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Postharvest Physiology and Quality of Cilantro (*Coriandrum sativum* L.)

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Abstract. **Respiration rates of freshly harvested cilantro were moderately high (CO_2 at 15 to 20 $\mu L \cdot g^{-1} \cdot h^{-1}$) and ethylene production rates were low (<0.2 $nL \cdot g^{-1} \cdot h^{-1}$) at 5 °C and were typical of green leafy tissues. Cilantro stored in darkness at a range of temperatures in air or controlled atmospheres was evaluated periodically for visual quality, decay, aroma, off-odor, color, and chlorophyll content. Cilantro stored in air at 0 °C had good visual quality for 18 to 22 days, while at 5 and 7.5 °C good quality was maintained for about 14 and 7 days, respectively. An atmosphere of air plus 5% or 9% CO_2 extended the shelf-life of cilantro stored at 7.5 °C to about 14 days. Quality of cilantro stored in 3% O_2 plus CO_2 was similar to that stored in air plus CO_2. Atmospheres enriched with 9% to 10% CO_2 caused dark lesions after 18 days; 20% CO_2 caused severe injury after 7 days. Although visual quality could be maintained for up to 22 days, typical cilantro aroma decreased notably after 14 days, regardless of storage conditions.**

Cilantro, also called Chinese parsley or coriander, is an important fresh culinary herb in the United States, widely used in Mexican and Asian cuisines. Quality characteristics of fresh culinary herbs include a fresh appearance; uniformity of leaf size, form and color; characteristic aroma and flavor; and a lack of defects, such as decay or yellowing (Cantwell and Reid, 1993).

Leafy products senesce rapidly at high temperatures (Lipton, 1987; Paull, 1992). Spinach (*Spinacea olearacea* L.) lost ≈65% of its chlorophyll content after 4 days at 25 °C, and ethylene further hastened leaf senescence (Yamauchi and Watada, 1991). Low temperature (0 to 1 °C) retarded the senescence of parsley [*Petroselinum crispum* (Mill.) NYM. ex A.W. Hill] over a 3- to 4-month period, and controlled atmospheres (CA) containing low levels of O_2 and/or elevated levels of CO_2 further extended shelf-life (Åpeland, 1971). Aharoni et al. (1989) observed that modified atmospheres (MA) created inside polyethylene liners from the CO_2 respired by various fresh herbs were effective in retarding yellowing and decay. Yamauchi and Watada (1993) demonstrated the beneficial effect of modified atmospheres on the retention of chlorophyll content in parsley. In addition to its role as an inhibitor of ethylene synthesis and action, CO_2 may also delay senescence by an ethylene-independent mechanism (Philosoph-Hadas et al., 1993).

Postharvest changes of numerous fresh culinary herbs have been reported (Aharoni et al., 1989; Cantwell and Reid, 1993; Hruschka and Wang, 1979; Lange and Cameron, 1994). The quality of most of the fresh culinary herbs is best maintained by low-temperature and high-humidity storage (Cantwell and Reid, 1993). Besides a study on modified atmosphere packaging that included cilantro (Aharoni et al., 1989), to our knowledge, there is no detailed postharvest information about this culinary herb. The objective of this study was to evaluate the effects of temperature, time, and atmosphere composition on the postharvest physiology and quality of cilantro.

Materials and Methods

Freshly harvested cilantro was obtained from commercial fields in May and June in the coastal area near Santa Maria, Calif., and transported in plastic bags in ice-cooled containers (product arrival temperature was 5 °C) to the Mann Laboratory, Davis, Calif., and held overnight at 0 °C. The product was cleaned of damaged leaves, washed in chlorinated water (50 $\mu l \cdot L^{-1}$ NaOCl pH 7), and excess water was removed by manual centrifugation in a salad spinner.

Quantities of 60 g of cilantro were placed as bunches in plastic containers in darkness in temperature controlled (±0.25 °C) rooms at 0 to 20 °C and connected to a humidified air (≈95% relative humidity) flow-through system. The flow rate was calculated to permit accumulation of CO_2 to ≈0.5%. The CO_2 and C_2H_4 concentrations were determined from 1-mL gaseous samples taken from the inlet and outlet ports of the containers and injected on an infrared analyzer and a gas chromatograph equipped with a flame ionization detector, respectively. Standards of 0.5% CO_2 and ethylene at 1 $\mu l \cdot L^{-1}$ were used for calibration. Separate samples of cilantro at 0 and 10 °C were treated with ethylene at 5 $\mu l \cdot L^{-1}$ in air.

