degradation.

GA_3 , a widely used plant growth regulator, has well-documented

effects on citrus fruit quality. Coggins (1969) demonstrated the positive effects of preharvest GA₃ applications on maintaining peel firmness and delaying overall rind senescence. El-Otmani and Coggins (1991) observed that GA₃ applications reduced wax deposition on the navel orange fruit surface and delayed the transition of the epicuticular wax structure from crystalline to amorphous.

Applying GA₃ before color break reduced the incidence of navel orange rindstain (Coggins et al., 1963). Arpaia and Eaks (1990) have studied the effect of a preharvest GA₃ application on navel orange susceptibility to chilling injury, specifically in response to an insect disinfestation quarantine cold treatment. Chilling injury development in navel oranges is largely restricted to the peel and is characterized by increased decay, and pitting and staining of peel tissue. A preharvest GA₃ application at color break will reduce the fruit's susceptibility. The magnitude of the response depended on fruit maturity, with the greatest response observed in late-season navel oranges.

Garcia-Luis et al. (1985) examined the effect of GA₃ on Satsuma mandarin (*Citrus reticulata* Blanco) fruit quality. They observed, as have others, that GA₃ maintained peel resistance as compared to nontreated controls at both sampling dates. The effect of GA₃ was concentration dependent. They also noted that fruit ripened more slowly (as indicated by external fruit color and peel chlorophyll content) with increased GA₃ concentration. Most important, they observed a significant reduction in the percentage of fruit that were puffy, a senescence disorder affecting fruit marketability.

Preharvest GA₃ applications also influence mango fruit quality (Khader, 1991). In this study, Khader obtained a slight but significant delay in the speed of fruit ripening associated with GA₃ treatment. He noted that treated fruit had lower SSC, higher TA, and ascorbic acid at harvest and after 6 days of ripening. Treated fruit also had less total carotenoids and increased chlorophyll even after complete ripening. In an earlier study, Khader (1990) tested the response of mango fruit ripening to paclobutrazol. Paclobutrazol was applied twice, at the time of fruit bud differentiation and $\approx$ 20 days before harvest. Trees treated at the higher concentrations flowered $\approx$ 1 week before the control, and at harvest, they had significantly more color (less chlorophyll and greater carotenoids), SSC, and amylase activity. This effect was concentration dependent.

Andam (1980) studied the effect of ethephon on 'Caraboa' mango. He found that ethephon applied 40 to 54 days from flowering did not hasten maturation, but ethylene and respiratory activity was enhanced during the postharvest life of the fruit. Lertpuk and Mendoza (1988) reported that a preharvest ethephon application had no significant effect on the total postharvest life of 'Caraboa' mango.

PLANT NUTRITION

The amount of applied N influences volatile oil yield of 'Bearss' lemon (Kesterson et al., 1974; Koo et al., 1973). Koo et al. (1973) also reported that K influenced oil yield in a negative manner, but this effect was nonsignificant. Embleton and Jones (1968) reported that K affected lemon fruit quality; peel thickness, juice percent, TA, and ascorbic acid were related to leaf K content.

An interesting effect of preharvest plant nutrition on banana postharvest handling was elucidated by Johnson (1979). Water tanks are used at packing stations for conveying bananas to transport them within the packinghouse with minimal damage. The specific gravity of the banana is normally <1.0 , but at times up to 5% of the fruit may sink to the bottom of the wash tanks. Fruit that sink are subject to more mechanical damage due to abrasion. Johnson found that the pulp K content of affected fruit was 36% lower than that of nonaffected fruit and that peel K differed by 20%. He studied this in field experiments that involved varying levels of K nutrition. His results showed a 48% difference in the incidence of sinking fruit between the control and the K treatment.

Calyx separation is a disorder observed in persimmons (*Diospyros kaki* L. f.) produced in New Zealand and has been related to excessive N levels and improperly timed fruit thinning (Glucina, 1987). High N also depressed color development in mangos. Potassium can counteract this effect, but excessively high levels of K may induce a Ca imbalance in the fruit. Calcium levels within mango fruit influence the

development of internal flesh breakdown (Mercado, 1979; Smith, 1989).

Soft nose or tip pulp of mangos is a breakdown of the fruit flesh at the fruit apex. The severity of this disorder varies from season to season. Young and Miner (1961) illustrated that the incidence of soft nose was influenced by an interrelationship between high N and Ca, with Ca tending to prevent or retard soft nose. Burdon et al. (1991) reported finding a gradient of Ca and Mg levels in fruit. The lowest levels of pulp Ca were in the area of the fruit normally associated with soft nose. When they compared tissue from affected and nonaffected areas, they found higher levels of Ca in affected tissue. They hypothesized that during symptom development Ca may be relocated to deficient areas.

Extensive research on 'Fuerte' avocado has been conducted in South Africa. This research focuses on the relationship of postharvest avocado fruit quality and the role of plant nutrition. Witney et al. (1990) demonstrated the impact of fruit Ca levels on fruit ripening duration. They reported a significant interaction between these two variables, with high-Ca fruit taking longer to ripen. They also reported on fruit Ca levels during fruit growth from vigorous vs. nonvigorous trees for both 'Hass' and 'Fuerte'. In both instances, fruit borne on nonvigorous trees had higher Ca levels, especially during the early stages of fruit growth. This period also correlates with the time of maximal vegetative flushing. They suggest that it is the early levels of Ca in the fruit that influence subsequent postharvest fruit quality. The work of Whiley et al. (1992) confirmed this observation.

Postharvest problems of avocados in South Africa are a combination of several disorders. Swarts (1984) differentiates between pulp spot and mesocarp discoloration or grey pulp. Pulp spot is a blackening of the pulp region surrounding cut vascular bundles and is localized in nature and more prevalent in early season fruit. Mesocarp discoloration or grey pulp is an overall grey-brown flesh discoloration that normally increases with fruit maturity. Vorster and Bezuidenhout (1988) reported lower Zn and Ca levels in fruit exhibiting pulp spot. More recently, Smith and Köhne (1992) surveyed a large population of 'Fuerte' avocado trees in which low-yielding trees had poorer fruit quality following storage and lower Ca and Zn levels and higher B levels in flesh tissue.

This picture is complicated by the recent multi-year study of du Plessis and Koen (1992). They concluded that the incidence of grey pulp (or mesocarp discoloration) is strongly correlated with the subsoil Ca and Mg : K ratio. They also reported a significant reduction in the incidence of pulp spot with high levels of subsoil K, which, however, was found to aggravate grey pulp.

CONCLUSIONS

There is ample evidence in current literature that preharvest factors may influence the postharvest fruit quality of tropical and subtropical fruit. Preharvest factors are perhaps especially critical to the success of handling tropical and subtropical fruit since typically long transit times to market are required and fruit are subject to insect disinfestation treatments. Understanding the effects of the preharvest environment on growth and maturation processes and susceptibility to physiological and pathological disorders will help to explain inconsistencies in postharvest fruit performance for a given cultivar. There will also be an indirect benefit of this line of research. Typically, growers do not usually understand the postharvest biology of their particular commodity nor do they particularly care since they perceive that "postharvest" is anything past the farm gate. Efforts toward understanding the role of preharvest factors on postharvest quality brings growers into actively controlling the quality of their product and helps to make them willing participants in the quest for optimizing product quality.

