Reviews

Heat Treatments for Improved Postharvest Quality of Horticultural Crops

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Summary. Commercial, ecological, and agrotechnical considerations have recently renewed interest in the use of physical rather than chemical means to maintain postharvest quality of horticultural crops. This review discusses prestorage heat treatments that protect against physiological disorders, enhance natural resistance to pathogen infection, reversibly inhibit fruit ripening, and permit flexibility in storage temperatures.

Introduction

The development of nonchemical techniques to maintain postharvest quality of fruits and vegetables is increasingly emphasized in many research

programs. This research has been stimulated by concern among consumers that many of the chemicals used to control postharvest disorders are potentially harmful to humans. The majority of such postharvest chemicals are used to control pathological disorders such as latent fungal infections or insect infestations. Some chemicals, such as the fumigant ethylene dibromide, have lost their Environmental Protection Agency (EPA) registration, others may soon be withdrawn. However, even if certain fungicides retain their registration, many fungal pathogens have developed resistance to commonly used chemicals. Since the cost of developing, testing, and registering a new fungicide is becoming prohibitive, there is added impetus for research into alternative methods of control.

Management of physiological disorders, such as storage scald of pome fruits or chilling injury of subtropical and tropical crops, demands careful use of agrotechnical practices, such as harvesting at appropriate maturity, and precise control of temperature, humidity, and atmospheric composition throughout storage. Although disor-

ders such as scald can be managed chemically on a single-treatment basis, development of physical methods that can be applied briefly, yet have long-lasting effects that are independent of storage conditions, would be of major benefit.

Prestorage heating of fruit shows promise as a nonchemical method for managing both pathological and physiological disorders of fruits and vegetables. Ripening characteristics of heated fruit are also different from those of non-heated, allowing a longer shelf life. This review will emphasize the postharvest benefits that are obtained by a long-term (12 h to 4 days) treatment at 38 to 46°C, as opposed to short-term (up to 60 min) heat treatments at 45 to 60°C. The latter have recently been reviewed by Paull (1990), while we have previously reviewed the effect of heating on postharvest physiological processes (Klein and Lurie, 1991).

Heat protects against pathogens

Fungal pathogens. High temperatures exert either lethal or sublethal effects to inhibit fungal germination and growth (Barkai-Golan and Phillips, 1991). Although there is considerable variation in sensitivity to high temperature among various fungi (Sommer et al., 1967), postharvest heat treatments of fresh fruits and vegetables are considered to have potential as nonchemical control measures against decay-inducing organisms (Couey, 1989). The use of water dips at 38 to 60°C for 2 to 60 min has been reported to control *in vivo* and *in vitro* spore germination and decay development of postharvest fungi in melons (Teitel et al., 1991), papayas (Couey et al., 1984), strawberries (Couey and Follstad, 1966), and tomatoes (Barkai-Golan, 1973). Both Couey (1989) and Barkai-Golan and Phillips (1991) have reviewed the results from these studies and others comprehensively.

Despite the evident success of water dips to reduce populations of microorganisms, the high temperature necessitated by the short treatment time (up to 60 min) can easily damage fruit tissue if the recommended exposure time is exceeded. The low tolerance for variation in treatment time thus limits the value of such heat treatments (Mayberry and Hartz, 1992; Teitel et al., 1991). In addition, the stage of fruit maturity may limit the

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period during which such treatments can be applied safely (Couey and Hayes, 1986; E. Fallik, personal communication). Despite these limitations, antifungal hot-water dips have been used commercially for anthracnose control in mango (53C, 3 min) (Spalding and Reeder, 1986) and for general postharvest fungal control in papaya (49C, 20 min) (Akamine and Arisumi, 1953; Couey, 1989).

