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Effect of temperature and relative humidity on fresh commodity quality

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Abstract

Low temperature has been used to extend the shelf life of temperate fruits and vegetables since antiquity, while the negative effect of low temperature (< 10ºC) on the shelf life of tropical plants and commodities has been known since at least the eighteenth century. Low temperature storage has the additional benefit of protecting non-appearance quality attributes: texture, nutrition, aroma and flavor. Time of day when harvest is performed can influence shelf life. In addition, delays in cooling after harvest can reduce commodity shelf life and quality. In commercial handling, shelf life of commodities may vary greatly from laboratory studies. The distribution chain rarely has the facilities to store each commodity under ideal conditions and requires handlers to make comprises as to the choice of temperature and relative humidity (RH). These choices can lead to physiological stress and loss of shelf life and quality. This limitation, especially late in the handling chain during retailing, requires all participants in the distribution chain to increase their understanding of the need to improve management of handling, temperature and RH, to limit losses in quality. Simulated storage studies should be conducted under conditions that approximate the average to better levels of commercial practices. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Temperature; Relative humidity; Fresh commodity quality

1. Introduction

The initial uses of cold to preserve or extend the shelf life of fresh commodities in many cultures, is lost in antiquity. Examples of the use of cold for storage of fresh produce range from the use of clamps, cellars, basements, caves and ice houses. Industries developed around the harvesting of ice in the winter for use in the summer. Cave storage of vegetables is still practiced in parts of China

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Table 1
Percentage of fresh fruits and vegetables in supermarket display cases held at their optimum temperature range during the summer (LeBlanc et al., 1996)

Commodities (examples)	Percentage of samples		
	Below range	Within range	Above range
Apples, lettuce, cabbages	0	7	93
Mandarins, snap beans, summer squash	11	37	52
Winter squash, peppers	41	48	11
Sweet potatoes, bananas, green tomatoes	67	33	0

(Qi, 1982). The limitations of cold for tropical plants were well recognized by the eighteenth century, for example, the Palace of Versailles greenhouse. An understanding of the range of suitable temperatures for fruits and vegetables followed the development of reliable calibrated thermometers in the 1700s by the Dutch instrument maker Gabriel Fahrenheit and the Swedish astronomer Anders Celsius. The choice and acceptance of common fixed temperature points, led to standardization of temperature scales. The impact of relative humidity on quality, such as appearance and texture, was no doubt ascribed to water loss. The understanding of the driving force for water loss awaited work in the nineteenth century on the composition of air, the factors controlling evaporation, and instruments for measuring humidity.

In earlier studies on the effects of temperature and relative humidity, the focus was on product appearance (color, gloss, wrinkling, mass loss, etc.). The development of analytical procedures and the heightened awareness of safety has expanded the range of our studies, to consumer quality aspects such as nutritional value and safety. In this review, I will deal with whole commodities and how low temperature and relative humidity impact on quality during postharvest handling. This will be related to the conditions in the distribution chain that are often not ideal and recommendations based upon published information may be misleading. This published information is generated under conditions that do not simulate conditions encountered in commercial practice.

2. Handling chain

During the movement of fresh products to market, wholesalers and retailers frequently do not have enough facilities set to the optimum conditions for each commodity. Inventory management and marketing largely determines how a product will be handled (Prussia and Shewfelt, 1993). These limitations are especially true for speciality commodities, handled in small quantities (Paull et al., 1997).

Fresh fruits and vegetables probably receive the greatest temperature abuse at the retail level (Table 1). Temperature abuse is a function of time and temperature during holding and the relative perishability of a particular commodity. For examples, apples and cabbages are often displayed at improper temperature at retail but they do not lose quality rapidly when compared to strawberries or broccoli. Mean temperatures of display cases used for fruits and vegetable are 7.6 and 8.4°C in winter and summer, respectively (LeBlanc et al., 1996). The majority (90%) of those commodities that should have been stored at less than or equal to 4°C were above the recommended temperature range. The same percentage was found for commodities that should have been held greater than or equal to 12°C (Table 2). The significance of laboratory studies and to a lesser extent simulated shipping studies may therefore not be relevant to commercial practices in many cases. Broccoli held under simulated retail display and overnight storage treatments showed considerable reduction in shelf life and indicate the possible extent of the commercial retail handling problem (Perrin and Gaye, 1986).

