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# Storage Temperature

**MARIA CECÍLIA DO NASCIMENTO NUNES and JEAN PIERRE EMOND**

*Laval University, Quebec City, Quebec, Canada*

## I. IMPORTANCE OF TEMPERATURE MANAGEMENT IN POSTHARVEST HANDLING OF FRESH VEGETABLES

Temperature is the characteristic of the postharvest environment that has the greatest impact on the storage life of vegetables. All vegetables deteriorate after they are harvested; only the rate at which the deterioration occurs can be changed. Thorne and Alvarez (1982) have pointed out that it is well established that the deterioration of most agricultural products is a direct function of temperature. Within the range of temperatures bounded on the lower end by chilling injury or freezing and on the upper by heat injury, deterioration of vegetables caused by physiological, pathological, or physical factors is a function of time and environment (Holt et al., 1983).

Postharvest losses of horticultural crops are estimated to be as high as 25% to 50% of the production due to poor postharvest handling techniques, mainly poor temperature management, especially in some regions of the globe such as tropical and subtropical regions and where refrigeration facilities are not available (Desai and Salunkhe, 1991; Harvey, 1978; Rippon, 1980). For example, a large quantity of onions (*Allium cepa* L.) is lost between the field and the consumer in India due to lack of adequate postharvest handling procedures (Desai and Salunkhe, 1991). Good temperature management is, in fact, the most important and simplest procedure for delaying product deterioration. In addition, optimum temperature storage retards the aging of vegetables, softening, and textural and color changes as well as slowing undesirable metabolic changes, moisture loss, and losses due to pathogen invasion. Temperature is also the factor that can be most easily and promptly controlled. Optimum preservation of vegetable quality can only be achieved when the produce is promptly cooled to its optimum temperature as soon as possible after harvest.

## A. Optimum Storage Temperatures and Vegetable Shelf Life

Low temperature during the storage of fresh vegetables depress both the physiological activity of vegetable tissues and the activity of micro-organisms capable of causing spoilage of the product. Figure 1 shows the effect of temperature on the storage life of lettuce (*Lactuca sativa* L.) and illustrates the importance of keeping products at low temperatures after harvest (Alvarez and Thorne, 1981). In general, the lower the storage temperature, within the limits acceptable for each type of commodity (above the freezing point or chilling injury threshold), the longer the storage life. For each horticultural commodity there is presumed to be an optimal postharvest storage temperature at which the rate of product deterioration is minimized. Many studies have demonstrated that maintenance of an optimum temperature during storage and transport is crucial for maintaining vegetable quality (Apeland and Hoftun, 1974; Bourne, 1982; King et al., 1988; Lownds et al., 1994; Percival et al., 1993; Rosenfeld et al., 1995; Siomos et al., 1995a; b; Toivonen et al., 1993; Toivonen, 1997; Van den Berg, 1981).

Vegetables are, in fact, highly perishable products, and losses due to inadequate temperature management are found to be mainly due to water loss and decay (Van den Berg, 1981; Desai and Salunkhe, 1991). For example, Apeland and Hoftun (1974) recommended that carrots (*Daucus carota*, L.) should be stored at 0 to 1°C in order to maintain quality during long-term storage (between 150 and 190 days). They also added that the carrot temperature should be reduced to about 0°C as soon as possible after harvest, and that the temperature should be maintained constant during the storage period. Toivonen et al. (1993) also reported that carrots that were preconditioned at 1°C prior to distribution lost approximately 30% less weight when transferred to the supermarket shelf than carrots that had been kept continuously at 13°C (shelf conditions). Van den Berg (1981) reported that the type of decay in carrots was temperature-dependent and varied from relatively small, dry, brown lesions observed mainly at 0 to 2°C to watery, soft rot lesions, prevailing at 3 to 8°C.

Prior storage temperature has a large effect on subsequent vegetable shelf life. In the case of asparagus (*Asparagus officinalis* L.), a very highly perishable vegetable, re-

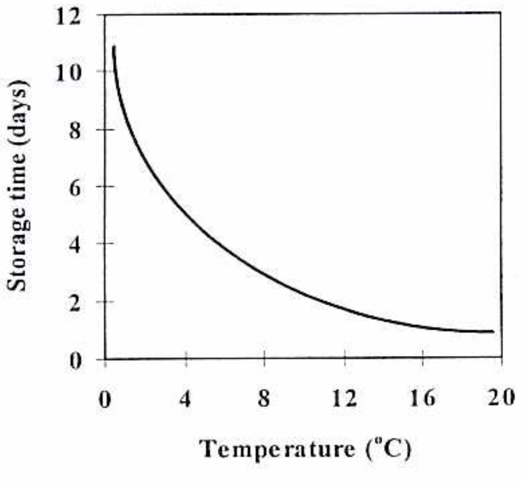

**Figure 1** The effect of temperature on the storage life of lettuce. (Adapted from Alvarez and Thorne, 1981.)

search has demonstrated that the higher the storage or shipping temperature, the greater the loss in quality (King et al., 1988; Siomos et al., 1995a, b). King et al. (1988) reported that when asparagus spears were held at simulated air transport temperatures, shelf life at 20°C was reduced by 1.7 days following the 0°C and 15°C treatments. They also observed that, after simulated transport at 20 or 25°C, the shelf life of asparagus was further reduced by 2 days, to a total of less than 2 days at 20°C. When held at simulated transport temperatures above 15°C, spears of asparagus showed symptoms of wilting within a short period of time. Therefore, the quality of asparagus could be best maintained with a 0°C holding temperature throughout the marketing chain (note, however, that chilling injury can occur after extended storage of asparagus at <2°C; see Chapter 18). For broccoli (*Brassica oleracea* L., Botrytis group), storage for 10 days at 5°C resulted in a much shorter shelf life at 13°C than did storage at 1°C, owing to significantly more yellowing following 5°C storage (Toivonen, 1997). Broccoli stored at 5°C became fully yellow by the fourth day at 13°C, while broccoli stored at 1°C remained fully dark green for the 5-day observation period.