In contrast to hot-water dips, an extended hot-air treatment can be given at a lower temperature (Klein and Lurie, 1990a; Lurie and Klein, 1991). Generally, fruit are held at 38C for 3 or 4 days at a relative humidity >85%. In experiments in our laboratory with apples, pomegranates, avocados, and tomatoes, water loss under these conditions was <5%, with no external signs of shriveling. Fruit tissue was not damaged, and preliminary data showed that, in several fruit, resistance to pathogens was enhanced by the heat treatment. *Alternaria alternata* caused 30% to 50% decay in nonheated tomatoes after storage at 2C for 21 days, while <5% decay was found in tomatoes that had been heated before storage (Lurie and Klein, 1991). Decay due to *Colletotrichum gloeosporioides* in avocado and *Alternaria alternata* in apples was decreased or delayed in fruit that had been heated (S.L., J.D.K., and Prusky, unpublished data). Mucor rot and philaphora side rot were reduced in pears held 4 days at 37C, even when fruit were inoculated after heating, demonstrating induction of resistance or a wound-healing response (Spotts and Chen, 1987).

Ben-Yehoshua et al. (1988) reported that holding citrus fruit at 36C for 3 days induced resistance to decay by *Penicillium digitatum*. They subsequently showed that heating inoculated fruit induced the accumulation of scoparone, a potent phytoalexin (Kim et al., 1991). There is also evidence that lignin synthesis is activated in heated tomato pericarp in the presence of a fungal pathogen (E. Fallik, personal communication). Therefore, this heat treatment may be effective either by directly inhibiting pathogen development or by inducing natural resistance in the fruit.

Insect pathogens. The short hot-water dips used to control fungal pathogens are insufficient to disinfest fruit and vegetables. Since treatment for >60 min at temperatures >50C

causes plant tissue damage, vapor heat treatment regimes between 42 and 48C have been developed (reviewed by Couey, 1989). Vapor heat treatments for fruit fly disinfestation were initially developed in the 1920s by Baker and coworkers (Baker, 1952) and were widely used for 30 years. The treatment generally consists of a "run-up" preheating period, during which the commodity is gradually warmed to the target temperature and then held there. Total treatment time ranges between 6 and 20 h, although this may be reduced at lower produce load densities. However, the ease of application and effectiveness of fumigants for insect disinfestation relegated vapor heat to a minor position in the arsenal of postharvest treatments for the past 35 years. The recent withdrawal of registration for ethylene dibromide as a fumigant, however, prompted renewed interest in developing vapor heat regimes that effectively disinfest fruit and vegetables of insect eggs and larvae, particularly that of fruit flies. The vapor heat treatment has been used on citrus (Hawkins, 1932), papaya (Seo et al., 1974), green pepper (Sugimoto et al., 1983), eggplant (Furusawa et al., 1984), and mango (Merino et al., 1985). Each fruit required different regimes for the rate of heating and the length of exposure to 43 to 46C to prevent unacceptable levels of tissue damage while still achieving insect control.

To the best of our knowledge, no attempts have been made to control insect pests by long-term, low-temperature heat treatments. However, these conditions have been used as a pretreatment in combination with hot-water dips to control melon fly on cucumbers. Melons were disinfested and no heat damage was incurred if they were held for 24 h at 32C and then dipped in hot water for 60 min at 45C. The fruit suffered heat damage only when the hot-water dip was given without temperature conditioning (Chan and Linse, 1989).

Heat protects against physiological disorders

Unlike pathological disorders of fruits and vegetables, most physiological disorders of horticultural commodities can be controlled by physical means. Superficial scald is a disorder that affects apples during storage. It is characterized by irregular areas of skin

browning that may be faint upon removal of the fruit from storage, but darken and expand when apples are removed to room temperature. Scald is frequently less severe in late-harvested fruit and can also be managed by keeping apples in controlled-atmosphere storage (Anet, 1972). However, commercial control of scald is currently achieved by prestorage dips in diphenylamine (DPA) or etoxyquin (Smock, 1961), which allows greater latitude in harvesting and storing the fruit. Nonetheless, the use of such powerful antioxidants may be viewed by consumers with increasing suspicion, particularly in light of the recent "Alar scare."