Table 2
The storage potential of selected fruits and vegetables and the recommendations for optimum storage temperature and relative humidity from published literature (Anon, 1986; Hardenburg et al., 1986; Snowdon, 1990, 1992)[a]

Commodity	Shelf life (days)	Opt. storage temperature (°C)	Relative humidity %
Vegetables			
Asparagus	14–21(14–28 (S))	0–2 (1–2°)	95–100 (90–95)
Cabbage Chinese	60–90 (30–60)	0°	95–100 (90–95)
Carrots (immature and mature)	28–180	0°	(95–100) 90–95
Cassava	30–60 (14–21) (140–170 (S))	0–5 (12.5°)	85–90 (nv)
Corn (sweet)	4–6 (5–8)	0°	90–95 (95–98)
Cucumbers	10–14	(10–13°) 10°	95 (nv)
Ginger	180 (90–180)	12.5°	65 (85–90)
Green onions	21–28 (7–10)	0°	95–100 (nv)
Bell peppers	14–21	7–13° (7.5–10°)	90–95 (95)
Water chestnuts	(0–60 (100–128)	0–2° (5–7.5°)	98–100 (nv)
Fruit			
Apples	30–365 (90–240)	−1–4° (−0.5)	90–95
Banana (green)	7–28	13–14	90–95 (85–90)
Cherries (sweet)	14–21	−1–0°	90–95
Carambola	21–28 (nv)	9–10 (nv)	85–90 (nv)
Coconuts	30–60 (25–56)	0–1.5° (0°)	80–85 (90–95)
Durian	42–56	nv 4°	nv
Limes (Mexican)	42–56	9–10° (11°)	85–90 (95)
Litchi	21–35	2°	90–95
Mango	14–21 (14–25)	13 (5–12.5°)	85–90
Papaya (turning)	7–21	7 (7.5–12)	85–90
Peaches	14–28 (30–32 (S))	−0.5	90–95
Pineapple	14–28 (14–36)	7–13 (10)	85–90
Strawberries	2–7	0°	90–95
Watermelon	14–21	10–15°	90

[a] The values in brackets are those given by the second reference if they differ from the first reference, (nv) indicates no values given and single value indicates agreement in the recommendations. Snowdon (1990, 1992) values are similar to Hardenburg et al. (1986) and if different are devoted (S).

This study also questions the value of laboratory studies that do not approximate commercial practices and have led to unattainable recommendations as to shelf life.

An understanding of the impact of various commercial handling practices in the marketing system has been suggested as an approach to evaluate the above commercial practices (Prussia and Shewfelt, 1993). This system analysis assumes that the handling steps at different levels are not isolated and secondly that the system responds to final consumer needs and not to handlers' desires. However, the current system tends to be unidirectional in both product and information exchange. Any improvement in the handling system practices must be integrated with the associated costs and management skills needed. Therefore, this analysis protocol requires a greater emphasis on improving quality at all levels of handling system and recognition that every step and procedure can impact fruit and vegetable quality. However, this recognition requires subjective and objective measures of quality and the recognition of its loss at each step along the way to the consumer. Attempts have been made to estimate the value assigned to tomato quality characteristics such as size, color, damage and storability (Jordan et al., 1985). These are crucial aspects of product quality, though they are only part of the criteria used by a consumer to evaluate a product.

Food borne illness and industry products recalls have led to a greater concern about the management temperatures and relative humidity (RH) used during shipping and storage. Temperature and relative humidity are two major criteria used to define critical limits in monitoring programs associated with the hazard analysis and critical control point (HACCP) system. HACCP, a preventive quality assurance system, is required so that safety programs are being properly implemented. Such safety programs involve a number of principles including early detection of critical areas of concern, identification of trends in deterioration, develop a plan to carry out inspections, good record keeping and steps to ensure safety throughout handling, shipping and storage and monitoring to ensure that procedures are being implemented and assignment of responsibility. Guidelines to minimize microbial food safety hazards on fresh fruits and vegetables are now being developed (FDA, 1998), along with recommendations for good agricultural practices (Anon, 1998).

3. Temperature and RH

Psychrometric charts give a graphical representation of the relationship between temperature, RH and water vapor pressure (WVP) in moist air (Gaffrey, 1978). The water vapor pressure deficit (WVPD) is the difference between actual vapor pressure (RH and is temperature dependent) from the saturated vapor pressure and determines the rate of evaporation from a fresh commodity at the same temperature.

In many of our storage studies, temperature is controlled but RH is not. RH is dependent upon by the surface area of the refrigeration evaporator coil in the storage room and temperature difference between the coil and the air, along with air exchange rates, temperature distribution in the room, commodity and packing material used. There are practical difficulties in maintaining RH in large storage rooms within a narrow range at high relative humidities. To illustrate the difficulty, to maintain 95% RH at 0°C, the mean temperature differential between the air and the evaporator must be ca. 0.5°C. A measurable and controllable temperature difference of ca. 1°C is available at 90% RH. These small differences test the limits of sensitivity needed to measure temperatures to this degree of accuracy and platinum resistance elements are recommended (standard industrial accuracy ± 0.16°C). At high RH, a small fluctuation in temperature (<0.5°C) can result in condensation on cool surfaces. Poor air distribution could mean that air at 0°C, 95% RH from the coil would be 70% RH in an area at 5°C. Fiberboard and wood absorbs water and may decrease RH in a room. A fiberboard box held at 50% RH has a moisture content of 7% (dry mass basis), at 90% RH, the moisture content would be 16% (Soroka, 1995). High RH will not prevent moisture loss if the product temperature is not near the air temperature. Newer refrigeration controls, more rugged humidity detectors and humidification technologies have increased the ability to vary both temperature and RH. These controls are now appearing in cold rooms and shipping containers.