Van den Berg (1981) also studied the role of several factors, including temperature and relative humidity, on the quality of some vegetables during storage. He observed that the optimum temperature for reducing decay of beets (*Beta vulgaris* L. ssp. *vulgaris*) was 4 to 5°C rather than 0 to 1°C or 2 to 3°C. However, he noticed that the sprouting of beets increased at 4 to 5°C. For cabbage (*Brassica oleracea* L., Capitata group), rooting and internal growth depends mostly on temperature but is not affected by relative humidity. Therefore, the storage life of cabbage is limited to 4 to 5 months owing to internal growth and rooting when the product is stored at 3.5 to 4.5°C, and 2 to 3 months when storage temperature is maintained at 7 to 8°C. But at 0 to 1°C, the symptoms are not significant until after 7 months (Van den Berg, 1981).

Although leeks (*Allium ampeloprasum* Tausch.) are a vegetable that can be stored at very low temperatures, from −1 to −1.5°C, this is commercially impractical. Therefore, a temperature close to 0°C would be acceptable for the storage of leeks (Hardenburg et al., 1986; Van den Berg, 1981). Storage of parsnips (*Pastinaca sativa* L.) at 0 to 1°C reduces losses due to decay to 10% or less by weight after 9 months of storage, while for parsnips stored at 3.5 to 4.5°C, decay losses can be as high as 10% to 30% (Van den Berg, 1981). Decay in rutabagas (*Brassica napus* L., Napobrassica group) increases as the storage temperature increases. Rutabagas stored for 9 months at 0 to 1°C showed a 10% reduction in initial weight due to decay, while during storage at 3.5 to 4.5°C, a 5% to 15% reduction in initial weight was observed (Van den Berg, 1981).

Although carrots, asparagus, broccoli, cabbage, beets, and leeks differ in their degree of perishability, their optimum storage temperature is identical; that is, they should be maintained at temperatures around 0 to 2°C if their best quality is to be maintained. Howtated by their sensitivity to chilling injury limit the storage life of these vegetables compared to temperate vegetable crops.

Recommendations of optimum storage temperature such as those suggested by Hardenburg et al. (1986) constitute a very useful tool for all professionals, from researchers to growers, who work with fresh horticultural crops (Table 1). However, in some cases, the generalized optimum value for storage temperature of a certain commodity might not be the ideal for different cultivars of the same commodity. In fact, the behavior of cultivars of a vegetable crop can be quite different with respect to optimum storage temperatures. For example, cultivars of bell-type peppers (cvs. Keystone and Mexibell), and New Mexican–type peppers such as New Mexican (cvs. NuMex R Naky, NuMex Conquistador, and New Mexico 6-4), Yellow wax (cvs. Santa Fe Grande and Cascabella), Jalapeño (cv. TAM Jalapeño), and Serrano (cv. TAM Hidalgo) were shown to respond differently to storage temperatures of 8, 14, and 20°C (Lownds et al., 1994). Thus, bell pepper types lose more weight when stored at 8, 14 or 20°C than New Mexican types (Lownds et al., 1994). Another study using four different cucumber cultivars (''Kokard,'' ''Plura,'' ''Rhensk Druv,'' and ''Spångbergs Vit'') also showed different optimum storage temperatures (Kapitsimadi et al., 1990). ''Plura'' was reported to store best at 10°C, while ''Rhensk Druv'' stored best at 12°C, ''Kokrad,'' stored best at 13°C, and finally, 14°C was recommended for ''Spångbergs Vit'' (Kapitsimadi et al., 1990). Melon cultivars can also behave differently when stored at the same temperature. For example, when melons were stored for 3 weeks at 7, 12, or 15°C, the firmness of some of melons (*Cucumis melo* L. Inodorus group)—cultivars ''Honeydew,'' ''Amarelo,'' ''Juan Canary,'' and ''Golden Casaba''—decreased an average of 67%, 63%, 60%, and 54%, respectively, while firmness of ''Paceco'' and ''Honey Loupe'' melon cultivars decreased only 40% and 32%, respectively (Miccolis and Salveit, 1995).

## B. Effects of Storage Temperature on the Quality of Vegetables

The visible quality of the product—that is, the appearance of the product—is perhaps the most important factor that determines the market value of fresh vegetables. When consumers were asked about fresh fruits and vegetables, ripeness, freshness, and taste were named by 96% as the most important selection criteria, while appearance and condition of the product came in second in order of importance (94%) (Zind, 1989). Although not visually perceptible, nutritional value was considered by about 66% of the consumers to be the decisive factor for buying the product (Zind, 1989).

### 1. Appearance and Texture of Vegetables

Color, one of the major factors of product appearance, is a primary indicator of maturity or ripeness and is due to the presence of particular pigments in the product. Undesirable changes in the uniformity and intensity of color can be observed when vegetables are not stored at recommended temperatures. Temperature can therefore have a direct effect on color changes during storage of fresh vegetables. For example, while loss of chlorophyll is a desirable process in a few vegetables such as tomatoes and some sweet pepper cultivars, yellowing of green vegetables such as broccoli or Brussels sprouts (*Brassica oleracea* L. Gemmifera group) is considered undesirable. Subjective visual observations combined with CIE L*a*b* uniform color space (CIELAB) determinations, and total chlorophyll and carotenoid content constitute a very good indicator of color changes in many vegetables during storage.