Superficial scald development was inhibited in heated apples (Lurie et al., 1991). The degree of inhibition was proportional to the length of prestorage heating and independent of time of harvest. One or 2 days at 38C resulted in a reduction, but not an inhibition, of scald. However, a 4-day heat treatment before 3 months of storage was as effective in suppressing scald as a prestorage dip in DPA. Although the mode of action of DPA in controlling scald appears to be directly anti-oxidative (Lurie et al., 1989), heating appears to prevent scald by inhibiting both accumulation and oxidation of certain volatile compounds in the cuticle (Lurie et al., 1991). Internal browning in pears, another oxidative postharvest disorder of fruit, was also alleviated by heat treatment (Maxie et al., 1974; S.L. and J.D.K., unpublished data).

We have previously mentioned that a conditioning treatment at 32C protected cucumbers against injury from a subsequent exposure to a higher temperature (Chan and Linse, 1989). Exposure to one kind of stress can protect plant tissues not only against an intensified application of that stress, but also against another kind of stress. Wheat leaves that were initially heated were protected against subsequent exposure to heavy metals (Burke and Orzech, 1988). Water stress conferred cold hardiness on a variety of winter cereals (Cloutier and Siminovitch, 1982). Therefore, we hypothesized that heat treatment could protect a fruit against low-temperature injury.

Subtropical fruit develop chilling injury (CI) if held more than a few days below 10 to 12C. Symptoms of CI include skin discoloration, pitting,

uneven ripening, and increased susceptibility to decay (Couey, 1986). When mature-green tomatoes were held 3 days at 36, 38, or 40C before being placed for 3 weeks at 2C, they did not develop CI, whereas nonheated tomatoes did (Lurie and Klein, 1991, 1992). The heated tomatoes ripened normally, although more slowly than freshly picked mature-green tomatoes, and exhibited climacteric respiration and ethylene evolution. The nonheated tomatoes remained green after removal from 2C, developed surface pitting, and had a high level of fungal infection. A similar prevention of CI was obtained when mangoes were held at 38C for 48 h before being stored at 5C for 11 days (R. McDonald, personal communication).

There may be multiple benefits to reducing the sensitivity of horticultural commodities such as citrus, tomato, cucumber, avocado, mango, papaya, and banana to low temperature by means of prestorage heating. First, the cold-temperature insect disinfection treatment now used for several tropical and subtropical crops may be used with less low-temperature injury to the fruit (Couey et al., 1984). Second, the fruit may be stored longer than is currently feasible, with no loss of quality. Most important, such a treatment may allow mixed storage of commodities previously thought incompatible in storage due to their requirements for different temperature regimes. Since heat treatment results in a marked decrease in ethylene production and sensitivity by apples (Klein and Lurie, 1990a; Klein et al., 1990), it may eventually be possible to store together fruit that produce ethylene and those that do not, but are sensitive to it.

Heat regulates postharvest fruit ripening

Ripening of most climacteric fruit is characterized by softening of the flesh, an increase in the sugar : acid ratio, enhanced color development, and increases in respiratory activity and ethylene production. Exposing fruit to high temperatures attenuates some of these processes while enhancing others. This anomalous situation results in heated fruit being more advanced in some ripening characteristics than nonheated fruit while maintaining their quality longer during shelflife at 20C.

Firmness. A number of research-

ers have described the effect of continuous storage at elevated temperatures on fruit firmness. Plums (Tsuji et al., 1984), pears (Maxie et al., 1974), avocados (Eaks, 1978), and tomatoes (Biggs et al., 1988) softened more slowly when held continuously at temperatures between 30 and 40C than at 20C. The rate of softening increased when heated fruit were returned to 20C, but it was still less than that of nonheated fruit. Even after 6 months of storage at 0C and subsequent shelf life of 7 to 10 days at 20C, apples that had been held at 38C for 3 to 4 days prestorage were 10 N firmer than nonheated fruit (Klein and Lurie, 1990a; Klein et al., 1990; Porritt and Lidster, 1978).

Total soluble solids : acid ratio.