For the first CA experiment, samples were stored up to 21 days at 0, 5, or 10 °C in glass containers through which the following humidified atmospheres flowed: air (21% O_2), air containing 10% or 20% CO_2, 3% O_2, and 3% O_2 containing 10% or 20% CO_2. Product quality was evaluated after 7, 14, and 21 days of storage. In the second CA experiment, cilantro was stored up to 22 days at 0, 5, or 7.5 °C in air or in air containing 5% or 9% CO_2. Product was evaluated after 10, 14, 18, and 22 days of storage.

For some storage experiments, commercially packaged cilantro was used. The cilantro was obtained on the day of harvest after it was washed in chlorinated water, dried by centrifugation, and manually packed at 7 °C into bags (low-density polyethylene with 12% ethyl vinyl acetate) containing 85 g each. The bags were placed in polystyrene-lined carton boxes with gel ice and transported to the Mann Laboratory. Bags were stored in carton boxes on shelves at 0, 5, 10, or 15 °C. Liquid silicone patches 1 cm in diameter were applied to the packages to serve as gas sampling ports, and ethylene, oxygen, and carbon dioxide were determined daily as described. Product quality was evaluated after 6 days on two bags per storage temperature. The experiment was repeated once.

The visual quality of the cilantro was scored on a 9 to 1 scale, where 9 = excellent and 1 = unusable (Kader et al., 1973). Typical aroma was evaluated after breaking the stems and was scored on a 5 to 1 scale where 5 = maximum, 4 = near typical, 3 = moderate, 2 = slight and 1 = none. Off-odor was evaluated after breaking the stems and was scored on a 1 to 5 scale, where 1 = none, 2 = slight, 3 = moderate, 4 = moderately severe, and 5 = severe. The defects of discoloration (dark lesions caused by CO_2 injury) and decay were estimated as area percentages of tissue affected.

The color of the adaxial side of the leaves was evaluated on a 5 to 1 scale, where 5 = dark green, freshly harvested, 4 = bright green, 3 = light green with yellowing or browning affecting <5% of leaf area, 2 = light green with noticeable yellowing or browning on 5% to 20% of leaf area or an overall light green appearance, and 1 = light green with >20% yellowing or browning. The leaves in each category were weighed, and an average color score was calculated from the sum of the weight percentage multiplied by the score of each category. Color values were determined with a Minolta Chroma Meter CR-200 (Ramsey, N.J.) calibrated with a green tile (L = 64.96, a = –28.59, b = 8.43). Reflected color as L, a, and b values was determined directly, and hue angle and chroma values were calculated (Gnanasekharan et al., 1992). Leaf samples were frozen at –10 °C for later chlorophyll extraction in acetone (Witham et al., 1971).