**Table 1** Recommended Temperature, Relative Humidity, and Approximate Transit and Storage Life for Vegetables

| Product | Temperature | | Relative humidity (%) | Approximate storage life |
|---|---|---|---|---|
| | °F | °C | | |
| Artichoke, globe | 32 | 0 | 95–100 | 2–3 weeks |
| Artichoke, Jerusalem | 31–32 | −0.5–0 | 90–95 | 4–5 months |
| Asparagus | 32–35 | 0–2 | 95–100 | 2–3 weeks |
| Bean, dry | 40–50 | 4–10 | 40–50 | 6–10 months |
| Bean, green or snap | 40–45 | 4–7 | 95 | 7–10 days |
| Bean, lima | 37–41 | 3–5 | 95 | 5–7 days |
| Bean sprouts | 32 | 0 | 95–100 | 7–9 days |
| Beet, bunched | 32 | 0 | 98–100 | 10–14 days |
| Beet, topped | 32 | 0 | 98–100 | 4–6 months |
| Broccoli | 32 | 0 | 95–100 | 10–14 days |
| Brussels sprouts | 32 | 0 | 95–100 | 3–5 weeks |
| Cabbage, early | 32 | 0 | 98–100 | 3–6 weeks |
| Cabbage, late | 32 | 0 | 98–100 | 5–6 months |
| Cabbage, Chinese | 32 | 0 | 95–100 | 2–3 months |
| Carrot, bunched | 32 | 0 | 95–100 | 2 weeks |
| Carrot, mature | 32 | 0 | 98–100 | 7–9 months |
| Carrot, immature | 32 | 0 | 98–100 | 4–6 weeks |
| Cassava, yucca | 32–41 | 0–5 | 85–90 | 1–2 months |
| Cauliflower | 32 | 0 | 95–98 | 3–4 weeks |
| Celeriac | 32 | 0 | 97–99 | 6–8 months |
| Celery | 32 | 0 | 98–100 | 2–3 months |
| Chard | 32 | 0 | 95–100 | 10–14 days |
| Chayote | 45 | 7 | 85–90 | 4–6 weeks |
| Chicory, witloof, Belgian endive | 32 | 0 | 95–100 | 2–4 weeks |
| Collard | 32 | 0 | 95–100 | 10–14 days |
| Corn, sweet | 32 | 0 | 95–98 | 5–8 days |
| Cucumber | 50–55 | 10–13 | 95 | 10–14 days |
| Eggplant | 46–54 | 8–12 | 90–95 | 1 week |
| Endive and escarole | 32 | 0 | 95–100 | 2–3 weeks |
| Garlic | 32 | 0 | 65–70 | 6–7 months |
| Ginger | 55 | 13 | 65 | 6 months |
| Greens, leafy | 32 | 0 | 95–100 | 10–14 days |
| Horseradish | 30–32 | −1.0–0 | 98–100 | 10–12 months |
| Jicama | 55–65 | 13–18 | 65–70 | 1–2 months |
| Kale | 32 | 0 | 95–100 | 2–3 weeks |
| Kohlrabi | 32 | 0 | 98–100 | 2–3 months |

**Table 1** Continued

| Product | Temperature °F | Temperature °C | Relative humidity (%) | Approximate storage life |
|---|---|---|---|---|
| Mushroom | 32 | 0 | 95 | 3–4 days |
| Okra | 45–50 | 7–10 | 90–95 | 7–10 days |
| Onion, green | 32 | 0 | 95–100 | 3–4 weeks |
| Onion, dry | 32 | 0 | 65–70 | 1–8 months |
| Onion sets | 32 | 0 | 65–70 | 6–8 months |
| Parsley | 32 | 0 | 95–100 | 2–2.5 months |
| Parsnip | 32 | 0 | 98–100 | 4–6 months |
| Pea, green | 32 | 0 | 95–98 | 1–2 weeks |
| Pea, southern | 40–41 | 4–5 | 95 | 6–8 days |
| Pepper, chili (dry) | 32–50 | 0–10 | 60–70 | 6 months |
| Pepper, sweet | 45–55 | 7–13 | 90–95 | 2–3 weeks |
| Potato, early crop | 40 | 4 | 90–95 | 4–5 months |
| Potato, late crop | 45 | 7 | 90–95 | 5–10 months |
| Pumpkin | 50–55 | 10–13 | 50–70 | 2–3 months |
| Radish, spring | 32 | 0 | 95–100 | 3–4 weeks |
| Radish, winter | 32 | 0 | 95–100 | 2–4 months |
| Rhubarb | 32 | 0 | 95–100 | 2–4 weeks |
| Rutabaga | 32 | 0 | 98–100 | 4–6 months |
| Salsify | 32 | 0 | 95–98 | 2–4 months |
| Spinach | 32 | 0 | 95–100 | 10–14 days |
| Squash, summer | 41–50 | 5–10 | 95 | 1–2 weeks |
| Squash, winter | 50 | 10 | 50–70 | Depends on type |
| Sweet potato | 55–60 | 13–16 | 85–90 | 4–7 months |
| Tamarillo | 37–40 | 3–4 | 85–95 | 10 weeks |
| Taro | 45–50 | 7–10 | 85–90 | 4–5 months |
| Tomato, mature-green | 55–70 | 13–21 | 90–95 | 1–3 weeks |
| Tomato, firm-ripe | 46–50 | 8–10 | 90–95 | 4–7 days |
| Turnip | 32 | 0 | 95 | 4–5 months |
| Turnip greens | 32 | 0 | 95–100 | 10–14 days |
| Waterchestnut | 32–36 | 0–2 | 98–100 | 1–2 months |
| Watercress | 32 | 0 | 95–100 | 2–3 weeks |
| Yam | 61 | 16 | 70–80 | 6–7 months |

*Source*: Adapted from Hardenburg et al. 1986.

Yellowing of broccoli it is very often due to storage above the recommended temperature and it is a major cause of product rejection. Several studies show that temperature can have an important effect on color changes of broccoli during storage (Makhlouf et al., 1991; Toivonen, 1997; Zhuang et al., 1997). Makhlouf et al. (1991) studied the effect of temperature on the chlorophyll content of broccoli florets stored for 5 days at 25 or 1°C. They concluded that storage at 1°C greatly reduces chlorophyll losses compared to 25°C storage. In another study, reduction in broccoli quality was associated with the degree of yellowing (Toivonen, 1997). The author reported that storage temperature has a significant effect on the color changes of stored broccoli. Broccoli stored for 10 days at 10°C became fully yellow by the fourth day after being transferred to 13°C, while broccoli stored at 1°C for 10 days remained fully dark green in color for 5 days at 13°C. Zhuang et al. (1997) observed no significant changes in the total chlorophyll content of broccoli stored at 2°C for 6 days. However, chlorophyll content declined in broccoli stored at 13 or 23°C for the same period of time. The authors also reported that after a 6-day storage period at 13 or 23°C, a 42% or 86% reduction, respectively, was observed in the total chlorophyll content of broccoli. At the end of the storage period, they observed that the broccoli stored at 13°C contained significantly lower levels of total chlorophyll than that stored at 2°C. Chlorophyll content tends to decrease while lycopene content (red pigment) increases during storage of tomatoes harvested mature-green and stored at 20°C (Syamal, 1990). The red color of sweet pepper fruit stored for 14 days at 14°C was 2.4 to 3.7-fold higher than that of fruit stored at 8°C (Lownds et al., 1994)