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Chilling Injury of Tropical Horticultural Commodities

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Most tropical horticultural commodities are sensitive to chilling temperatures. Therefore, chilling injury (CI) is a serious problem in the postharvest handling of tropical horticultural commodities. From the standpoint of CI, we can classify all horticultural crops into three categories: A) chilling resistant; B) chilling sensitive; and C) slightly chilling sensitive. The storage life of commodities in group A is inversely related to storage temperature. The lower the storage temperature, the longer the storage life, as long as the temperature is not below the freezing point. The storage life of commodities in group B increases with decreasing storage temperature down to a certain point; then, storage life decreases with any further temperature decrease. This point is called the critical chilling temperature. It usually occurs at ≈ 10 to 13°C . Most crops of tropical or subtropical origin are chilling sensitive and belong to group B. The critical chilling temperature in group C plants is lower than that in group B plants. It usually occurs at ≈ 3 or 4°C . Some temperate crops are in this group, such as 'McIntosh' apples (*Malus domestica* Borkh.). About one-third of all fruits and vegetables in U.S. markets are susceptible to CI. Most of the susceptible crops are of tropical or subtropical origin.

CI SYMPTOMS IN TROPICAL COMMODITIES

CI symptoms vary with commodities. Some common CI symptoms in tropical horticultural commodities are pitting, discoloration, water-soaked appearance, internal breakdown, failure to ripen, loss of flavor and aroma, and decay (Hardenburg et al., 1986). Symptom development depends not only on species and cultivars, but also on maturity, types of tissues, and other environmental factors, such as storage humidity. Pitting, circular or irregular-shaped pits on the fruit surface, is the most common form of CI and the first CI symptom in many tropical horticultural commodities. Surface pitting can occur on beans (*Phaseolus vulgaris* L.), citrus fruits [*Citrus sinensis* (L.) Osbeck], cucumbers (*Cucumis sativus* L.), eggplants (*Solanum melongena* L.), melons (*Cucumis melo* L.), okra (*Hibiscus esculentus* L.), papayas (*Carica papaya* L.), pomegranates (*Punica granatum* L.), sweet peppers (*Capsicum annuum* L.), sweetpotatoes [*Ipomea batatas* (L.) Lam.], and tamarillos [*Cyphomandra betacea* (Cav.) Sendt.]. Failure to ripen is another common CI symptom in tropical and subtropical crops; it can occur in avocados (*Persea americana* Mill.), bananas (*Musa* spp.), mangos (*Mangifera indica* L.), melons, papayas, sapodilla (*Achras zapota* L.), and tomatoes (*Lycopersicon esculentum* Mill.). There are CI symptoms that are specific to individual commodities; some examples include subepidermal brown streaking of vascular tissues in bananas, membranous staining in lemons [*Citrus limon* (L.) Burm. f.], and mahogany browning in potatoes (*Solanum tuberosum* L.).

RESPONSE OF TROPICAL COMMODITIES TO CHILLING TEMPERATURE

There are two schools of thought concerning the response of chilling-sensitive commodities to chilling temperature. According to the first concept, a single, unifying primary response to chilling temperature exists in all chilling-sensitive species. This primary response would lead to secondary events that include various physiological and biochemical alterations. These alterations would eventually lead to the development of a variety of CI symptoms. Several events have been proposed as possible candidates for a primary response, such as a transition in membrane lipids; an alteration in the kinetics or substrate specificity of a regulatory enzyme; a change in the cytoskeletal structure; or an increase in the cytosolic Ca (Raison and Orr, 1990). However, there is still no conclusive proof to substantiate or pinpoint such events. The second concept holds that CI originates from a multitude of responses to low temperature. Considering the

diversity of tropical horticultural crops in structure and in expression of CI symptoms, proponents of this concept question that a single universal primary event can set in motion a chain of events cascading into a wide range of CI symptoms (Lyons and Breidenbach, 1987; Shewfelt, 1992; Wade, 1979). The second concept suggests that there are multiple responses over a wide range of conditions.

IMPORTANCE OF ALLEVIATING CI IN TROPICAL COMMODITIES

Postharvest losses resulting from CI are probably greater than has been recognized. Quite often, CI symptoms may not be apparent while the produce is still in cold storage; the symptoms show up later, only after the produce has been transferred to market where the temperature is higher. At the market, a substantial portion of losses resulting from CI may be mistakenly ascribed to pathogen-induced or ripening disorders.

Low-temperature storage is considered to be the most effective method for maintaining the quality of most fruits and vegetables because low temperature retards respiration, ethylene production, ripening, senescence, undesirable metabolic changes, and decay (Hardenburg et al., 1986). Unfortunately, for CI-sensitive crops, such as tropical horticultural commodities, low-temperature storage is often more detrimental than beneficial. Therefore, chilling-sensitive crops do not always benefit from refrigeration. However, if these chilling-sensitive commodities are not refrigerated, they tend to break down rapidly and have a short storage life. This dilemma results in tremendous postharvest losses for tropical horticultural commodities. It is apparent that alleviating CI in these crops is vitally important.

POSTHARVEST TECHNIQUES FOR REDUCING CI

Postharvest researchers have taken several approaches to lessen chilling-induced injury. These postharvest techniques include temperature conditioning, intermittent warming, controlled-atmosphere storage, chemical treatments, and growth regulator application. The first three techniques involve manipulating and modifying the storage environment, while the other methods involve directly treating the commodities. These techniques reduce CI by either increasing the tolerance of commodities to chilling temperature or retarding the development of CI symptoms.

Temperature conditioning

Prestorage temperature can significantly affect the susceptibility of tropical commodities to CI (Hatton, 1990; Paull, 1990). In low-temperature conditioning, exposing commodities to temperatures slightly above the critical chilling range can increase their tolerance to chilling exposure. This low-temperature conditioning is effective in reducing CI in the following tropical and subtropical crops: cucumbers, eggplants, grapefruit (*Citrus paradisi* Macfad.), lemons, limes [*Citrus aurantifolia* (Christm.) Swingle], mangos, papayas, sweet peppers, tomatoes, and zucchini squash (*Cucurbita pepo* L.). Temperature conditioning can be performed as a single step or in multiple steps. Usually, multistep conditioning is more effective. For example, eggplants conditioned at 15°C for 2 days followed by 1 day at 10°C had less pitting (after storage at 6.5°C) than those conditioned for 2 days at 15°C alone (Nakamura et al., 1985). In bananas, gradually decreasing the temperature in 3C steps from 21 to 5°C at 12-h intervals resulted in the least CI compared to a 5°C decrease every 24 h, an 8°C decrease every 36 h, or a single change from 21 to 5°C (Pantastico et al., 1967). Low-temperature conditioning has been associated with maintaining high levels of phospholipids in membranes, increasing the degree of unsaturation in membrane fatty acids, suppressing the increase in the

sterol : phospholipid ratio, and increasing polyamine, squalene, and long-chain aldehyde concentrations. All these factors may contribute to reducing CI.