The experimental units were bunches and

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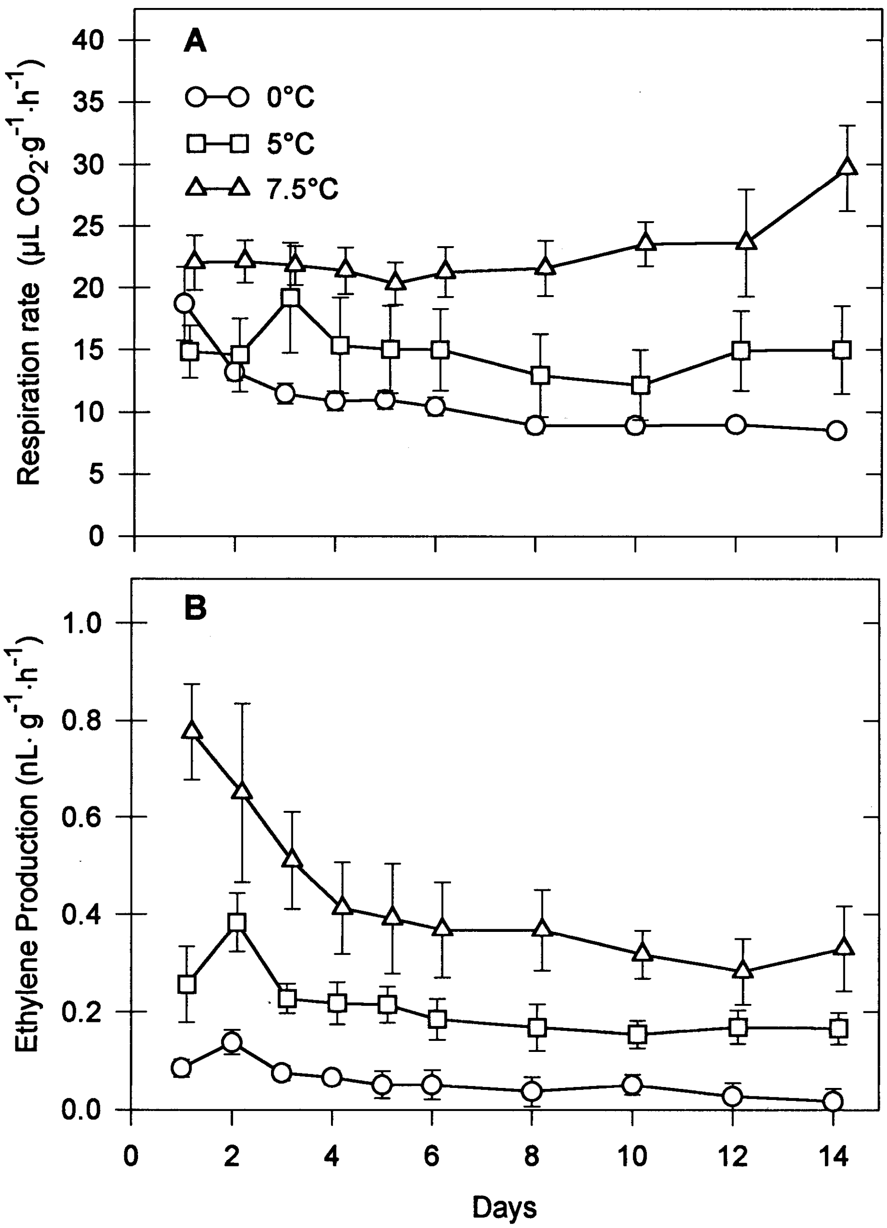

Fig. 1. (A) Respiration rates and (B) ethylene production rates of cilantro stored at 0, 5, and 7.5 °C for 14 days after harvest. Data are the means ± SD of three replications.

three replications per treatment per evaluation period were used in all experiments, except those with commercially packaged cilantro in which duplicates were used. Data were averaged ± standard deviation or were analyzed by analysis of variance with mean separation by Duncan's multiple range test at $P \leq 0.05$.

Results

Storage in air. During the first 7 days of storage in air, average CO_2 production was 11, 15, and 23 $\mu L \cdot g^{-1} \cdot h^{-1}$ at 0, 5, and 7.5 °C, respectively (Fig. 1A). Respiration at 0 and 5 °C declined slowly with time, whereas it remained constant at 7.5 °C and then increased after 12 days, probably due to decay. In another experiment, CO_2 production of cilantro stored at 10 °C averaged 29 $\mu L \cdot g^{-1} \cdot h^{-1}$ over 6 days of storage, with rates increasing after day 4. In cilantro stored at 20 °C respiration rates increased from 70 to more than 95 $\mu L \cdot g^{-1} \cdot h^{-1}$ between day 1 and 3, respectively. Decay was visible at day 4 on cilantro stored at 20 °C.

Average ethylene production rates by cilantro stored 7 days at 0 or 5 °C (Fig. 1B) were low (0.1 and 0.2 $nL \cdot g^{-1} \cdot h^{-1}$, respectively); over the first 7 days at 7.5 and 10 °C, rates averaged 0.5 and 0.7 $nL \cdot g^{-1} \cdot h^{-1}$, respectively. After 14 and 8 days at 7.5 and 10 °C, respectively, ethylene production rates increased notably, probably due to decay. Ethylene production increased dramatically but variably in leaves stored at 20 °C (1 to 3 $nL \cdot g^{-1} \cdot h^{-1}$) for up to 3 days.

Respiration rates were not affected by an exposure to ethylene at 5 $\mu l \cdot L^{-1}$ at 0 and 10 °C (data not shown), but ethylene did accelerate deterioration at 10 °C after 6 days (lower visual quality, a 10% to 15% decrease in chlorophyll concentration, and more decay than air-stored cilantro). At 0 °C there were no differences in visual quality or chlorophyll concentration between the ethylene or air-stored product after 6 days.