The nature of the commodity evaporative surface is determined by commodity type and cultivar (Fig. 1) and both have a major influence on the rate of evaporation (Van Den Berg, 1987). Sastry et al. (1978) compiled data from a number of sources and found that the transpiration coefficient varied by almost 176-fold for 19 commodities. Surface area to volume ratios is a significant

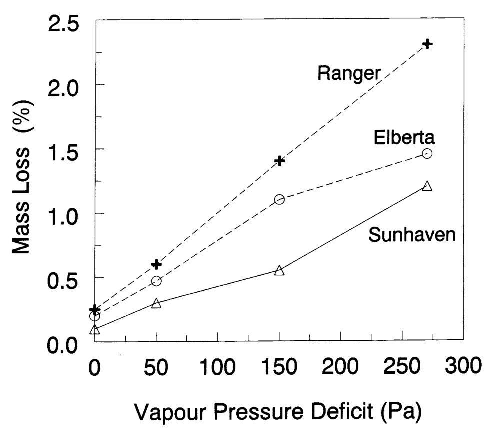

Fig. 1. The mass loss from three peach cultivars of the same size held at a range of vapor pressure deficits (Whitelock et al., 1994).

commodity factor influencing evaporation. The ratio varies widely for different commodities: individual edible leaves have 50–100 cm^2 cm^{-3}, strawberries 2–5 cm^2 cm^{-3}, bananas 0.5–1.5 cm^2 cm^{-3}, and densely packed cabbage 0.2–0.5 cm^2 cm^{-3} (Burton, 1982). In order to compare fresh commodities, it is necessary to incorporate these factors into loss units such as % day^{-1} mPa^{-1} WVPD. This enables the time to reach a permissible water loss as a percentage of the original mass at which a commodity becomes unmarketable or has to be sold for a lower price to be calculated. Maximum permissible losses can vary from 10% for onions, 8% in asparagus, 7% for papayas to 3% for lettuce (Burton, 1982; Paull and Chen, 1989). The corresponding loss rates are 0.02% initial mass day^{-1} $mbar^{-1}$ WVPD, 3.6, 0.5 and 7.5, respectively (Robinson et al., 1975). This loss can be modified by postharvest handling practices such as packaging, waxing, wax removal during washing and defuzzing of peaches.

4. Temperature and quality

4.1. Appearance and commercial shelf life

Heat treatments are used for insect disinfestation and disease control (Couey, 1989; Paull, 1990). Exposing commodities to heat treatment can cause severe injury to fruit, vegetables and ornamentals (Paull and Armstrong, 1994). Sometimes this injury only develops when the commodity is stored at low temperature after heat treatment and can be related to the rate of cooling. In other cases, the heat treatments can reduce chilling injury development of tomato (Lurie and Klein, 1991; Saltveit, 1991) and avocado (Florissen et al., 1996). These heat treatments can be coupled to gradual cooling to 2°C to further decrease chilling injury in tomato (Lurie and Sabehat, 1997). Heat sensitivity is also modified by differences in response between season, cultivar and rate of heating (Paull and McDonald, 1994).

Kidd and West (1936) at the Low Temperature Research Station, Cambridge, were some of the first to generalize the relationship between storage

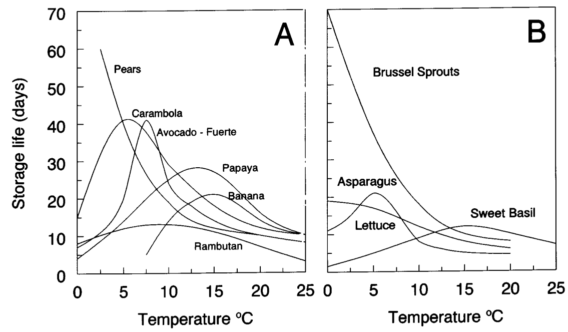

Fig. 2. The shelf life of fruits (A) and vegetables (B) held at various temperatures until storage life was terminated because of cold or chilling injury, ripening or senescence. Data derived from a number of sources (Pears, Tomkins, 1996; Avocado (Fuerte), Zauberman et al., 1977; Carambola, O'Hare, 1993; Papaya, Chen and Paull, 1986; Banana, Paull and McDonald, 1994; Rambutan, O'Hare et al., 1994; Brussel sprouts, Lyons and Rappaport, 1959; Asparagus, King et al., 1993; Lettuce, Pratt et al., 1954; Sweet Basil, Lange and Cameron, 1994).

temperature and shelf life (Fidler et al., 1973). In this relationship, they incorporated varietal differences to low temperature injury at less than 5°C for a temperate fruit crop-apples. There is now a considerable body of information for tropical, subtropical and temperate commodities about maximum shelf life at different storage temperatures (Fig. 2). There are also varietal differences for fruits such as for apples (Fidler et al., 1973), melons (Miccolis and Saltveit, 1995), rambutan (O'Hare et al., 1994) and persimmon (Collins and Tisdell, 1995).