Softening of fleshy tissues of some vegetable crops—such as tomato, cucumber, sweet pepper, and others—is one of the most important changes occurring during storage and has a major effect on consumer acceptability. The texture of the living plant tissues is mainly influenced by its cellular anatomy, the water relations of the cells, and the composition of the cell walls (see Chap. 12). Changes in the overall textural quality of vegetables include decreased crispness and juiciness or increased toughness. Crispness is expected in fresh carrots and celery (*Apium graveolens* L.), but tenderness is desired in asparagus. In the particular case of leafy vegetables, as they lose water they can wilt, shrivel, and become flaccid, losing their attractive and expected appearance. Toivonen (1997) reported that when fresh broccoli was stored for 10 days at 1 or 5°C plus 5 days at 13°C, loss of quality was highly correlated with weight loss due to water loss during storage.

Decreased firmness can be due to decreased turgidity, thinning of the cell walls, or increased cell size coupled with decreased tissue cohesiveness caused by degradation of pectin and cell disarrangement. Decreased crispness in some leafy vegetables may be associated with folding of the cell wall and cytoplasmic disarrangement. In addition, increased juiciness can be correlated with the liquefaction of cell contents and the general disarrangement of cell structure (Szczesniak and Smith, 1969).

It has been documented that when storage temperature increases, the firmness of the product tends to decrease (Bourne. 1982; Lownds et al., 1994; Miccolis and Salveit, 1995). For example, Miccolis and Salveit (1995) reported a decrease in firmness of melons that were held for 3 days at 15°C plus 3 days at 20°C compared with those first held at 7°C. And flaccidity of several pepper cultivars, measured as surface depression in response to applied finger pressure, increased 4.5- to 9-fold in peppers stored for 14 days at 14°C compared with those stored at 8°C (Lownds et al., 1994).

Bourne (1982) studied the effect of tissue temperature over a range of 0 to 45°C on firmness of several fruits and vegetables by using the firmness-temperature coefficient (FT). This coefficient was defined as the percent change in firmness per degree centigrade temperature increase over the temperature range and the following formula was used to the increase in firmness might be an artifact caused by water loss, which results in toughening of the epidermis of fleshy tissues rather than retention of flesh firmness. For example, Nunes et al. (1995) observed that when the firmness of strawberries was measured as the bioyield point, berries stored for 6 h at 30°C plus 1 week at 1°C plus 1 day at 20°C were firmer than those immediately stored at 1°C. But, when the firmness data were expressed as the force required to compress a berry by 3 mm, flesh firmness was shown actually to be lower in the berries from the 6 h at 30°C treatment.

Bourne (1982) also found that while the FT relationship is approximately linear for all commodities, it is also highly variable, since it differs from commodity to commodity, from cultivar to cultivar within the same commodity, and for the same commodity during storage as well as with the type of firmness test used (Table 2). For example, for a product with a FT coefficient of 0.3%·$°C^{-1}$, a change of 10°C would change the firmness measurement by 3%, a sometimes imperceptible amount due to the high coefficient of variation that is usually found in firmness measurements of horticultural crops. But a commodity with a FT coefficient of 1.0%·$°C^{-1}$ would show a change in firmness of 10% with a 10°C temperature change—an amount that would most likely be detected.

### 2. Compositional Characteristics of Vegetables: Nutritional Value

Vegetables contribute a high concentration of micronutrients such as vitamins and minerals to the human diet with a low contribution of calories and fats. Vegetables are especially rich sources of vitamins, particularly vitamin C, and also vitamin A in the form of β-carotene, the precursor of vitamin A. In fact, fruits and vegetables are the major source of the vitamin C and A required in the human diet. For example, the daily requirement for vitamin C is about 50 mg, and many commodities such as broccoli and pepper contain this amount in less than 100 g of tissue. However, the importance of vegetables as a source of a nutrients depends both on the amount of the nutrient present in the tissue as well as the per capita quantity of a particular crop that is consumed by the population. For example, carrots, leafy green vegetables, and sweet potatoes (*Ipomoea batatas* L.) are good sources of vitamin A owing to their high concentrations of the nutrient, and peppers and tomatoes are very good sources of vitamin C.

However, the nutritional value of vegetables can also be greatly affected by storage temperature. In general, vitamin C degradation is very rapid after harvest and increases as the storage time and temperature increase (Fennema, 1977, 1985). Nunes et al. (1998) observed that losses in vitamin C content in several strawberry cultivars stored at 1°C ranged from 20% to 30% over 8 days while berries at 10°C lost from 30% to 50% of their initial vitamin C content. At 20°C, losses were very high and berries lost 55% to 70% of their initial vitamin C content in only 4 days. The vitamin C content of tomatoes stored for 12 days at room temperature (20°C) also tended to decrease during storage (Syamal, 1990).

The concentrations of carbohydrates, in particular sugars, as well as organic acids in vegetables can also decrease when temperature increases. Carbohydrates are used as energy reserves as well as structural material of cells, and organic acids have an important role in the general metabolism of horticultural products and are essential components of the respiratory cycle. Thus, sugars and acids are used as respiratory substrates, leading to the depletion of product reserves. Differences in sugar and acid contents at different storage temperatures are due to the fact that, when temperature increases, the respiration rate of the product increases and complex carbohydrates and organic acids are transformed into glucose to provide substrate for the respiratory processes. For example, total sugar