Brooks and McColloch first reported using prestorage high-temperature conditioning to reduce CI in 1936. They found that conditioning at 38C for 17 to 22 h significantly reduced pitting in grapefruit stored at 4.5C. Since then, other tropical fruits and vegetables, including cucumbers, lemons, mangos, pomelos [*Citrus grandis* (L.) Osbeck], sweetpotatoes, tomatoes, and watermelons [*Citrullus lanatus* (Thunb.) Mansf.], have also been found to benefit from high-temperature conditioning. Ben-Yehoshua et al. (1987) found that heat treatment increased antifungal materials, such as scoparone and umbelliferone, and reduced decay and CI in lemon and pomelo fruits. Curing sweetpotatoes at high temperatures promotes the healing of cuts and bruises, reduces moisture loss, and provides protection against invasion by microorganisms during subsequent cold storage. Protection against CI by prestorage heat treatment in tomatoes is related to the accumulation of heat-shock proteins (Lurie and Klein, 1991).

Intermittent warming

Intermittent warming is the interruption of low-temperature storage with one or more periods of warm temperature. This treatment must be applied before CI becomes irreversible. Otherwise, if the critical time at chilling temperature has been exceeded and CI has progressed beyond recovery, then raising the temperature would only accelerate degradation. Therefore, timing the treatment is critical and detecting CI early is important. Intermittent warming has been used successfully in commercial operations for lemon fruit in Israel (Cohen, 1988). CI in lemons can be reduced by warming the fruit for 7 days at 13C after every 21 days in cold storage at 2C. Market quality of 'Eureka' and 'Villa Franca' lemons can be maintained for at least 6 months by using this storage technique (Cohen et al., 1983). For crops with a short storage life, such as cucumbers, sweet peppers, and zucchini squash, intermittent warming must be applied earlier and more frequently (Kramer and Wang, 1989; Wang and Baker, 1979). A popular hypothesis for intermittent warming states that raising the temperature in the middle of chilling exposure usually induces higher metabolic activities and allows the tissue to metabolize excess intermediates or toxic materials accumulated during chilling (Pentzer and Heinze, 1954). Warming chilled tissues for short periods may also help to repair damage to membranes, organelles, or metabolic pathways and to replenish any substances that are depleted or are unable to be synthesized during chilling. Another hypothesis regarding the mechanism of intermittent warming states that shifting the temperature from low to high and then from high to low probably induces a rapid metabolic readjustment that increases polyunsaturated fatty acid synthesis (Wang, 1982). Fatty acid elongation and desaturation can occur when the temperature is changed from high to low (Fukushima et al., 1979). This change likely affects membrane fluidity and increases tolerance to low temperature.

Controlled-atmosphere storage

Controlled-atmosphere storage may be beneficial, detrimental, or ineffectual in reducing CI. Controlled-atmosphere storage is beneficial in preventing CI in avocados, grapefruit, okra, pineapples [*Ananas comosus* (L.) Merr.], and zucchini squash. In contrast, controlled-atmosphere storage accentuates CI symptoms in cucumbers, limes, and sweet peppers. In some crops, such as lemons, papayas, and tomatoes, controlled-atmosphere storage does not seem to have any effect on their susceptibility to CI.

Chemical treatments

Chemicals reported to be effective in reducing CI include Ca, ethoxyquin, sodium benzoate, 1-(2-(2,4-dichlorophenyl)-2-(2-propenyloxyethyl)-1H-imidazole) (imazalil), 2-(4-thiazolyl) benzimidazole (thiabendazole), mineral oil, safflower oil, vegetable oil, and squalene. Calcium apparently strengthens cell walls and cell membranes and helps tissues withstand chilling stress. It has reduced

CI in avocados (Chaplin and Scott, 1980), okra (Ilker and Morris, 1975), and tomatoes (Moline and Teasdale, 1981). Ethoxyquin and sodium benzoate are free-radical scavengers. Scavenging free radicals can reduce the peroxidation of unsaturated fatty acids in membrane lipids, thereby helping to maintain membrane integrity and reduce CI. These free-radical scavengers are effective in reducing CI in cucumbers and sweet peppers (Wang and Baker, 1979). The fungicides imazalil and thiabendazole inhibit latent infections, reduce pitting, and delay peel senescence in oranges and grapefruit (McDonald et al., 1990; Schiffmann-Nadel et al., 1972). Mineral oil and safflower oil prevent chilling-induced underpeel discoloration of bananas (Jones et al., 1978). Vegetable oil delays CI in grapefruit (Aljuburi and Huff, 1984). These oils may have antitranspirant and antioxidant activities that reduce moisture loss and oxidative damage, thereby reducing CI. Squalene is a highly unsaturated C30 isoprene hydrocarbon. Nordby and McDonald (1990) found that squalene is a natural wax compound in grapefruit peel and applying additional squalene can effectively protect grapefruit from CI.

Growth regulator application

Growth regulators affect many biochemical and physiological processes in plant tissues. Their effect on these processes may in turn alter the chilling tolerance of tissues. Absciscic acid (ABA) has been studied extensively in relation to CI. ABA induces stomatal closure, reduces water loss, and prevents chilling-induced wilting of seedlings (Rikin and Richmond, 1976). ABA also stabilizes the microtubular network, suppresses ion leakage, and prevents the loss of reduced glutathione and membrane phospholipids (Rikin et al., 1979). ABA applications reduce CI of grapefruit (Kawada et al., 1979) and zucchini squash (Wang, 1991). Ethylene treatment reduces CI in 'Honey Dew' melons (Lipton and Aharoni, 1979), but increases CI in avocados (Chaplin et al., 1983). Since ethylene is a ripening hormone, the effect of ethylene on CI may be mediated through its effect on maturity and ripening. Several triazole plant growth regulators increase the tolerance of plants to CI (Asare-Boamah and Fletcher, 1986; Lee et al., 1985; Senaratna et al., 1988). Compounds such as β -[(4-chlorophenyl)methyl]- α -(1,1-dimethyl)-1H-1,2,4-triazole-1-ethanol (paclobutrazol), E-(p-chlorophenyl)-4,4-dimethyl-2-(1,2,4-triazol-1-yl)-1-penten-3-ol (uniconazole), and 1-(4-chlorophenoxy)-3,3-dimethyl-1-(1,2,4-triazol-1-yl)-2-butanone (triadimefon) may protect membrane components from oxidative damage during chilling by increasing the defense mechanism of tissues against free-radical attack. Polyamines are a group of polycationic organic compounds and are ubiquitous in cells. Postharvest treatments with exogenous polyamines increase internal polyamine levels and reduce CI in zucchini squash (Kramer and Wang, 1989). The reduction of CI by polyamines may be related to their antioxidant activity and stabilizing effect on membranes.

CONCLUSIONS

CI is responsible for substantial postharvest losses in tropical horticultural commodities. Although no method can completely eliminate CI, several approaches do show promise in alleviating this problem. These techniques reduce CI either by retarding the development of injury symptoms or by increasing the tolerance of commodities to chilling. The search for better techniques will continue, so that we can continue to improve the quality and reduce the postharvest losses of all tropical horticultural commodities.

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Response of Tropical Horticultural Commodities to Insect Disinfestation Treatments

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Postharvest treatments are required to disinfest fresh fruits, vegetables, and flowers of economically important quarantined insects. The damage caused by such insects includes small surface blemishes, destruction of the edible flesh, fruit drop, and spoilage from decay organisms entering the fruit at the site of insect activity (Hagen et al., 1981). These insect pests are of quarantine importance because they are absent from the importing country or region, or the importing country has a "zero tolerance" for all live insects regardless of their economic importance (Armstrong and Couey, 1989). Monitoring insect populations and having regulatory personnel inspect commodities are required to ensure that quarantine treatment protocol and regulations are carried out properly, including proper handling to preclude reinfestation after treatment. Failure to apply disinfestation protocols correctly can result in expensive quarantine and eradication procedures, product losses due to infestation, and costly new quarantine treatments due to introduction of a new pest (Armstrong, 1992). Recent outbreaks of Mediterranean fruit flies in California attest to these failures.