A crucial point of these storage studies is that for climacteric tropical and temperate commodities showing low temperature injury, there is an interplay of reasons for the termination of shelf life (Paull, 1993). For papaya (Fig. 2(A)), at storage temperatures above 10–12°C shelf life is terminated because of fruit ripening, while at lower temperatures ripening is not the concern, the limitation to storage being imposed by chilling injury. Chilling injury is seen in a commercial setting as greater susceptibility to disease, as well as skin scald, failure to ripen and flesh breakdown (Paull and McDonald, 1994). However, if fruits are removed from chilling temperature storage to a higher temperature before chilling symptom development occurs, fruits ripen normally, hence they have an overall longer shelf life and some retailing time. This is the reason why the recommended storage temperature for many tropical fruits is in the chilling range. Maximum useable shelf life is obtained when storage time at chilling temperatures does not exceed the threshold for injury. However, other quality attributes such as texture, flavors and aromas may be lost before obvious changes occur in external criteria used to judge storage life.

Storage recommendations for vegetables are generally the minimum temperature that provides the maximum shelf life (Fig. 2(B)). Chilling susceptible tropical vegetables such as sweet basil need to be stored at about 15°C, as chilling injury develops rapidly at lower temperature (Lange and Cameron, 1994). For these commodities ripening is not an issue, senescence at higher temperature and injury at lower temperature impose the limits on storage.

The commercial postharvest storage potential for most fresh fruits and vegetables are give in numerous publications (Anon, 1986; Hardenburg et al., 1986; Snowdon, 1990, 1992; Thompson, 1996). The values given for shelf life (Table 2) should be regarded as the maximum, as they are probably based upon laboratory studies using appearance criteria and did not allow for loss of the other quality criteria such as texture, nutritional value and flavor. The ranges of shelf life given (Table 2) indicate the variability in the information available, different criteria probably being used to evaluate the end of storage life, differences associated with stationary or transport storage, and the absence of market data that would provide quality price elasticity data and availability of alternative marketing channels. The simulated laboratory studies used may not have allowed for the vagaries of commercial handling and storage. An important aspect of this variation is associated with the retailing phase (Table 1), where proper temperature maintenance is frequently lost for various reasons.

The research on sweet basil (Lange and Cameron, 1994) suggests an aspect that has been overlooked with respect to shelf life and quality maintenance: time of day when harvested. The results showed that shoots harvested at 18:00 and 22:00 h had longer shelf life than shoots harvested during the day. The increase in shelf life at 15°C was from about 9 days when harvested at 06:00 h to nearly 17 days when harvested at 22:00 h. Whether this increase applies to other commodities, or varies widely with preharvest conditions needs to be ascertained. This finding may relate to the greater chilling tolerance found for stressed and unstressed tomato plants placed at chilling temperature during the day and the evening (King et al., 1982). Fruits can have higher turgidity in the early morning and this can led to damage, such as oleocellosis damage in lemons (Eaks, 1955).

Some harvesting is practiced at night but this is done to either meet a harvesting schedule and to reduce field heat but not for a direct product shelf life and quality reasons. However, small stems of prickly pear cactus are CAM inactive, while large stems are CAM active showing a diurnal variation in acid content (Cantwell et al., 1992). Time of day when harvested could be used to reduce initial acid level and hence improve flavor of mature cactuses.

If cooling is delayed, shelf life can be significantly reduced (Fig. 3). Simple shading, if there is a delay, can limit loss of quality (Rickard et al., 1978). A unshaded commodity can rapidly warm to 10°C higher than the ambient air. A 2-h delay

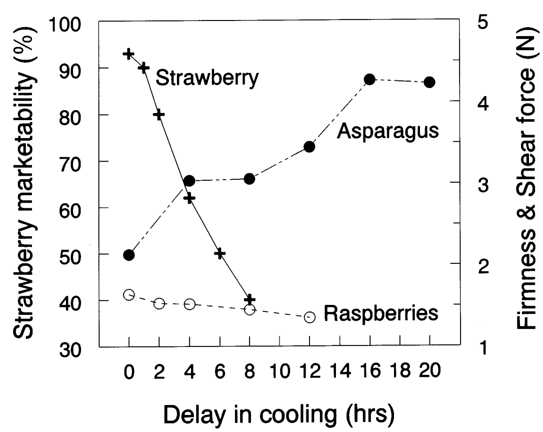

Fig. 3. The impact of a delay in cooling after harvest on strawberry market ability (Mitchell et al., 1972), asparagus, basal stem shear force (Hernandez-Rivera et al., 1992) and raspberry fruit firmness (Robbins and Moore, 1992).