**Table 2** Effect of Temperature on Firmness of Fresh Vegetables

| Commodity | Description | Type of measurement | FT coefficient (% change in firmness per 1°C increase) |
|---|---|---|---|
| Bean, snap | Early Wax, sieve size 3 | Puncture, 30-mm tip | −0.09 |
| | Early Wax, sieve size 4 | | −0.10 |
| | Slim Green, sieve size 4 | | +0.11 |
| | Slim Green, sieve size 5 | | +0.06 |
| Beet | Detroit Dark Red | Deformation to 1 N | +0.28[a] |
| | | Puncture, 30-mm tip | −0.09 |
| Carrot | Chantenary, phloem tissue | Puncture, 20-mm tip | +0.12 |
| Corn, sweet | Jubilee 10–35°C | Shear press | −1.31 |
| | | Back extrusion | −0.82 |
| | Deep Gold 10–35°C | Shear press | −1.08 |
| | | Back extrusion | −0.5 |
| Cucumber | Marketor 0–30°C | Deformation to 0.5 N | −0.27 |
| | | Puncture, 30-mm tip | +0.04 |
| Onion | Autumn Keeper | Deformation to 4 N | −0.58 |
| | | Puncture, Magness-Taylor 78-mm tip | −0.18 |
| Pea, green | Early Sweet 11, sieve size 3 | Shear press | −0.32 |
| | | Maturometer | −0.52 |
| | | Back extrusion | −0.62 |
| | Early Sweet 11, sieve size 4 | Shear press | −0.35 |
| | | Maturometer | −0.30 |
| | | Back extrusion | −0.12 |
| | Target, sieve size 3 | Shear press | −0.37 |
| | | Maturometer | −0.28 |
| | | Back extrusion | −0.26 |
| | Target, sieve size 4 | Shear press | −0.16 |
| | | Maturometer | −0.15 |
| | | Back extrusion | −0.07 |
| Potato | Katahdin, stored 1 month | Magness-Taylor 30-mm tip | −0.02 |
| | Katahdin, stored 7 months | | +0.06 |
| | Katahdin, stored 1 month | Deformation to 0.25 N | +0.28 |
| | Katahdin, stored 7 months | | +0.12 |
| | Russet Burbank, stored 1 month | Magness-Taylor 30-mm tip | +0.06 |
| | Russet Burbank, stored 7 months | | +0.04 |
| | Russet Burbank, stored 1 month | Deformation to 0.25 N | +0.014 |
| | Russet Burbank, stored 7 months | | +0.09 |
| Tomato | New Yorker, stem-end down, 1973 | Deformation 1 N | +0.87 |
| | New Yorker, stem-end down, 1978 | | +0.20 |
| | Nova (plum type), sideways, 1973 | | +0.58 |
| | Nova (plum type), sideways, 1978 | | +0.17 |

[a] A positive sign (+) for deformation tests indicates that the deformation increases as temperature increases (i.e., firmness decreases as temperature increases).

Source: Adapted from Bourne, 1982.

kilogram of fresh weight can cause glycoalkaloid poisoning (Valkonen et al., 1996). Generally, very low storage temperatures result in greater glycoalkaloid accumulation, although glycoalkaloid concentrations have been shown to fluctuate at different storage temperatures (Percival et al., 1993; Rosenfeld et al., 1995). Therefore very low or very high storage temperatures might lead to a rise in the α-solanine content of potato tubers. Tubers stored at 24°C accumulated higher total glycoalkaloids than tubers stored at 5°C (Percival et al., 1993). In fact, the solanine content may almost double in potatoes stored for 1 week at 23°C compared to 1 week at 5°C (Rosenfeld et al. 1995). Thus, in order to keep the glycoalkaloid content within acceptable limits, early-crop potatoes should be stored at low temperatures, such as 4°C, and late-crop potatoes at 7°C (Hardenburg et al., 1986; Rosenfeld et al., 1995).

In conclusion, good temperature management is recommended for fresh vegetables since it retards aging due to ripening; softening; textural and color changes; undesirable metabolic changes and respiratory heat production; moisture loss and wilting of vegetables that results from moisture loss; spoilage due to invasion by bacteria, fungi, and yeast; undesirable growth, such as sprouting of potatoes; and synthesis of toxic compounds like solanine.

## II. EFFECT OF STORAGE TEMPERATURE ON VEGETABLE METABOLISM

During the postharvest storage of vegetables, several metabolic changes essential to the tissues occur. For example, increased respiration rate, softening of the tissues, color changes caused by the synthesis of new pigments or destruction of others, and changes in the composition of products due, for example, to conversion of starch to sugars are some of the metabolic reactions that occur after harvest. Most of these metabolic changes are temperature-dependent; that is, they are slowed down by lowering the storage temperature. Respiration is, among all, the main metabolic activity that is affected by lowering the storage temperature. Singh (1994) has reviewed the various models used to describe changes in food quality during storage and the use of time-temperature indicators in monitoring the quality of stored foods. The parameter most commonly used by postharvest physiologists to describe the relationship between temperature and fruit and vegetable metabolism is the $Q_{10}$ value.

### A. Temperature Quotient of Respiration: $Q_{10}$

The marked effect of temperature on the metabolism of harvested vegetables has long been recognized (Appleman and Smith, 1936; Benoy, 1929; Platenius, 1942). When the storage temperature increases, the product temperature increases, leading to an increase in reaction rates. However, not all the reactions have the same relative rate of change in response to temperature. In order to characterize the changes in the rates of reactions due to temperature, a value called the $Q_{10}$ is often used. The $Q_{10}$ value can be defined as:

$$Q_{10} = \frac{\text{Rate of specific reaction at } T_1 + 10°\text{C}}{\text{Rate of specific reaction at } T_1}$$

The respiration rate of fresh horticultural crops is often used as a general predictor of the effect of temperature on the overall metabolism of plant tissue. Therefore, in postharvest applications, the $Q_{10}$ value is most commonly used for evaluation of temperature effects on respiration. The $Q_{10}$ value can be applied almost ideally to respiration, since the product respiratory rate is markedly reduced at lower temperatures. This principle constitutes the basis of cold storage of horticultural crops. Therefore, the $Q_{10}$ relationship can be very useful in predicting loss of quality of fresh vegetables, since an increase in storage temperature will cause an increase in respiration rate, and depletion of sugars and organic acids from the tissue may occur as a consequence.

The $Q_{10}$ values of fresh fruits and vegetables are usually given within specified temperature ranges, since rates of product deterioration are not exactly first-order with respect to the reciprocal of the temperature. For many products, the $Q_{10}$ for respiration is between 2.0 and 2.5 for the temperature range from 5 to 25°C. Therefore, for every 10°C rise in temperature, the respiration rate increases 2.0 to 2.5 times. The $Q_{10}$ is, in general, lower for storage temperatures above 10°C than for lower temperatures. This indicates that the use of low temperatures during storage will markedly slow down the inevitable changes due to product metabolism. However, there are certain limitations in the use of $Q_{10}$ values for respiration rates. Most importantly, it must be realized that the $Q_{10}$ values can be applied to initial rates only because at any later stage vegetables would be of different physiological age and different chemical composition (Platenius, 1942). The $Q_{10}$ value is not valid at low temperatures for chilling sensitive commodities (Shewfelt, 1986).