Expansion of world trade in fresh horticultural products has compounded problems associated with regulating quarantine treatments.

The expansion of international passenger traffic and short transit times has meant repeated violations of quarantine barriers. The greatest risk may be associated with contraband fruit smuggled by airline passengers rather than commercial fruit shipments. For example, a 1-week inspection "blitz" during May 1990 of all passenger baggage coming through Los Angeles International Airport from selected Central and South American countries resulted in 677 interceptions of contraband fruit. The total weight seized was almost 1 t and contained 61 fruit fly larvae. This contrasts with the average interception rate of 434 contraband fruit per week with random baggage inspections of all international arrivals.

The reproduction rate, short life cycle, and adaptability of pest insects, as well as their destructive potential, underscore the need for quarantine treatments and regulatory and physical barriers (Carey and Dowell, 1989; Mitchell and Saul, 1990). The reproduction rates for many insects of quarantine importance are rapid, especially under optimum conditions, including moderate to high temperatures and the absence of low winter temperatures (Fletcher, 1987). The time required for life cycle completion differs with environmental factors and species. Development times are similar for all fruit fly species: egg, 1–

2 days; larvae, 7–9 days; pupae, 10–11 days at 25C (Fletcher, 1987). Oriental fruit flies (*Dacus dorsalis* Hendel) can have three to 18 generations per year (Saeki et al., 1980; Vargas et al., 1984), depending on temperature (O'Loughlin et al., 1984). This time can be modified by moisture content, ripeness of fruit and degree of larvae crowding (Couey et al., 1985; Ibrahim and Rahman, 1982; Vargas et al., 1983). Most adults have long life spans (50–93 days) and high fecundity (800 to 1600 eggs/female) (Vargas et al., 1984).

Insect host status clearly depends on stage of host development, i.e., stage of fruit ripeness, and cultivar (Greany, 1989). Green fruit normally are not hosts. Fruit flies apparently do not infest mature-green 'Brazilian', 'Valery', and 'William's' bananas (*Musa* spp., AAA group) and 'Sharwil' avocados (*Persea americana* Mill.) (Armstrong, 1983; Armstrong et al., 1983), although these fruits are fruit fly hosts when ripe. At commercial maturity, 'Eureka' and 'Lisbon' lemons [*Citrus limon* (L.) Burm.f.] are not hosts for the Mediterranean fruit fly (*Ceratitis capitata* Weideman) (Spitler et al., 1984); and papaya (*Carica papaya* L.) with <25% skin yellowing are not preferred fruit fly hosts (Seo et al., 1982). Pineapples [*Ananas comosus* (L.) Merr.] having at least 50% 'Smooth Cayenne' parentage are not fruit fly hosts (Armstrong and Vargas, 1982; Armstrong et al., 1979; Seo et al., 1973).

Increased restrictions on the use of postharvest fungicides means that safe postharvest disease control treatments need to be developed. Heat treatments have been the method of choice (Couey, 1989). Until 1984, ethylene dibromide was the fumigant of choice, with methyl bromide used for some commodities. Ethylene dibromide was banned in 1984, and methyl bromide's use is seriously threatened. This review will focus on the physiological response of horticultural products to alternative physical insect disinfection treatments.

QUARANTINE TREATMENTS AND PLANT RESPONSES

Irradiation

There is some uncertainty regarding the irradiation dose required to satisfy insect quarantine requirements. Dose levels of 200 to 300 Gy have been proposed for fruit fly sterilization (Balock et al., 1966; Seo et al., 1973), 74 to 101 Gy for Australian fruit flies (Heather et al., 1991), and 50 Gy for codling moth (*Cydia pomonella* Linne) (Toba and Burditt, 1992). Horticultural responses of few fruit have been studied at these dose levels. Limited data is available on disinfection of flowers using gamma irradiation (Goodwin and Wellham, 1990; Wit, 1986). This lack of information is due in part to the apparent greater sensitivity of the tissue (unpublished data) and the possible wide spectrum of insects involved.

Gamma irradiation was initially studied in the 1960s and recommended for extending the shelf life of fresh fruit, including papaya (Akamine and Moy, 1983). A semicommercial irradiator also operated in Hawaii during the late 1960s (Dollar et al., 1971). However, the availability of less expensive alternative technologies, such as fumigation, made irradiation uneconomical (Maxie et al., 1971). Irradiation has potential, however, as an insect quarantine procedure (Sommer and Mitchell, 1986), and irradiation ≤1.0 kGy was approved for use in the United States (U.S. Food and Drug Administration, 1986). There are consumer concerns regarding the use of irradiation on food products (Schultz et al., 1989); however, a commercial irradiator (Vindicator, Mulberry, Fla.) is operating in Florida.

Fruit responses to irradiation can vary widely. Papaya can tolerate up to 1 kGy γ -radiation before surface scald occurs, surface color development is not disrupted by up to 2 kGy, flavor and aroma 4 kGy, and tissue breakdown 5 kGy (Akamine and Moy, 1983; Akamine and Wong, 1966). A 0.75-kGy dose was considered optimum for retaining fruit firmness in papaya, with only slight control of storage decay (Akamine and Wong, 1966). Papaya respiratory activity immediately after irradiation is initially elevated, but returns to the level of non-treated controls within 24 h (Akamine and Goo, 1971). A delay in climacteric peak and, hence, ripening occurred only in fruit with <25% surface color at time of treatment (Akamine and Goo, 1977a, 1977b).

Irradiated papaya ripen more uniformly as a cohort than nonirradiated fruit. Fruit placed immediately into storage at 10C after

irradiation and having <25% yellow developed skin scald. Delaying storage by 6 to 12 h after treatment prevents skin scald (unpublished data). Irradiation slightly retarded softening in papaya fruit during fruit ripening. Premature softening of papaya flesh occasionally occurs in fruit that had 15% to 35% yellowing when irradiated. Preharvest conditions that predispose fruit to more rapid fruit softening following irradiation are known but not understood.

Heat

Heat treatments offer a viable alternative to other quarantine treatment technologies. Heat treatments also can provide disease control (Couey, 1989), are easy to apply, and leave no residues. The disadvantages are the potential for fruit damage, individual commodity variability in response, and higher application cost compared to fumigation. Some heat treatments can improve fruit quality (Klein and Lurie, 1991; Lurie and Klein, 1992). Insect responses to heat treatment and thermal death relationships are better understood than commodity responses (Jang, 1986, 1991; Moss and Jang, 1991; Yokoyama et al., 1991). Mortality due to heat depends on O₂ availability, pH, previous temperatures, general energy status of the insects, and insect age and stage (Jang, 1991; Moss and Jang, 1991).