after harvest can mean a loss of marketable strawberries from about 93 to 80% (Mitchell et al., 1974) and 6 h leads to an increased loss of ascorbic acid, soluble solids, fructose, glucose and sucrose, firmness and titratable acidity and firmness (Nunes et al., 1995). Titratable acidity and ascorbic acid in tomatoes are preferentially lost compared to soluble solids, if the fruit are held at greater than or equal to 30°C for 24 h prior to cooling (Kader and Morris, 1978). A 4-h delays before cooling results in an increase in shear force (toughness) in asparagus spears 5 cm from the cut base of from 2.1 to 2.8 N (Hernandez-Rivera et al., 1992), and a 20-h delay almost doubles the shear force (Fig. 3). Market life of broccoli is reduced by a 3-h delay in cooling (Brennan and Shewfelt, 1989), while 6 h is the maximum delay for lettuce (Lipton and Barger, 1965) and 2 h for red raspberries before loss occurs (Robbins and Moore, 1992). Apples with a long shelf life and lower rate of respiration should be cooled within 3 days of harvest (Liu, 1986), to prevent loss of apple firmness and acidity during storage for 7.5 months at 3.3°C. For most climacteric tropical commodities, the delay in cooling allows continued ripening and overall loss of storage potential. This is a problem especially for commodities such as peaches, papaya and atemoya that have a short shelf life (10–14 days). In general, the higher the metabolic rate or shorter the overall shelf life, the greater the impact of delayed cooling on preserving quality.

4.2. Texture attributes

Warm fruits are generally more plastic than cold fruit and therefore better able to withstand impact injury while being more susceptible to vibration injury (Somner et al., 1960). In cherries, this response is cultivar dependent and differences in impact injury depend on fruit temperature at the time of impact. To minimize impact bruising, fruit should be packed at between 10 and 20°C (Crisosto et al., 1993) and the fruit cooled to 0°C within 4–6 h of harvest (Micke et al., 1965). This, however, is difficult to carry out logistically when fruit are rapidly ripening during hot weather. Neither differences in cherry cultivar nor temperature affect susceptibility to vibrational injury (Crisosto et al., 1993). This suggests the need for different evaluation criteria at different steps in handling with different temperatures being recommended. Besides the logistical difficulty mentioned above, a better approach would be to design equipment for handling and packing to prevent damage.

Studies on the effect of storage temperature on textural changes have been carried out on commodities that show dramatic deleterious changes. Asparagus spears can rapidly develop vascular fiber lignification and stringy, with a higher shear force near the cut base. This lignification is rapid if cooling is delayed or spears are held at a higher temperature than recommended (Hernandez-Rivera et al., 1992). Toughening of mushrooms is also strongly repressed at temperatures of 10°C and less (Murr and Morris, 1975), as is the associated browning (Burton and Noble, 1993). Mushroom maturation is retarded at 0°C and reduced at 10°C and related to toughening due to wall thickening. Broccoli loses considerable firmness if held at temperature of 5°C or higher (Toivonen, 1997). Storage temperature can significantly influence fruit firmness and the loss increases with storage time. The loss of firmness in apples (Landfald, 1966), and avocado (Zauberman and Jobin-Decor, 1995) is concomitant with an increase in color, hence related more to ripening than a direct effect of temperature on firmness. Similar losses of firmness due to ripening have been found in six melon cultivars stored at different temperatures (Miccolis and Saltveit, 1995). The maturity or harvest (early or late) can interact with storage temperature to vary the effect on firmness in apples (Watkins and Thompson, 1992).

4.3. Nutritional attributes

Composition is a significant quality attribute and storage temperature can influence vitamins and other nutrients in many fruits and vegetables. Ninety percent of the vitamin C in the US diet is derived from fresh fruits and vegetables (Goddard and Matthews, 1979). Loss of vitamin C is generally more rapid at higher storage temperatures (Watada, 1987) and slower in acid fruit than more neutral commodities. There is a 40% loss of vitamin C in tangerines at higher storage temperature (7–13°C) over 8 weeks (Bratley, 1939), while a negligible loss is found in lemon at 13°C, although it is significant at 24°C (Eaks, 1961) and no significant loss in grapefruit held at 8 and 12°C, with an increase in concentration following a 2-month storage at both temperatures (Schirra, 1992). Immature potatoes show a rapid loss of vitamin C during the first weeks of storage while mature tubers show minimal loss (Panitkin et al., 1979). Less vitamin C is found in tubers stored at 15°C than 1°C, with the least lost at 5°C (Effmert et al., 1961), up to 50% loss can be expected over 8 months at 7.5°C (Augustin, 1975). Vitamin C loss can be significant during fruit ripening and the impact of temperature is not regarded as nutritionally significant.