Although the soluble solids concentration in heat-treated apples did not differ from that in nonheated fruit, the heat-treated fruit were markedly lower in titratable acidity (Klein and Lurie, 1990a; Klein et al., 1990; Liu, 1978). This may be beneficial in the removal of undesirable tartness from some apple varieties, particularly those picked early in the harvest season. However, after removal from storage, heated tomatoes had higher soluble solids concentrations and lower titratable acidity than nonheated (Lurie and Klein, 1992). By the end of shelflife, however, titratable acidity was the same in heated and nonheated tomatoes, while soluble solids concentration remained higher in heated fruit. The 10% to 30% increase in the sugar : acid ratio that was induced by heating is another characteristic that may make heat-treated fruit attractive to consumers.

Color. Ripening of apples is accompanied by a change in the ground color from green to yellow. Prestorage heating accelerates the rate of color change (Klein et al., 1990; Liu, 1978). Although yellowing is generally considered by consumers to be a sign of over-ripeness in most apple varieties, we have successfully used heating to enhance yellow color development of 'Golden Delicious' apples while retaining fruit firmness (Table 1). Similarly, heated tomatoes were redder, but not softer, than nonheated fruit after storage at 12C and shelf life at 20C (Lurie and Klein, 1992).

Respiratory activity. Carbon dioxide production rises as climacteric fruit ripen. The presence of ethylene, either exogenous or endogenous, usu-

ally promotes respiration. In the case of heated apples, avocados, and tomatoes, however, a simultaneous increase in CO₂ production and decrease in ethylene production occurred during exposure to high temperatures (Kerbel et al., 1987; Lurie and Klein, 1990, 1991). Paradoxically, upon removal from heating, CO₂ production fell below that of controls, while ethylene production recovered and even exceeded that of nonheated fruit. It appears that the usual physiological responses of fruit to endogenous ethylene are impaired as a result of heating.

Ethylene production. The inhibition of ripening by heat may be mediated by its effect on the ripening hormone ethylene. Heat treatment inhibited ethylene synthesis in both apples and tomatoes within a few hours (Biggs et al., 1988; Klein, 1989). Apples held at 20C after a heat treatment showed a lag in ethylene production compared with nonheated fruit. Production eventually recovered, however, and even exceeded control levels (Klein, 1989; Lurie and Klein, 1990). Despite the increased rate of ethylene production compared to the control, fruit did not soften at an enhanced rate. Apparently, the "physiological lesion" caused by the heat treatment affected softening, which is normally linked with the ethylene-recognition mechanism in fruit, to a greater extent than it affects autocatalytic ethylene production. Similar results were obtained with tomato, irrespective of fruit development stage (Biggs et al., 1988). Ethylene scrubbing, considered beneficial in storage of climacteric fruits and vegetables (Wojciechowski et al., 1985), may therefore be unnecessary with heated fruit.

Table 1. Firmness and ground color of 'Golden Delicious' apples held at 38C for 4 days before storage at 0 or 4C for 4 months and a further 7 days at 20C.

Treatment	Storage temp (°C)	Firmness (N)	Color ^a
Control	0	50 b ^y	5.1 c
	4	42 c	5.5 b
Heat	0	57 a	5.5 b
	4	54 ab	5.9 a

^aColor was measured with a Techwest apple color meter, where 1 = green and 10 = yellow.

^yMean separation by Duncan's multiple range test, P = 0.05.

Heat enhances effectiveness of Ca treatments

Calcium treatments can extend postharvest life of horticultural crops by delaying ripening processes and reducing the severity of pathogen attack (Conway et al., 1992; Ferguson 1984). Since prestorage heating can have the same beneficial effects as Ca, we combined the two treatments. Apples held at 38C for 4 days before being dipped in 3% CaCl₂ were firmer upon removal from storage than fruit that were solely heated or dipped in Ca (Lurie and Klein, 1992). Heated/dipped fruit yellowed less than fruit that were only heated; they also showed a synergistic reduction in superficial scald development (Klein and Lurie, 1990b). These effects were not observed if fruit were dipped before heating, nor did temperature of the dipping solution affect the results (Klein et al., 1990; Lurie and Klein, 1992). Calcium content of heated/dipped apples was similar to that of nonheated/dipped fruit, but the Ca appeared to be bound more tightly to the cell wall of the former (Lurie and Klein, 1992).