Hot-water immersion treatments have been developed to disinfest Mediterranean fruit fly, melon fly (*Dacus cucurbitae* Coq.), and oriental fruit fly from bananas (Armstrong, 1982) and papayas (Couey and Hayes, 1986; Hayes et al., 1984) in Hawaii; Caribbean fruit fly (*Anastrepha suspensa*) in guava (*Psidium guajava* L.) (Gould and Sharp, 1992); and Caribbean fruit fly, Mexican fruit fly (*Anastrepha ludens* Loew.), and West Indian fruit fly (*Anastrepha obliqua* Macquart) from Florida, Mexican, Haitian, or Peruvian mangos (*Mangifera indica* L.) (Animal and Plant Health Inspection Service, 1987; Sharp, 1986, 1989; Sharp and Picho-Martinez, 1990; Sharp and Spalding, 1984; Sharp et al., 1989b). Possible heat treatments are being considered for codling moth (Yokoyama et al., 1991), oriental fruit moth (*Grapholitha molesta* Busck) (Yokoyama and Miller, 1987), and Caribbean fruit fly in stone fruit (Sharp, 1990), carambola (*Averrhoa carambola* L.) (Hallman and Sharp, 1990), and flowers (Hansen et al., 1992). A 20-min, 49C water-bath dip (Akamine and Arisumi, 1953) has been used widely for effective control of some postharvest diseases of papaya. Similar heat treatments have been tested to control disease in other fruit with varying success (Couey, 1989).

Vapor heat was first used in the United States to kill Mediterranean and Mexican fruit flies (Baker, 1952; Hawkins, 1932). Easy-to-use and inexpensive chemical fumigants [ethylene dibromide (EDB) and methyl bromide] for quarantine meant interest in vapor heat faded with their introduction. Research was conducted to develop vapor heat treatments for bell pepper (*Capsicum annum* L.), chinese peas (*Pisum sativum* L.), cucumber (*Cucumis sativus* L.), eggplant (*Solanum melongena* L.), green beans (*Phaseolus vulgaris* L.), lima beans (*Phaseolus lunatus* L.), litchi (*Litchi chinensis* Sonn.), mango, papaya, tomato (*Lycopersicon esculentum* Mill.), and yellow wax beans (*Phaseolus vulgaris* L.) (Balock and Kozuma, 1954; Balock and Starr, 1946; Jones, 1940b; Seo et al., 1974). Commercial vapor heat facilities for many tropical commodities, especially papaya, were built in the United States after 1984, when EDB fumigation was banned. Commercial facilities operate in Okinawa, Philippines, and Thailand.

A high-temperature, forced-air quarantine treatment to kill Mediterranean fruit fly, melon fly, and oriental fruit fly on papaya has been developed (Armstrong et al., 1989; Hansen et al., 1989). This treatment is similar to the vapor heat treatment without the saturated vapor, and is equally as effective.

Heat effects on plant cells. The effect of heat stress on plant cell physiology has been reviewed recently (Alexandrov, 1977; Berry and Bjorkman, 1980; Blum, 1987; Lange et al., 1981; Levitt, 1980; Paull, 1990b). Heat damage is similar in most cells, and in extreme cases, leads to the death of cells, tissues, organs, or the whole plant.

Transferring plants from an ambient to an elevated temperature produces stress. The severity of stress is determined by the temperature differential and duration of exposure. Other factors, such as rapidity of the change in temperature and the previous growing conditions, are also important (Levitt, 1980; Paull, 1990b). The effect of exposure

time, although recognized by many (Alexandrov, 1977; Blum, 1987; Levitt, 1980; Paull, 1990b), has not been fully investigated and its implications are unclear. A short exposure to near-lethal temperature, such as in insect disinfestation, is a "crisis" situation that relates to survival and the capacity to recover, while longer exposures to less extreme temperatures are more difficult to quantify. Excessive exposure leads to death of plant tissue, and high temperatures can only be tolerated for short periods (Paull, 1990b).

Cellular membranes have been stressed with heat (Alexandrov, 1977). Levitt (1980), in his work on chilling, suggested the use of the term "phase transition." The meaning of this term is unclear, although Levitt (1980) claims cell death occurs at the point of lipid "liquefaction." Much of the chilling-related work on lipids has been on bulk cellular extracts, and its relevance in vivo has been questioned (Blum, 1987). The loss of cellular membrane integrity with increasing temperature is gradual, with repair and reversibility possible up to the point where a lethal cell temperature is reached.

The role of the membrane in cell death induced by heat has been reviewed (Blum, 1987; Lange et al., 1981) and many hypotheses have been proposed to explain heat injury (Crisan, 1973; Levitt, 1980). Most involve protein denaturation or protein synthesis disruption. Denaturation at lethal temperatures is regarded as nonreversible, while lower temperatures can lead to a reversible inactivation. Heat effects on proteins and enzymes also were reviewed (Alexandrov, 1977; Bernstam, 1978; Brandts, 1967). Lower than lethal temperatures can lead to disruption of transcription and translation steps in protein synthesis (Bernstam, 1978) and possibly protein secretion. Single amino acid substitutions in a protein can significantly alter its thermal stability (Matthews et al., 1980).

Heat shock response. Bacteria, plants, and animals exposed to high temperatures (38–42°C) for a brief period acquire transient thermotolerance in the heat shock (HS) response (Burdon, 1988; Chen et al., 1982; Cooper et al., 1984; Kanabus et al., 1984; Key et al., 1981, 1985; Lindquist and Craig, 1988; Yarwood, 1961). As thermotolerance develops, a unique group of proteins is synthesized. These proteins are produced within 30 min after exposure to temperatures between 34 to 42°C (Kanabus et al., 1984) and are called heat-shock proteins (HSP). Thermotolerance and associated HSP have been reported for field-grown cotton (*Gossypium hirsutum* L.) (Burke et al., 1985) and soybean [*Glycine max* (L.) Merr.] leaves (Kimpel and Key, 1985), sorghum [*Sorghum bicolor* (L.) Moench] (Ougham and Stoddart, 1986), and papaya fruit (Paull and Chen, 1990). This phenomenon confers a temporary, acquired heat resistance to sublethal temperatures (Altschuler and Mascarenhas, 1982). There appears to be a fundamental but unclear role for these HSP in cellular function during high-temperature stress (Johnson and Kucay, 1988; Yost and Lindquist, 1988). Tolerance acquired by sudden HS differs from tolerance acquired by sustained growth at a moderately high temperature. Apparently, there is a different mechanism of tolerance induced by the two treatments (Wu and Wallner, 1984). This is supported by HSP being produced at higher temperatures when the temperature is raised slowly (3°C/h) vs. more rapidly (Altschuler and Mascarenhas, 1982), thus emphasizing the importance of the HS profile.

Physiological and biochemical evidence exists for HS response in ripening fruit (Klein and Lurie, 1990; Paull and Chen, 1990). Exposing ripening papaya fruit to either 42°C for 4 h or to 38 to 42°C for 1 h followed by 3 h at 22°C results in thermotolerance to the otherwise injurious heat treatment of 49°C for 70 min (Paull and Chen, 1990). Polypeptides with molecular weights similar to those of HSP are translated on extracted polysomal RNA following the 42°C treatment. The levels of all these polypeptides peaked 2 h after heat treatment and declined within 24 h. The amount of these polypeptides in the nonheated control varied with season of fruit harvest.