Temperature coefficients of respiration are also dependent on the age of tissues, but that difference tends to disappear at higher temperatures. As the storage temperature increases above 25°C, the $Q_{10}$ for most products decreases, and at very high temperatures the metabolic rates are completely depressed due to enzyme denaturation (Kays, 1991). However, when Watada et al. (1996) studied the effect of temperature on whole and fresh-cut fruits and vegetables, they observed that respiration rates were higher in fresh-cut than in whole product and increased with temperature, and the degree of increase was commodity-dependent. The $Q_{10}$ of several fresh-cut products was higher, similar, or lower than that of the whole product when stored in the 0 to 10°C temperature range, but, unexpectedly, the $Q_{10}$ of fresh-cut products was greater in the 10 to 20°C temperature range than in the 0 to 10°C temperature range for most of the commodities studied (Table 3). The higher $Q_{10}$ values of several fresh-cut products in the temperature range from 10 to 20°C was explained by the occurrence of a rapid deterioration of the products at 20°C. Thus, $Q_{10}$ values, in particular for the range from 10 to 20°C, indicate the importance of adequate storage temperature for both intact and fresh-cut products (i.e., near 0°C if the product is not chilling-sensitive).

The calculation of the $Q_{10}$ value given above is not always obvious, in particular when respiration rate data are measured at intervals other than 10°C, such as 3 or 12.5°C. Therefore, in order to determine the exact $Q_{10}$ value, the following equation can be used:

$$/ \quad \backslash^{10/(T_2-T_1)}$$

**Table 3** $Q_{10}$ Values of Whole and Fresh-Cut Vegetables Between 0 to 10°C and 10 to 20°C

| | | $Q_{10}$ | |
|---|---|---|---|
| Commodity | Type | 0 to 10°C | 10 to 20°C |
| Bell pepper | Whole | 1.9 | 5.2 |
| | Cut | 2.0 | 7.5 |
| Crenshaw melon | Whole | 3.2 | 3.3 |
| | Cubes | 7.5 | 8.6 |
| Cucumber | Whole | 2.4 | 2.3 |
| | Cut | 2.9 | 4.6 |
| Honeydew melon | Whole | 3.7 | 1.9 |
| | Cubes | 3.6 | 7.5 |
| Green bean | Whole | 4.0 | 2.5 |
| | Cut | 5.6 | 2.0 |
| Muskmelon (large) | Whole | 3.1 | 5.4 |
| | Cubes | 3.3 | 18.9 |
| Muskmelon (small) | Whole | 4.4 | 4.2 |
| | Cubes | 3.6 | 8.3 |
| Squash | Whole | 2.3 | 2.6 |
| | Cut | 2.7 | 4.4 |
| Tomato | Whole | 2.9 | 4.3 |
| | Cut | 7.1 | 3.5 |
| Zucchini | Whole | 4.4 | 2.5 |
| | Cut | 3.9 | 3.4 |

*Source*: Adapted from Watada et al., 1996.

**Table 4** Examples of $Q_{10}$ Values as Function of storage Temperature Calculated from Respiration Rates Values Reported by Hardenburg et al. (1986)

| | Temperature | |
|---|---|---|
| Commodity | 0 to 10°C | 10 to 20°C |
| Asparagus | 3.3–3.8 | 1.6–3.0 |
| Broccoli | 3.9–4.1 | 3.6–3.7 |
| Cauliflower | 1.8–2.0 | 2.3–2.4 |
| Celery | 3.4 | 2.7 |
| Cucumber | [a] | 2.0 |
| Lettuce, head | 2.3–3.5 | 1.5–2.4 |
| Spinach | 4.3–6.2 | 1.6–3.0 |
| Sweetcorn | 2.4–3.5 | 2.5–2.6 |
| Tomato, mature-green | [a] | 1.8–2.3 |

[a] Cucumbers and mature-green tomatoes are susceptible to chilling injury and thus are not normally stored below 10°C.

## B. Prediction of Vegetable Shelf Life

The $Q_{10}$ value is usually used to determine the change in storage life of a vegetable when storage temperature is increased or decreased. Based on this concept, within a normal range of storage temperatures, the shelf life is inversely proportional to the respiratory activity of the product. However, data presented in the literature do not always agree with this concept, even when all other parameters, such as relative humidity, are kept constant. This can be verified by comparing the observed shelf life at different storage temperatures for vegetables with their calculated shelf life based on the $Q_{10}$. For example, the observed shelf lives for cauliflower (*Brassica oleracea* L., Botrytis group), lettuce, and sweetcorn as reported by Hardenburg et al. (1986) do not always match the shelf lives calculated from the $Q_{10}$ values reported by the same authors (Table 5). As shown in Table 5, prediction of the shelf life based on the $Q_{10}$ cannot be applied in all cases. For this reason, some researchers (Thorne and Meffert, 1978; Wells and Singh, 1988) have proposed using the concept of the time-temperature relationship as a better way to predict the loss of shelf life as function of temperature.

## C. Time-Temperature Relationship

Predicting the shelf life based on the $Q_{10}$ is appropriate as long as the storage temperatures do not fluctuate. For this reason, researchers (Thorne and Meffert, 1978) have adapted the $Q_{10}$ concept to predict the shelf life when the product is exposed to fluctuating storage temperatures. The basis of this method consists of starting from the storage life-temperature curve of a product using constants found in the literature. From this curve, it is possible to consider the cumulative time-temperature as the area under the curve, which translates into the total deterioration occurring up to that time. An example of deterioration-time curves constructed from data for rate of change in some quality factor against time for storage in constant or variable temperatures is shown in Figure 2, in this case the rate of color change in ripening tomatoes.