Combinations of Ca and heat were also more effective than either treatment alone in enhancing resistance to postharvest diseases while maintaining fruit quality. 'Golden Delicious' apples held at 38C for 4 days before 5 months of storage at 0C had 25% less decay than nonheated fruit after being inoculated with *Penicillium expansum* spores upon removal (W. Conway and C. Sams, unpublished data). Pressure infiltration with 4% CaCl₂ resulted in 60% less decay than controls, while heating followed by infiltration reduced decay by 40%. However, heated Ca-treated apples had virtually no lenticel burn compared to nonheated infiltrated fruit. The absence of Ca damage was likely because heating decreased the amount of Ca that entered the tissue by 75%. Calcium that entered heated tissue was evidently more effective, on a quantitative basis, in protecting against disease. The greater effectiveness of heated fungicide solutions compared to nonheated (Palti, 1981) may also be due to heat causing beneficial changes at the tissue level.

Can prestorage heating be economical?

The energy requirements of prestorage heat treatments are un-

doubtedly a commercial liability. In addition, delaying storage by 3 or 4 days after harvest while heating the fruit presents logistical difficulties. The energy input can be reduced, however, by shortening the treatment time and using temperatures >38C. Holding apples for 24 h at 42C or 12 h at 46C produced results similar to those obtained by keeping fruit at 38C for 72 or 96 h before storage (Klein and Lurie, 1992).

The strain on the cooling system of the storage room caused by placing hot apples inside can be alleviated by hydrocooling with solutions of CaCl₂ before storage. The synergistic benefits derived from dipping heat-treated (38C for 3 days) fruit in 3% CaCl₂ have also been found with fruit heated for shorter periods at higher temperatures before being dipped in 1.5% CaCl₂ (J.D.K. and S.L., unpublished data). Since Ca dips are already standard procedure in many storage facilities, it is possible that part of the cost of heating can be defrayed by saving on materials.

As mentioned earlier, mixed storage of chilling-sensitive and -insensitive crops at low temperatures is a potential benefit arising from heat treatment. The resulting greater efficiency in the use of coolrooms could offset the cost of heating. However, heat-treated apples that were stored for 5 months at 4C were just as firm after shelf life as nonheated fruit that had been kept at 0C (Table 1). The energy invested in heating fruit before storage can thus be recovered by holding such fruit at higher temperatures during storage.

Conclusion

Although prestorage heat treatments are a promising alternative to chemical treatments, several aspects of the technique require continued research. Fine tuning the heating regime for specific commodities may be necessary. For example, avocados respond well to 36C, but at 38C they develop heat injury, typified by skin scald, surface pitting, flesh browning, and sometimes a failure to ripen normally (S.L. and J.D.K., unpublished data). However, tomatoes, asubtropical fruit, as are avocados, respond well to temperatures from 36 to 40C without evincing injury (Lurie and Klein, 1991). Further research on Ca × temperature interactions will develop the potential

for heat/Ca treatments to increase protection against pathological and physiological disorders. The possible synergistic benefits to be derived from combining heat treatments with other storage methods, such as modified-atmosphere packaging, also bear investigation.

We have deliberately adopted a positive, polemic tone in this review, since we feel that prestorage heating is a treatment with exciting possibilities and we want to encourage further research and development of the technique. We have described the advantages of a longer-term, lower-temperature prestorage heat treatment than the high-temperature treatments currently used commercially. The latter are mainly brief dips in hot water or exposures to vapor heat intended to control fungal or insect pathogens. The longer-term, lower-temperature heat treatment protects against physiological disorders, enhances natural resistance to pathogen infection, reversibly inhibits fruit ripening, and permits flexibility in storage temperatures. These benefits occur as the residual effects of a *nonchemical* treatment, which does not need to be imposed continuously throughout storage to be effective, in contrast to controlled-atmosphere storage, for example.

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