The color scale does not represent a linear change in leaf color, but rather emphasizes marketable (color scores of 4 and 5) and unmarketable (color scores of 1 and 2) color ranges. Cilantro of color score 3 might still be sold, although it was of inferior visual quality. As cilantro greenness decreased, the L, b, and chroma values increased and the a and hue values decreased (Table 1). The chlorophyll concentration of cilantro with a score of 3 differed little from that with a score of 2. As cilantro leaves senesced, chlorophyll *a* decreased more than chlorophyll *b*, and the ratio of *a* to *b* decreased from 3:1 in the dark green leaves to 2.4:1 in the yellowed leaves. Freshly harvested cilantro had an average color score of 4.4, and a total chlorophyll concentration of 1.9 $mg \cdot g^{-1}$ fresh mass.

The dramatic effect of temperature on the deterioration rate of cilantro was documented over the range of 0 to 20 °C. Commercially packaged cilantro stored at 20, 15, and 10 °C typically began to yellow within 3, 6, and 8 days, respectively (data not shown). The desirable dark green of cilantro was maintained at low temperature. The chlorophyll concentration of leaves stored at 20 °C in air decreased 50% after 4 days, whereas there was no change during 4 days at 0 or 5 °C. Low temperatures also retarded decay development and helped maintain typical aroma. The importance of storage temperature on these important quality criteria is illustrated by the changes in commercially packaged cilantro stored 6 days at 0, 5, 10, or 15 °C (Fig. 2). Visual quality, aroma and color scores decreased with increasing storage temperature and decay followed the reverse pattern. Although visual quality and color scores of cilantro stored at 0 °C were excellent, aroma scores had decreased and were similar to those of cilantro stored at 5 °C.

CA storage. There was little difference in the visual quality of cilantro stored 7 days at 0, 5, or 10 °C in air or 3% O_2 containing 0%, 10%, or 20% CO_2, with the exception of the air-stored cilantro at 10 °C, which showed significant deterioration (data not shown). After 14 days few differences were noted among the 0 and 5 °C samples, but by 21 days, the quality of samples stored at 0 °C was notably better. The quality of cilantro stored in air or in 3% O_2 at the three temperatures was similar. In addition, no consistent differences were found in cilantro quality following storage with CO_2 in air or in 3% O_2 over the 21-day storage period.

The atmospheres containing 20% CO_2 resulted in severe injury (17%, 38%, and 18% of the product showed injury at 0, 5, and 10 °C, respectively), whereas those containing 10% CO_2 showed only slight discoloration (2% of the leaves were affected) after 14 days. No injury was induced by 10% or 20% CO_2 during 7 days of storage. Carbon dioxide injury was manifested as discrete darkened spots on the leaves which then coalesced into large black-brown areas; it was distinct from decay, which appeared as amorphous dark brown areas.

Table 1. The relationship between subjective color scores and the objective measurement of color values and chlorophyll concentration of cilantro leaves.[z]

Color score	Color values L	a	b	Hue angle	Chroma	Chlorophyll concn ($mg \cdot g^{-1}$, fresh mass) chl *a*	chl *b*	total chl
5	27.6 ± 0.9	−22.9 ± 0.7	14.3 ± 0.4	148.1	27.0	1.95	0.66	2.60
4	32.1 ± 0.5	−27.3 ± 0.3	20.3 ± 1.0	143.4	34.0	1.20	0.41	1.61
3	34.8 ± 0.7	−29.5 ± 0.4	25.6 ± 0.7	139.0	39.1	0.66	0.25	0.91
2	37.6 ± 0.5	−30.6 ± 0.6	29.6 ± 1.4	135.9	42.6	0.57	0.24	0.81
1	42.8 ± 0.2	−30.6 ± 0.9	35.1 ± 1.4	131.1	46.2	0.22	0.09	0.31

[z]Five individual leaves representative of each color score were used to obtain the color values and then were extracted for chlorophyll determination.