Leafy vegetables lose vitamin C postharvest, but it is frequently unclear if this due to temperature or water loss. Kale, collards, turnip greens, spinach, grape, cabbage, and snap beans exposed to conditions favorable for water loss have more rapid loss of vitamin C (Ezell and Wilcox, 1959). However, wilting is much less important than temperature with the loss of vitamin C in kale being 0.32% h^{-1} at 10°C and 0.05% h^{-1} at 0°C with slow wilting, when exposed to rapid wilting conditions the rate is 0.69 and 0.11% h^{-1}, respectively.

There are few reports on vitamin B_1 (thiamine) and niacin loss during storage. Potato tubers had insignificant loss of vitamin B_1 and niacin after 30 weeks at 5°C and a slight loss at 10°C (Yamaguchi et al., 1960; Augustin et al., 1978). Small losses are found during storage of green beans, peaches and sweet potatoes (Elkin, 1979; Watada, 1987).

Carotene content (vitamin A) shows little loss in sweet potato during 4 months of storage at 24°C (Miller et al., 1949). Significant losses of β-carotene occurs in kale (17%) collards (30%), turnip greens and grape held at 10°C instead of 0°C (Ezell and Wilcox, 1962). Carrots show an increase in carotene during the first months of storage even allowing for water loss (Brown, 1949) and storage at different temperatures (Rygg, 1949). There is a steady increase in lycopene and other carotenes during tomato ripening at 15°C and 30°C, while at less than 1°C and above 30°C, no lycopene synthesis takes place (Goodwin and Jamikorn, 1952). Folic acid losses of up to 40% can occur in potatoes stored at 7.5°C for 8 months (Augustin et al., 1978).

4.4. Flavor and aroma attributes

Flavor is determined largely by the sugar to acid ratio. Changes in these two components can vary independently and so alter flavor. Storage temperature can influence the rate and direction of change. There is also cultivar by storage time and temperature interactions on sweetness and flavor, as with sweet corn (Evensen and Boyer, 1986) Melons show no change in soluble solids after 3 weeks storage at 7–15°C, and 3 days at 20°C (Miccolis and Saltveit, 1995). However, both soluble solids and acidity decline more in grapefruit held at 8°C, than 12°C (Schirra, 1992). Titratable acidity and soluble solids in guavas did not show any dramatic change during storage at temperatures between 10 and 15°C (Reyes and Paull, 1995). Non-chill injured persimmons fruit had no significant difference in soluble solids when stored at 5 and 10°C for 56 and 42 days, respectively (Collins and Tisdell, 1995). Tomatoes stored at 5°C for 7 days were more acidic, while light pink fruit held at 10°C has a lower sugar to acid ratio than those held at 12.5°C or higher (Kader et al., 1978). The holding temperature for tomatoes is less important than a maturity stage at picking. This last observation highlights a problem in studies in which commodities are held at different storage temperature, as to whether comparisons are being made at the same physiological stage or when different durations of storage are compared.

Higher storage temperature (10°C) leads to volatile loss of butyl, isopentyl and hexyl acetates and alcohols from 'Jonathan' apples. The rate of loss is reduced up to 6000-fold when stored at 0°C. Fruit levels of these same volatiles, except butanol, remain steady or slightly increase in fruit held from −1 to 10°C. The concentration of butanol at 10°C is double that at 0°C, after 12 weeks storage. Acetic acid levels in these fruits are lower at 10°C than at 0°C, ca. 4 mg kg^{-1} versus 20 mg kg^{-1} (Wills and McGlasson, 1971). Soursop aroma develops during ripening and is lost if the fruit is stored at 10°C for 2 days (Paull, 1990, personal observation). Off-flavors due to ethanol and acetaldehyde in citrus fruits are frequently associated with chilling injury or long term storage of tangerines (Cohen et al., 1990) and grapefruit (Schirra, 1992). The aroma of coriander (Chinese parsley) is maintained when stored below 5°C for 10 days at 7.5°C there is an increase off-odor (Loaiza and Cantwell, 1997). Longer storage leads to a loss of the aroma, irrespective of storage temperature, with little remaining after 22 days. The loss of coriander aroma is parallel to the loss of green leaf color, visual quality and an increase in decay. The ethylene induced formation of the bitter principal isocoumarin in carrots is halved by storage at 1°C versus 5°C (Lafuente et al., 1996).

'Sweet' onion pungency increases and sugar decreases at 4°C, more than at 1°C over 6 months storage (Hurst et al., 1985). This low temperature conversion of fructans to fructose occurs early in onion storage (Darbyshire, 1978).