Fruit ripening and heat treatments. The lethal temperature for tissue is 45°C for tomatoes, 63°C for grapes (*Vitis vinifera* L.), and 49 to 52°C for apples [*Malus domestica* (L.) Borkh.] (Huber, 1935). Even below such nonpermissive temperatures, growth and metabolism can be adversely affected by heat. For example, avocado fruit stored at 30 and 34°C ripened abnormally and showed considerable surface pitting, and poor flavor. Ethylene treatment increases the threshold temperature for injury in this fruit (Lee and Young, 1984). Tomato fruit held

for more than 6 h at >41°C show delayed ripening (Hall, 1964a, 1964b) and increased electrolyte leakage (Inaba and Crandall, 1988). Treatment at 49°C for 20 min is near the limit for heat tolerance in papaya (Akamine, 1960; Hayes et al., 1984; Paull, 1990b). Papaya ripen poorly above 30°C (An and Paull, 1990). Couey (1989) grouped fruit as heat-tolerant or heat-sensitive to hot-water treatment. The heat-tolerant fruit were bananas, papaya, mangos, pears [*Prunus communis* (L.) Batsch], and litchis, while the heat-sensitive fruit were peaches [*Prunus persica* (L.) Batsch], raspberries (*Rubus idaeus* L.), bell peppers, and muskmelons (*Cucumis melo* L.). Thermotolerance can vary with cultivar, fruit size, maturity, and postharvest handling (Claypool and Vines, 1956; Jones, 1942; Paull, 1990b; Paull and Chen, 1990; Sinclair and Lindgren, 1955; Sharp et al., 1989a).

Exposing pears (Maxie et al., 1974), tomatoes (Biggs et al., 1988; Ogura et al., 1976; Picton and Grierson, 1988; Yoshida et al., 1984), and papaya (An and Paull, 1990) to temperatures >30°C for ≥48 h disrupted ripening. This disruption is characterized by a failure to develop normal pigmentation, abnormal softening, and a marked decline in ethylene production (Biggs et al., 1988; Maxie et al., 1974; Paull and Chen, 1990; Picton and Grierson, 1988; Yoshida et al., 1984). Soluble solids concentration is not affected by heat treatment, while titratable acidity declines in apples (Klein and Lurie, 1990; Liu, 1978; Porritt and Lidster, 1978); both are unaffected in grapefruit (*Citrus paradisi* Macf.) (Miller and McDonald, 1992).

High temperatures affect respiration rate and ethylene synthesis (Akamine, 1966; An and Paull, 1990; Inaba and Chachin, 1988; Jones, 1940a; Maxie et al., 1974; Ogura et al., 1976; Paull and Chen, 1990). Temperatures >25°C reduce the extent of the respiratory climacteric in avocado (Biale and Young, 1971), and respiratory rise between the initial preclimacteric level and the climacteric peak was 250% at 25°C and only 30% at 30°C. Twelve or more days at ≈33°C suppress tomato respiration, ethylene synthesis, and fruit softening, and this action is not completely reversed after returning the tomato fruit to ambient temperatures (Cheng et al., 1988; Inaba and Chachin, 1988; Ogura et al., 1976; Yoshida et al., 1984). Ripening inhibition above 30°C has been ascribed to disrupted protein action during ethylene synthesis (Maxie et al., 1974; Ogura et al., 1975), disrupted polygalacturonase generation or activation (Chan et al., 1981), and suppressed ripening-related mRNA synthesis (Paull and Chen, 1990; Picton and Grierson, 1988).

Ethylene synthesis is reversibly inhibited at higher temperatures (Biale, 1960; Chan, 1991; Field, 1984; Paull and Chen, 1990). Temperatures >35°C cause endogenous ACC to accumulate in apple tissue (Yu et al., 1980), with accompanying reduced ethylene production. The conversion of ACC to C₂H₄ apparently is highly inhibited by heat. A rapid loss (75%) of ACC oxidase occurs in papaya and other fruit exposed for short periods to temperatures >40°C (Chan, 1986a, 1986b, 1991; Dunlap et al., 1990; Klein and Lurie, 1990; Paull and Chen, 1990). The heat inactivation in papaya and cucumber is biphasic (Chan, 1986a, 1986b). ACC oxidase activity fully recovers within 3 days in papaya (Paull and Chen, 1990), apples (Klein and Lurie, 1990), and muskmelon (Dunlap et al., 1990) after removing heat. Fruit exposed to high temperature for long periods quickly recover ethylene synthesis ability (Biggs et al., 1988; Dunlap et al., 1990; Ogura et al., 1976). The loss of ACC oxidase activity due to heat treatment in cucumber fruit can be modified by conditioning for 24 h at 32.5°C (Chan and Linse, 1989a, 1989b). Recovery of ethylene production may require protein synthesis (Biggs et al., 1988), which suggests low-level production of ethylene-related mRNA (Picton and Grierson, 1988), or reactivation of pre-existing proteins.

Heating leaves to 44°C leads to loss of chloroplast activity, especially photosystem II electron transport (Berry et al., 1975). Chlorophyll fluorescence has been used to monitor heat stress (Smillie and Gibbons, 1981). Delayed light emission, an associated characteristic, declines in papaya skin with first-order kinetics when fruit are heated between 42 to 48°C (Chan and Forbus, 1988). Heat inactivation is biphasic at higher temperatures (49 to 51°C). Color changes associated with ripening in tomato are inhibited at storage temperatures >30°C (Cheng et al., 1988; Goodwin and Jamikorn, 1952). Above 30°C, bananas (Burg, 1962) and papaya (An and Paull, 1990) fail to ripen normally and develop soft and watery pulp.

Electrolyte leakage from tomato disks is induced by increasing temperatures, although the fruit did not exhibit any visible heat injury (Inaba and Crandall, 1988). Critical exposure times for leakage were 34 min at 55C, 105 min at 50C, and 166 min at 45C. Fifty percent higher electrolyte leakage occurred in apple disks held at 38C (Lurie and Klein, 1990) than at ambient temperatures. After transferring disks to 20C, leakage declined within 2 days to control levels. Another factor crucial to interpreting leakage data is the increased leakage rate as fruit ripen (Chan, 1991).

Exposing ripening pear fruit to 40C led to protein synthesis disruption via a loss of polysomes (Romani and French, 1977). This response is readily reversible and established a close correlation between the protein synthesizing machinery and ripening progression. Apples held at 38C for 4 days have reduced S³⁵-methionine incorporation into what may have been HSP (Lurie and Klein, 1990). Papaya fruit protein synthesis changes following exposure to 38C for 2 h; there was no accumulation in the control held at 22C for 10 h. Translated polysomal RNA confirm that new polypeptides are synthesized following heat shock induction (Paull and Chen, 1990). Thermotolerance decreases with continued exposure of papaya fruit to 42C, suggesting that 42C is the limit for induction of tolerance. Continued exposure to 42C, though still allowing HS-polypeptide synthesis, also caused damage. These results agree with those for tomato fruit treated for long periods at 35C (Picton and Grierson, 1988). The synthesis of ripening-specific mRNAs and new enzymes is induced during ripening of tomatoes (Christoffersen et al., 1982; Grierson, 1986; Spiers et al., 1984; Tucker and Grierson, 1982). The elevated temperature treatments may lead to softening inhibition, reduced expression of softening, or both, and other ripening-related mRNAs (Picton and Grierson, 1988).