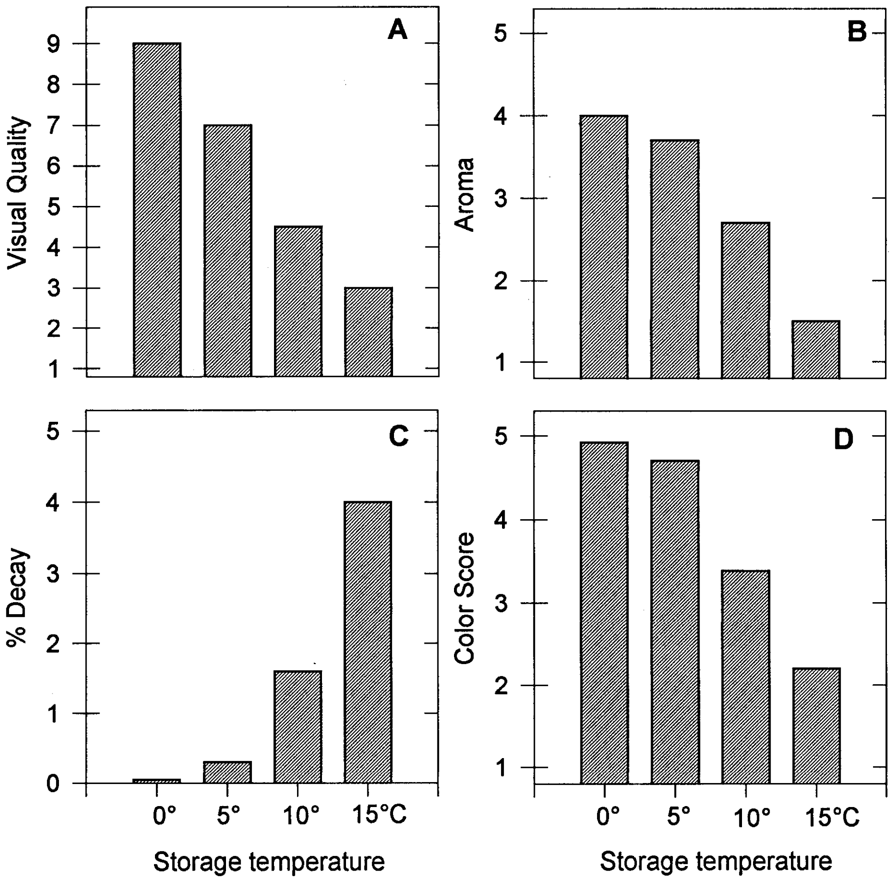

Fig. 2. (**A**) Visual quality, (**B**) aroma, (**C**) decay, and (**D**) color score of cilantro commercially packed in sealed plastic bags and stored 6 days at one of four temperatures. The average O_2 concentrations inside the bags were 17%, 16%, 12%, and 12% at 0, 5, 10, and 15 °C, respectively. The corresponding average CO_2 concentrations were 3%, 3%, 5%, and 5%; and the average corresponding C_2H_4 concentrations were 0.3, 0.2, 0.6, and 0.6 $\mu l \cdot L^{-1}$. Visual quality was scored on a 9 to 1 scale, where 9 = excellent and 1 = unuseable; aroma was scored on a 5 to 1 scale, where 5 = full typical and 1 = none; decay was calculated as the weight percentage of product with macroscopic decay; and color score was calculated from the weight percentage of leaves in each of five categories, where 5 = dark green, and 1 = yellow. Data are the means of duplicate samples.

Temperature greatly affected the visual quality of cilantro stored in air or in air containing 5 or 9% CO_2 at 0, 5, or 7.5 °C for up to 22 days (Table 2). Product stored in air at 0 or 5 °C had excellent visual quality at day 10. Product stored at 7.5 °C in 5 or 9% CO_2 had higher quality than product stored in air at day 10 and 14.

The high CO_2 atmospheres helped maintain green pigmentation, especially during storage at 7.5 °C (Table 2). At 0 °C, however, greenness was retained in cilantro from all treatments up to day 18. At day 18%, 3%, and 8% of the leaves stored in 5% and 9% CO_2 atmospheres, respectively, showed CO_2 injury at 0 °C. Although CA at 0 °C provided some benefit to color retention after 22 days of storage, CO_2 injury was present on 14% of the leaves and overall visual quality was lower than that of air-stored cilantro. The cilantro with the highest visual quality after 22 days was that stored in air at 0 °C.