A similar approach was taken by Wells and Singh (1988). In this case, the mathematical model to predict the shelf life was based on the theory of chemical kinetics. A first-order kinetic reaction model was used to describe changes in tomato firmness at different constant temperatures, and the resulting equation was used to successfully predict the tomato shelf life in a variable temperature regime. The shelf life of vegetables exposed to fluctuating temperatures can be predicted by calculating the remaining shelf life. This value can be obtained by subtracting the equivalent age of the product, defined as the

**Table 5** Observed Shelf Life (days) of Some Vegetables as a Function of Temperature as Reported by Hardenburg et al. (1986) and Shelf Life Calculated (days) from the $Q_{10}$ Values

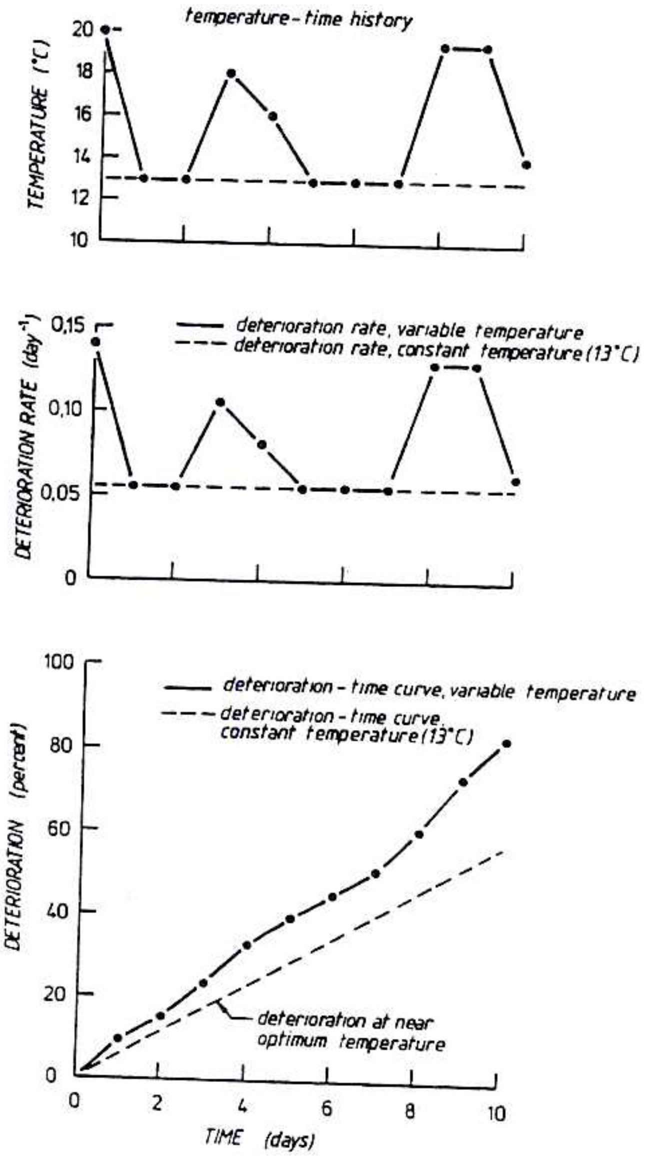

**Figure 2** Deterioration rates for tomatoes at constant and variable temperatures converted to cumulative deterioration-time curves. (Constructed from data of Thorne and Alvarez, 1982; redrawn by Holt et al., 1983)

length of time that would be necessary to bring about the same level of quality if the product had been stored at an isothermal reference temperature, from the total length of time at the reference temperature necessary to cause a change in quality from an initial level to a undesirable threshold. This method has been used successfully to predict the shelf life of mature-green tomatoes (Thorne and Alvarez, 1981; Wells and Singh, 1988).

## D. Bases for New Modeling Developments

The concept of predicting the shelf life of vegetables can be interpreted in many ways. The quality criterion that is chosen to model will depend greatly on the purpose of the simulation. However, modeling the shelf life of a vegetable is a dynamic process that needs to take into account the whole environment to which the product is exposed. Many quality parameters are linked to each other, and modeling only one may lead to a wrong prediction. For this reason, the best approach in the development of a model will be to predict the behavior of many quality parameters simultaneously.

Another aspect in simulation with a nonconstant temperature regime is the environmental effect on the physiological responses of a vegetable. The first is the thermal conductivity of the product itself. During a temperature fluctuation, the product will change its temperature much more slowly than the air temperature. This change will create a lag in the physiological responses and must be integrated into the model. Many other aspects of a typical distribution chain may have significant impacts on physiological responses of a vegetable that may be missed by a strictly temperature-based model. For example, during air shipment, pressurization of the aircraft will create an effect that is similar to that which occurs when a product is vacuum-cooled (Mitchell, 1992). The resulting rapid loss of water may create a stress on the product and induce a response (i.e., wilting) that can be missed by a temperature-based model. Similar observations may be made with regard to vibrations during ground transportation, which also increase water loss by disrupting the layer of high-humidity air (the ''diffusion shell'') that tends to surround individual vegetables.

Modeling the shelf life of a vegetable is a complex process. A temperature-based model can be a very useful tool in predicting vegetable shelf life. However, we should keep in mind that many other parameters may also significantly affect the prediction and, in striving for precision in future modeling efforts, such parameters should be taken into account.

## III. EFFECTS ON PRODUCT QUALITY OF NONCONSTANT TEMPERATURES DURING STORAGE AND TRANSPORT

Some studies have been conducted on the effect of temperatures during transit or retail display conditions on vegetable quality (King et al., 1988; Siomos et al., 1995a), although little work has been reported examining the effects of fluctuating temperatures versus constant temperatures during handling operations on vegetable quality. Thorne and Alvarez (1982) measured the changes in color and firmness of tomatoes during storage in fluctuating temperatures between 12 and 27°C and concluded that those changes were additive and that the total changes were independent of the order of presentation of the various temperatures. Similarly, Nunes and Emond (1999) compared the effect of storage at a constant but higher than optimum temperature for strawberries that can be found in mixed load shipping to storage at an equivalent time temperature regime consisting of