Thermal injury (46C for 65 to 90 min) in papaya results in uneven ripening and hard lumps in the flesh and is correlated with a 90% decrease in normal polygalacturonase levels with a partial recovery to 25% of normal after 6 days at 24C (Chan et al., 1981). A similar reduction occurred in tomatoes held for several days at 33C (Ogura et al., 1975). The injury is more severe in riper papaya fruit (one-fourth to one-half ripe). Responses similar to those observed in our laboratory (Paull and Chen, 1990), i.e., heated fruit showing delayed ripening and leaving a 1- to 1.5-cm-thick area of hard tissue at the center, had already been noted by Chan et al. (1981). The conclusion from this work is that when polygalacturonase activity or other wall-degrading enzymes are increasing in a particular area of the flesh (Paull and Chen, 1983), and transcription is disrupted by heat or protein denaturation, tissue can lose its capacity to soften. This disruption could occur as ribosomes release mRNAs, which has been documented in pears heated to 40C (Romani and French, 1977). The failure to soften could also be attributable to suppression of mRNA for wall-softening enzymes, as found in tomatoes (Picton and Grierson, 1988). The loss of polygalacturonase mRNA in heated tomatoes is not overcome by exogenous ethylene (Picton and Grierson, 1988). Polygalacturonase activity, however, does return after a 6-day lag when the fruit is returned to 25C (Ogura et al., 1975; Yoshida et al., 1984). A similar reversibility in fruit softening occurred in apples held at 38C for 4 days (Lurie and Klein, 1990) or 12 h at 46C (Klein and Lurie, 1992). Polygalacturonases show little loss of activity when heated to 45C in vitro (Chan and Tam, 1982; Tucker et al., 1980); hence, heat denaturation is unlikely to be the cause of reduced polygalacturonase activity.

Between 35 to 60C, considerable (87%) purified glucanase activity is lost from tomato fruit (Hinton and Pressey, 1980), also 50% glucanase activity can be lost by exposure to 50C for 5 min (Pressey, 1983). The role of these enzymes in fruit softening is unclear. Pectinesterase activity is suppressed in tomatoes held at 33C (Ogura et al., 1975), and the activity several days after returning fruit to room temperature is only one-third of normal ripening fruit.

Modifying heat response. Many procedures have been empirically developed to reduce the injury caused by heat treatment. Disruption of papaya fruit softening by heat treatment is reduced or prevented by a 4-h pretreatment at 42C or a 1-h pretreatment at temperatures higher than 35C followed by 3 h at 22C (Paull and Chen, 1990). The 8-h approach time to 44C for the papaya vapor heat treatment (Seo et al., 1974) is designed to reduce subsequent injury when the fruit is exposed

to 44C for an additional 8.75 h. The approach time would be expected to provide the conditions necessary to develop HSPs and associated thermotolerance. The same would likely occur in deciduous fruits (Claypool and Vines, 1956). The quick rise to 49C using vapor heat always damaged Valencia oranges [*Citrus sinensis* (L.) Osbeck] and grapefruit (Sinclair and Lindgren, 1955), but they are tolerant when heated for 8 h at 43C before the 49C treatment. Cucumber can be preconditioned by a 24-h treatment at 32.5C to tolerate subsequent exposure to hot water at 46C for 50 min (Chan and Linse, 1989b). Although 32.5C is lower than the temperature normally used to induce HSPs, the 24-h duration could probably induce HSPs.

The extent of protection against softening disruption depends on season, stage of fruit ripeness at exposure, and pretreatment time and temperature. The seasonal variation could be due to field-induced thermotolerance. Understanding the conditions necessary to induce thermotolerance is essential to optimize heat treatments used for insect disinfestation and disease control.

Cold

Cold treatments for insect disinfestation theoretically are easy to apply and leave no residue. Cold treatments have been suggested for fruit disinfestation based on the success of refrigeration against Mediterranean fruit fly (Back and Pemberton, 1916). Cold quarantine treatments are used to kill Caribbean fruit fly, Mediterranean fruit fly, and Queensland fruit fly (*Dacus tryoni* Frogg.) on a wide range of fruits (Animal and Plant Health Inspection Service, 1985; Benschoter, 1984, 1988; Gould and Sharp, 1990; Hill et al., 1988; Rippon and Smith, 1979). Eggs and larval stages of fruit flies are killed below 10C, with at least 10 days required below 2.8C (Burditt and Balock, 1985). The length of these treatments and the commercial difficulties of imposing these treatments during shipment limit the use of cold treatments. Most tropical fruit are damaged by extended storage below 10C (Chen and Paull, 1985; Couey, 1982; Paull, 1990a). For example, mature-green papaya can only withstand 7 days at 1C (Chen and Paull, 1985). Only temperate fruit and those tropical fruit that can tolerate temperatures <2C, such as litchi, which can be shipped at 0 to 1.1C (Chen and Paull, 1985) and carambola (Paull, 1990a; Miller et al., 1991), are candidates for cold treatment.

The postharvest storage life of tropical and subtropical crops gradually increases with decreasing storage temperature only within specific limits. The postharvest storage life of tropical, subtropical, and temperate crops reaches a maximum at ≈10 to 12C, 4 to 7C, and 0C, respectively. Higher temperatures allow continued senescence and ripening with an expected Q₁₀ of 2 to 4. Below the 10 to 12C or 4 to 7C thresholds, storage life decreases due to chilling injury (CI), and ripening and senescence are severely restricted (Paull, 1990a). This pattern explains why most storage recommendations for tropical commodities are just in the range where CI occurs. For example, papaya can be stored for ≈25 days at 10C and still have up to 1 week of life at 20C without developing chilling injury (Chen and Paull, 1985). Commercially, papaya is shipped at 7 to 10C. These storage temperature × duration relationships are in direct contrast to the increasing storage life found for temperate commodities stored at decreasing temperatures to near 0C (Hardenburg et al., 1986).

The response of plant tissue to CI has frequently been separated into primary and secondary responses. This separation is based on a series of events involving multiple events cascading from the primary event after a certain level of CI. Two distinct possibilities are suggested as the primary event: lipid changes or protein changes. Changes in either lipids or proteins as the primary event in CI are thought to occur instantaneously when the tissue is subjected to chilling temperatures. The lipid hypothesis has received the most attention since it was originally proposed in 1965 (Bishop, 1986; Graham and Patterson, 1982; Lyons, 1973). It gained more support, at least for green tissue, after Murata et al. (1992) demonstrated the ability to genetically engineer altered chilling sensitivity.

CI symptoms generally develop after transfer from chilling to nonchilling temperatures. Symptom development is slow, and the symptoms are similar to those that occur for other stresses and injury. CI symptoms have been described by many authors and are summa-

ized by Morris (1982). Surface lesions are most common and take the form of pitting (eggplant) (McColloch, 1966), scald (papaya, citrus) (Chen and Paull, 1985; Wardlaw, 1937), and large sunken areas (peppers) (Miller and Risse, 1986). Internal brown discoloration of pulp [pineapple, taro [*Colocasia esculenta* (L.) Schott]] (Paull and Rohrbach, 1985; Rhee and Iwata, 1982), vascular strands (avocado) (Chaplin and Scott, 1980), and seeds (eggplant, tomato) (Autio and Bramlage, 1986; McColloch, 1966) also is common. Water soaking of tissue coupled with wilting and desiccation [ung choi (*Ipomoea aquatica* Forsk.)] (Hirata et al., 1987) are common symptoms in leaves. The above visual symptoms frequently occur with dysfunction of several developmental processes. The most commonly reported is a failure of fruit to ripen (banana, mango, papaya) (Chen and Paull, 1985; Hatton et al., 1965; Wardlaw and McGuire, 1931) and accelerated senescence (ung choi) (Hirata et al., 1987). These symptoms often lead to reduced postharvest life and increased susceptibility to decay (Chen and Paull, 1985; Sommer and Mitchell, 1987). The sequence of events leading to visible symptoms after primary sensing of chilling temperatures clearly vary with tissue. Physiological CI symptoms in papaya include increased ethylene production and electrolyte leakage (Chan et al., 1985), and alternaria rot (Sommer and Mitchell, 1987); they occur before the appearance of visible symptoms. At 10C, increased ethylene production occurs after 7 days, electrolyte leakage after 14 days, and visible symptoms after 24 days. The relationship between physiological CI symptoms, ethylene production and electrolyte leakage, and visible CI symptoms in papaya is unknown. Information on the time-temperature response to incipient CI for tropical and subtropical fruit and vegetables is limited (Paull, 1990a), although such information is essential for developing optimum postharvest handling and disinfestation procedures.