Macroscopic decay was greatly retarded by low-temperature storage. At 0 and 5 °C, decay was first observed at 18 and 14 days, respectively (Table 2). Decay was first observed on product stored in air at 7.5 °C on day 10. High CO_2 atmospheres at 7.5 °C retarded decay, with 9% being more effective than 5% CO_2. Carbon dioxide-enriched atmospheres had no material effect on decay development during storage at 0 or 5 °C.

Cilantro aroma was maintained during 10 days of storage at 0 and 5 °C (Table 2). A lower aroma score at 7.5 °C was associated with an increase in off-odor score (data not shown). After 14 days of storage, aroma scores for all samples had decreased. By 22 days, typical cilantro aroma was lacking in all treatments, even those effective in preserving visual quality. The loss of characteristic aroma was similar for air and CA-stored product.

Discussion

The respiration rates of cilantro can be classified as moderately high and similar to those of other green leafy vegetables (Hardenburg et al., 1986). The average Q_{10} value for cilantro respiration over the 0 to 10 °C range was 3.3, a value similar to those reported for a wide range of fresh culinary herbs, but lower than that reported for other herbs of the family Apiaceae (Cantwell and Reid, 1993). The low ethylene production rates of cilantro were similar to those reported for other fresh culinary herbs stored at low temperatures (Cantwell and Reid, 1993). High ethylene production rates of cilantro at 15 and 20 °C are typical for rapidly senescing leaves (Aharoni et al., 1979; Paull, 1992).

Exogenous ethylene mainly accelerated yellowing in cilantro, a response similar to that of parsley which is considered among the more ethylene sensitive culinary herbs (Cantwell and Reid, 1993). Acceleration of chlorophyll loss by postharvest ethylene exposure has been well documented in a wide range of green tissues (Paull, 1992; Yamauchi and Watada, 1991), although it may not be demonstrable during rapid senescence at high temperature (Yamauchi and Watada, 1993).

The temperature response of stored cilantro is similar to that of other fresh herbs of the family Apiaceae (Åpeland, 1971; Cantwell and Reid, 1993; Hruschka and Wang, 1979) and of green leafy vegetables in general (Lipton, 1987; Paull, 1992). Chlorophyll degradation occurred rapidly at warm temperatures and could be greatly delayed with low temperature and/or controlled-atmosphere storage. The average ratio of chl *a* to chl *b* (2.6:1) and total chlorophyll concentration of cilantro were similar to values reported for other dark green leafy tissues (Gross, 1991). The decrease in the ratio of chl *a* : chl *b* with color loss in cilantro is considered typical during leaf senescence (Gross, 1991). The L, a, b, hue, and chroma values changed progressively in cilantro leaves varying from dark green to yellow. During senescence, the pattern of change in color values can differ among vegetables, and changes in cilantro color values were distinct from those reported for broccoli (*Brassica oleracea* L., Botrytis Group) and spinach (Gnanasekharan et al., 1992).

Atmospheres containing 5% to 10% CO_2 effectively retarded color loss and decay development in cilantro stored at intermediate temperature (7.5 °C). Beneficial CO_2 concentrations for the storage of numerous green vegetables typically range from 5% to 10% (Saltveit, 1993). Aharoni et al. (1989) reported

Table 2. Quality characteristics of cilantro stored at three temperatures in air or air containing 5% or 9% CO_2.