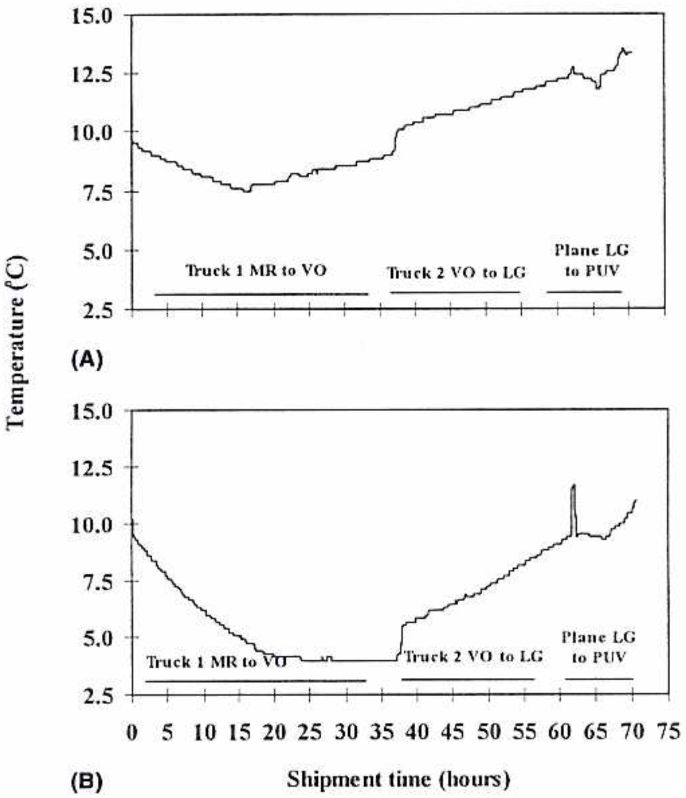

**Figure 3** Temperature profiles in two types of packages for the transport of iceberg lettuce from Montreal (MR) to Val d'Or (VO), from Val d'Or to La Grande (LG), and from La Grande to Puvirnituq (PUV). Standard package (A) or gel packs (B).

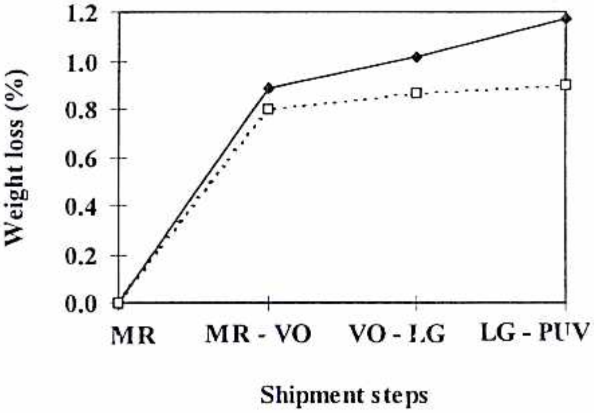

**Figure 4** Influence of temperature on the weight loss of iceberg lettuce transported from Montreal to Puvirnituq. ◆ = Standard package; □ = gel packs.

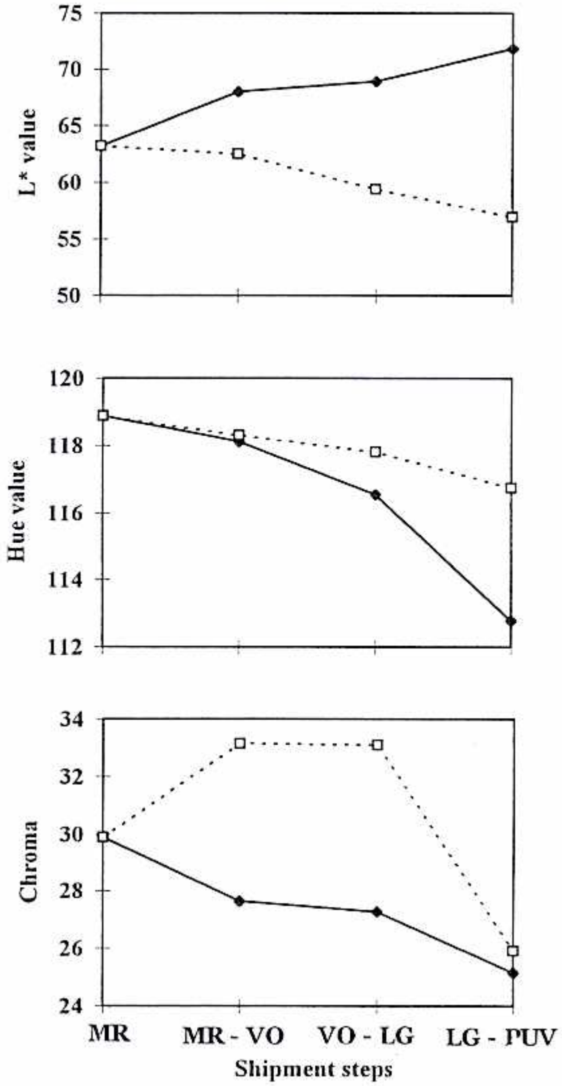

**Figure 5** Influence of temperature on the color of iceberg lettuce transported from Montreal to Puvirnituq. ◆ = Standard package; ☐ = gel packs.

In another study, the effect of fluctuating temperatures on the weight loss and color temperature recommended for storage of lettuce. Those temperatures were, on average, 5.3, 7.4, and 9.8°C during transport in truck 1, truck 2, and in flight, respectively. Although the lettuce was not transported at its optimum temperature, its weight loss when transported at higher temperatures (i.e., packed in the standard package) was higher than the weight loss of the lettuce transported at lower temperatures (i.e., with gel packs) (Fig. 4). In addition, lettuce transported at the higher temperatures developed a dull greenish-yellow color during transport, as shown by higher L* and lower hue and chroma values (Fig. 5). The lettuce transported at the lower temperatures better maintained its initial color, although its color intensity (i.e., chroma) decreased during the final, air transport segment of the postharvest chain, possibly due to water loss (Fig. 5).

For best results in the cold storage of vegetables, it is very important that the temperature during postharvest handling operations be maintained fairly constant. Fluctuations in temperature can often cause condensation of moisture on stored products, which is undesirable because it may favor the growth of surface mold and the development of decay. Furthermore, nonconstant temperatures during storage or transit can cause increased weight loss due to water loss and consequently loss of product quality.

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