Fruit ripeness stage and leaf tissue age at the time of low-temperature storage significantly influence sensitivity to visible CI symptom development. The preclimacteric stage is generally more sensitive than the postclimacteric stage for avocado, papaya, 'Honey Dew' melons (*Cucumis melo* L.), tomatoes, and mango. The extreme sensitivity of bananas to chilling does not allow a difference to be determined. However, banana fruit in less mature apical hands are less susceptible to CI than the more mature distally borne fruit (Marriott, 1980; Marriott et al., 1979). Avocado (Kosiyachinda and Young, 1976) and papaya (An and Paull, 1990) increase in CI sensitivity up to the climacteric, then sensitivity declines. Conditioning some commodities before cold treatment and intermittent warming can give some increased chilling tolerance (Wang, 1982, 1989). Prestorage heat treatments (38C, 3 days) can also increase chilling tolerance of some fruit (Lurie and Klein, 1992).

Controlled atmospheres

Controlled atmospheres (CA) (reduced O₂, elevated CO₂, added CO, or all three) have been evaluated as possible insect control treatments in several studies (Aharoni et al., 1981; Benschoter, 1987; Davis and Jay, 1977; Delate et al., 1990; Gaunce et al., 1981; Klaustermeyer et al., 1977; Lidster et al., 1984; Morgan and Gaunce, 1975; Soderstrom, 1977; Soderstrom and Brandl, 1990; Soderstrom et al., 1990; Yahia et al., 1992). This method is safe only when O₂ and CO₂ concentrations are used, as it does not employ toxic, flammable compounds and leaves no residue. Most fresh, tropical horticultural crops will not tolerate high CO₂ concentrations and <2% O₂ for the long periods effective in insect control in dry cereals and legumes (Bailey and Banks, 1975; Fleurat-Lessard, 1990). CA combinations may be effective in controlling certain insects, possibly in conjunction with other quarantine treatments (Klag, 1985). Little information is available on the effects of CA on tephritid fruit fly growth, development, and mortality. To my knowledge, there are no approved quarantine treatments using CA to disinfest fruit flies from tropical or temperate fruit.

Holding strawberries (*Fragaria × ananassa* Duch.) at 2.5C for 48 h in high CO₂ killed all western flower thrips (*Frankliniella occidentalis* Pergrande) and reduced fruit decay (Aharoni et al., 1981), but some flavor was lost and juice pH was higher (Ke et al., 1991a). Caribbean fruit fly eggs and larvae are susceptible to 40% and 100% CO₂ for 48

h at 10C and 22 to 23C, respectively (Benschoter et al., 1981). Aphids (*Myzus persicae* Sulzer) and cabbage loopers (*Trichoplusia ni* Hubner) on lettuce (*Lactuca sativa* L.) are not significantly affected by 70% CO₂ and 5% O₂ for 7 days at 2.5C (Klaustermeyer et al., 1977). San Jose scale [*Quadraspidiotus perniciosus* (Comstock)] on apples is controlled by 90% CO₂ and 1% O₂ for 2 days at 12C without quality loss (Morgan and Gaunce, 1975). Codling moth larvae in apples are not completely controlled after 132 days at CA levels normally used for this fruit (Glass et al., 1961). The survivors could have been diapausing larvae, as control of nondiapausing larvae is obtained with 13 weeks storage in normal CA (Toba and Moffitt, 1991). Apple maggots (*Rhagoletis pomonella* Walsh) do not survive beyond 7 days at 0C in 100% N (Kositrakun, 1989). Storing sweetpotato [*Ipomoea batatas* (L.) Lam.] roots at 25C, 2% to 4% O₂, and 60% CO₂ may control adult sweetpotato weevils (*Cylas formicarius* Fab.) (Delate et al., 1990). This method, however, cannot be applied during curing, but only during postcuring to avoid quality loss (Delate and Brecht, 1989). Dried fruit, such as raisins, can be stored in insecticidal atmospheres of <0.5% O₂ and 14% CO₂ at 27C (Soderstrom and Brandl, 1984, 1990). Most fresh fruit, including tropical products, cannot withstand insecticidal CA treatments (40% CO₂, 0.25% to 0.5% O₂, or both) without quality loss, especially if coupled with low temperature. Bananas are a possible exception, as they are harvested when mature green and can withstand modified-atmosphere storage (Scott et al., 1971). Valencia orange is a subtropical fruit that can withstand low O₂ but not high CO₂ (Ke and Kader, 1990).

Apples and pears stored in N gas at 0C for 25 days accumulated CO₂, had higher pyruvate decarboxylase and alcohol dehydrogenase activities, and increased acetaldehyde and ethanol levels (Ke et al., 1991b; Kositrakun, 1989). ACC oxidase decreased and aminocyclopropane carboxylic acid concentration increased in the same system. Blueberries (*Vaccinium* spp.), red raspberries, and blackberries (*Rubus ulmifolius* L.) could be kept under the same conditions for 9, 7, and 5 days, respectively. Longer periods lead to off-flavor that does dissipate (Kositrakun, 1989). Nectarines (*Prunus persica* L.) are probably unable to withstand the low-O₂ (0.5%) conditions needed to control insects; 6 days at 5C caused abnormal ripening, suppressed ethylene production, elevated ethanol and acetaldehyde levels, and increased internal browning (Smilanick and Fouse, 1989). Papaya can only be stored in low O₂ (0.4%) for 3 days at 20C before developing an off-flavor (Yahia et al., 1992), while mango tolerates up to 5 days (Yahia and Vazquez-Morena, 1993).

Reduced pressure

Limited information exists that shows this technology may be effective against some pests. Exposing lettuce to 2.66 kPa for 52 h killed all green peach aphids (*Myzus persicae* Sulzer) without apparently injuring lettuce (Aharoni et al., 1986).

Washing

Washing is only effective for surface insects, such as scales, and can only be used on those commodities able to withstand washing. It is used widely in conjunction with insecticidal soaps to disinfest flowers and ornamental cut-leaf materials (Hata et al., 1992).

SUMMARY

Heat treatments either alone or in combination with other treatments offer the best current alternative for insect disinfestation for tropical and subtropical commodities. The physiological changes that occur during short-term stress are poorly understood. Work is underway to understand these processes and develop approaches to reduce the impact of this stress. However, this work cannot be successfully implemented without understanding how preharvest factors influence a commodity's sensitivity to heat. In addition, the interaction of heat stress and susceptibility to disease is not understood. The optimum method would include heat treatment that achieves insect disinfestation and minimal fungicidal doses to control disease.

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