'Woolliness' and browning disorders in peaches and nectarines are major storage problems. The 'woolliness' imparts a dry mealy texture characteristic with poor flavor and the loss of flesh color. Flesh browning occurs in severe cases. The optimum storage temperature is less than or equal to 0°C, while storage at 2–5°C leads to severe 'woolliness' development (Mitchell et al., 1974; Von Mollendorf et al., 1992). The development of 'woolliness' does occur at low temperature, if stored for more than 3–4 weeks (Von Mollendorf et al., 1992).

5. RH and quality

5.1. Appearance and commercial shelf life

Recommendations on RH have been made for most commodities (Table 2), with variation in the recommendations from different sources. These differences in recommendations may reflect general conclusions for a particular commodity group or specific observations. The number of studies in which temperature and RH have been independently controlled is limited. As discussed above, this reflects the difficulty of controlling humidity at higher than 90% RH and at different temperatures.

There is fairly good agreement as to the degree of water (or mass) loss from initial field condition before a commodity shows wilting symptoms (Ben-Yehoshua, 1987). The wilting symptoms most often reported are less gloss, wrinkling or flaccidness. These values are then taken to more subjective levels: maximum permissible loss at which a commodity becomes unsaleable (Robinson et al., 1975). This latter loss criterion occurs at about double the loss required for the first visible symptoms to appear (Grierson and Wardowski, 1978) and integrates the overall loss rate that normally declines with storage. Mass loss is linear (Wells, 1962) and related to WVPD (Fig. 1), hence loss can be reduced by lowering the WVPD via reducing air temperature, increasing humidity or creating a barrier to water loss (Grierson and Wardowski, 1978; Ben-Yehoshua 1987). High air flow may be necessary during cooling, once cool, RH is crucial in determining rate of moisture loss (Lentz and Van Den Berg, 1973). For peaches, mass loss is directly related to WVPD (Fig. 1) and airflow (Whitelock et al., 1994). Nelson and Richardson (1960) showed the positive relationship between air speed and WVPD on grape weight loss. Curing root crops to develop the suberized layer significantly influences the subsequent water loss during subsequent storage (Thompson, 1996). The rate of loss by noncured sweet potatoes (ca. 0.5 kg kg^{-1} day^{-1}) is almost double that by cured roots (ca. 0.2 kg kg^{-1} day^{-1}).

Moisture loss from preclimacteric avocado, mango, banana, plantains, and pear fruit hastens ripening (Fig. 4). There is a linear negative relationship between water loss and green life of avocado and banana (Littmann, 1972) and mango (MacNish et al., 1997; Fig. 4). For example, the green life of bananas is about 22 days at 20°C with 95% RH and ca. 16 days at 13% RH (Littmann, 1972). There is also about a 50% reduction in the postharvest life of custard apple at

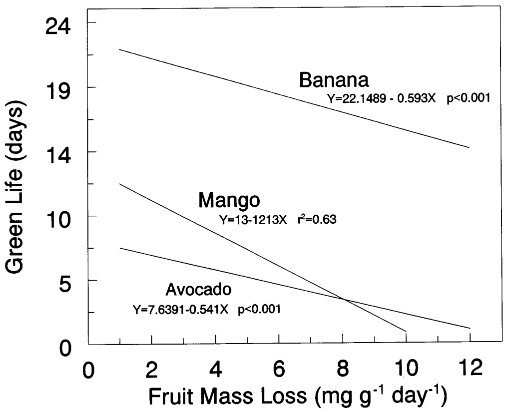

Fig. 4. The relationship between fruit mass loss rate and 'Hass' avocado and banana (Littmann, 1972) and mango green life (MacNish et al., 1997).

low RH (Broughton and Guat, 1979) and 65% reduction for plantains (George et al., 1982). The earlier suggestion that apple breakdown was related to temperature has been challenged and low RH may be the cause (Scott and Roberts, 1967).

Shelf life of peaches is not increased by storage at 95–99% RH, though cherries and lemons have extended life at 95–98% RH versus storage at less than 95% RH at 0°C (Sharkey and Peggie, 1984). The beneficial effects of high humidity for lemons are attributed to reduction of lemon peel desiccation and associated reduction in fruit deformation, peel degreening, chilling injury and decay (Sharkey and Peggie, 1984). Cherries have a fresher stalk, are firmer and have a less shriveled appearance when stored at higher relative humidities.

There is numerous studies relating reduced chilling injury symptom development in sensitive tropical commodities at high RH. Lemon chilling injury symptoms in the peel are reduced at high RH, though RH had no impact on flesh chilling injury symptoms (Sharkey and Peggie, 1984). Cassava roots vascular discoloration is more pronounced at 20°C than 10°C and significantly higher at lower RH (Rickard and Coursey, 1981). 'Woolliness' in peaches is however, increased by high RH (Sharkey and Peggie, 1984), as is core flush in apples (Scott and Wills, 1976). Water loss has been known for 80 years to reduce apple scald (Brooks et al., 1919), and senescent breakdown (Watkins and Thompson, 1992), though the degree can vary with early or late season harvest.