Quality criterion and temp (°C)	Duration of storage (days) 10			14			18			22		
	Atmosphere											
	Air	+5% CO_2	+9% CO_2	Air	+5% CO_2	+9% CO_2	Air	+5% CO_2	+9% CO_2	Air	+5% CO_2	+9% CO_2
Visual quality (rating)[z]												
0	9.0 a[y,x]	9.0 a	9.0 a	9.0 a	9.0 a	9.0 a	9.0 a	7.5 bc	6.7 d	7.8 a	5.7 bc	6.7 b
5	9.0 a	9.0 a	9.0 a	7.0 c	7.8 b	9.0 a	7.0 cd	6.7 d	8.0 b	4.3 d	4.7 cd	5.0 cd
7.5	4.7 b	8.8 a	9.0 a	3.7 d	7.0 c	8.0 b	1.0 f	1.7 e	2.0 e	1.0 f	1.3 f	3.0 e
Greenness (%)[w]												
0	98 a	98 a	99 a	94 a	99 a	99 a	88 ab	91 a	92 a	81 c	85 b	90 a
5	98 a	98 a	98 a	74 d	88 b	95 a	77 c	82 bc	94 a	56 e	80 c	88 ab
7.5	81 c	92 b	96 ab	54 e	80 c	88 b	10 e	69 d	81 c	3 g	47 f	75 d
Discoloration (%)[v]												
0	0	0	0	0	0	0	0 e	2 d	10 ab	0 e	6 c	13 b
5	0	0	0	0	0	0	0 e	2 d	8 bc	0 e	8 c	12 b
7.5	0	0	0	0	0	0	0 e	7 c	12 a	0 e	12 b	17 a
Decay (%)[u]												
0	0 b	0 b	0 b	0 c	0 c	0 c	1 d	2 d	1 d	2 e	8 cd	3 de
5	0 b	0 b	0 b	2 bc	0 c	0 c	1 d	1 d	1 d	8 cd	8 cd	5 c–e
7.5	2 a	0 b	0 b	14 a	3 b	1 bc	28 a	12 b	7 c	52 a	23 b	10 c
Aroma (rating)[t]												
0	5.0 a	4.7 ab	4.7 ab	4.0 a	3.3 ab	3.3 ab	2.3 a	2.0 ab	1.3 b	2.0 a	1.3 ab	1.2 b
5	5.0 a	5.0 a	4.3 bc	3.7 a	3.0 ab	3.0 ab	2.0 ab	2.0 ab	1.7 ab	1.5 ab	2.0 a	1.0 b
7.5	4.0 c	4.0 c	4.0 c	3.0 ab	2.3 b	2.3 b	1.3 b	1.7 ab	1.3 b	1.0 b	1.0 b	1.5 ab

[z]Visual quality was assessed on a scale, where 9 = maximum, excellent quality, 7 = good quality, 5 = fair, 3 = poor, and 1 = unuseable.
[y]Mean separation for a given quality criterion and storage duration by Duncan's multiple range test at $P \leq 0.05$.
[x]Data are means of three replications.
[w]Percent greenness was calculated from the summation of leaves with color scores of 4 and 5.
[v]Percent discoloration refers to the proportion of leaves showing dark spots due to CO_2 injury.
[u]Percent decay was calculated as the percentage by mass of product showing any visible decay symptoms.
[t]Aroma was evaluated after the stems were broken on a scale, where 5 = maximum typical aroma, 4 = near typical, 3 = moderate, 2 = slight, and 1 = none.

that 5% to 10% CO_2 retarded yellowing of fresh cilantro and dill (*Anethum graveolens* L). Color loss in parsley was reduced with low O_2 levels in combination with elevated CO_2 concentrations (Åpeland, 1971). This response to CO_2 is typical of many dark green leafy tissues (Aharoni et al., 1989; Saltveit, 1993; Wang, 1990). The fungistatic effect of CO_2 on cilantro is similar to that reported for a wide range of horticultural products (Barkai-Golan, 1990). It is possible that cilantro may benefit from CA with O_2 levels below 3% as used by us. Recommended atmospheres for a broad range of green leafy vegetables may contain from 1% to 3% O_2 (Saltveit, 1993).

The composition of aroma volatiles that impart the unique pungent flavor to cilantro has been described (Potter and Fagerson, 1990). Presumably the decrease in cilantro aroma scores with low temperature air and CA storage is due to changes in the concentrations of aroma volatiles, but this requires evaluation. Low-temperature CA storage of fruits can result in reduced capacity to generate aroma volatiles (Wang, 1990).

Summary

Cilantro provides another example of the importance of low temperatures for reducing respiration and retarding senescence of nonchilling sensitive green leafy tissues. Cilantro with very good visual quality was maintained for 18 to 22 days at 0 °C, 12 to 14 days at 5 °C, 7 to 8 days at 7.5 °C, and only 4 to 5 days at 10 °C. Aroma quality, paramount to the culinary value of the herb, usually decreased before visual quality decreased. Controlled atmospheres with 5% to 10% CO_2 were beneficial to retaining color and visual quality when cilantro was stored at intermediate temperature (7.5 °C). High CO_2 concentrations (20%) or prolonged exposure (>2 weeks) to moderate CO_2 levels caused injury and should be avoided. We conclude that the best postharvest conditions for cilantro are low temperature and high humidity storage in air. Under these conditions, a shelf-life of ≈14 days can be expected if aroma is considered an important attribute.

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