Shelf life of vegetables is frequently defined as the period during which produce loss due to "culling and trimming caused by weight loss (wilting and shriveling), yellowing, rooting sprouting and decay do not exceed 20–30%" (Van Den Berg and Lentz, 1978). This applies particularly to leafy vegetables, the limit (20–30%) is set by the rate of deterioration that rapidly increases after this threshold. The cost of labor and handling associated with trimming while still retaining its appearance as a vegetable, also increases (Van Den Berg and Lentz, 1977). High RH, (98–100%) are recommended for these commodities. For most leafy vegetable, the problem is whether this RH value is commercially achievable in a storage room, as it is more easily achieved by packaging, waxing and wraps. Crushed ice can be used to increase humidity in a packed container.

5.2. Texture

RH can significantly impact ripening related softening (Littmann, 1972), though in five cultivars of peaches, storage period had greater effect than WVPD difference (Whitelock et al., 1994). This last finding with peaches extends an earlier finding (Sharkey and Peggie, 1984) that fruit with a greater mass loss at 77–83% RH, lost turgor and firmness more than fruit stored at 95–99% RH. Similar findings have been made for non-climacteric sweet cherries and lemons where loss of firmness parallels mass loss. Broccoli held in micro-perforated wrap lost less mass and firmness after storage for 17 days at 1°C (Toivonen, 1997), though broccoli stored for 3 days at 1°C showed a different trend.

5.3. Nutritional

Wilting of leafy vegetable can led to loss of vitamin C, (Ezell and Wilcox, 1959). The loss of vitamin C in kale increases under slow wilting conditions from 0.05 to 0.11% h^{-1} under high wilting (lower RH) conditions. Reducing water loss not only reduces leaf yellowing, it increases sweetness and retards protein degradation and the loss of vitamin C in *Brassica juncea* (Lazan et al., 1987a,b). Carotene (vitamin A) loss is enhanced by storage at 0°C and a rapid wilting rate versus slow wilting of from 5% to 0% for kale and 13–2% for collards (Ezell and Wilcox, 1962). Preliminary information suggests that β-carotene synthesis is higher in durian pulp in fruit held at high RH (Ketsa and Pangkool, 1994).

5.4. Flavor

Apple volatile loss is greater at lower RH (Wills and McGlasson, 1970), suggesting a loss of flavor. In contrast, storage of sweet cherries at 90–94% versus 95–99% RH had no effect on soluble solids or flavor (Sharkey and Peggie, 1984). The lack of effect on soluble solids suggests some changes, as juice content is 9% lower (56% versus 65%) at the lower RH versus the higher RH, after 4 weeks storage at 0°C. The acid content, soluble solids and juice content of lemon are not significantly changed by storage at low (77–83% RH) versus high humidity (95–99%) for 10 weeks at 10°C. Lower RH storage has no significant effect on durian starch content, soluble solids and total sugars in durian (Ketsa and Pangkool, 1994). Peach flavor is better at low versus high RH (Sharkey and Peggie, 1984), reflecting the higher incidence of 'woolliness' at the higher RH after 4 weeks at 0°C. Water stress during storage of *Brassica juncea* at 2–4°C can lead to an increase in leaf sugar content (Lazan et al., 1987a). A two to three-fold increase in total sugar occurred in stressed leaves not kept in a polyethylene bag.

6. Future research needs

The marketing of fresh fruits and vegetable is becoming more integrated. The integration includes direct purchases from a producers and shippers to supermarkets, direct deliveries of commodities without wholesalers seeing the product and retailers using price look up (PLU) numbers. The industry-wide uses of PLU numbers allows a retailer to analyze commodity losses by commodity, store, season and source. This data will enable retailers to determine their deliveries, inventories and sales strategies. This ability to analyze losses will significantly change marketing practices and lead to a desire to obtain commodities having the highest quality and the longest shelf life. This will require the application of proper storage temperature and RH conditions.

The retailing situation for small volume speciality items will also be influenced by these changes. The range of commodities carried in different outlets of one chain can be expected to change to adjust to individual outlet consumer demands. This change in distribution will influence marketing of these commodities and increase the competition for display space in as many retail outlets as possible. Suppliers of speciality commodities who provide the highest quality product will still have an outlet, even if at a slightly higher price.

At both extremes, large volume regular commodities and speciality commodities, the market will be driven by quality. Visual quality criteria will probably incorporate criteria for flavor. Quality maintenance requires correct application of proper temperature and RH usage and handling from harvest to the consumer.

Simulated shipping studies need to be more realistic to ascertain commodity shelf life. Shelf life needs to include a retail phase and this depends on knowledge of temperatures and RH to which products are exposed. Improvements in retail display equipment may improve quality maintenance at the point of sale.

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