Available online at www.sciencedirect.com
SCIENCE DIRECT
Postharvest Biology and Technology 40 (2006) 269–278
Postharvest Biology and Technology
www.elsevier.com/locate/postharvbio

Combined effects of 1-methylcyclopropene, calcium chloride dip, and/or atmospheric modification on quality changes in fresh-cut strawberries

E. Aguayo [a,*], R. Jansasithorn [b], A.A. Kader [c]

[a] *Postharvest and Refrigeration Group, Department of Food Engineering, Technical University of Cartagena, Po Alfonso XIII, 48, 30203 Cartagena, Murcia, Spain*
[b] *Division of Postharvest Technology, King Mongkut's University of Technology, Thonburi, Bangkok, Thailand*
[c] *Department of Plant Sciences, University of California, One Shields Ave., Davis, CA 95616, USA*

Received 4 January 2006; accepted 24 January 2006

Abstract

The aim of this study was to determine the effects of 1-methylcyclopropene, 1-MCP (1 μL L^{-1} for 24 h at 5 °C) on quality attributes and shelf life of fresh-cut strawberries. The 1-MCP was applied before (whole product) and/or after cutting (wedges), followed by storage in a continuous flow of air or air +1 μL L^{-1} C_2H_4. The combined effects of 1-MCP and $CaCl_2$ dips (1% for 2 min) and/or CA (3 kPa O_2 + 10 kPa CO_2) were also examined. The application of only 1-MCP before and/or after cutting did not have a significant effect on firmness and appearance quality during storage for up to 12 days at 5 °C. The exposure to a continuous flow of 1 μL L^{-1} C_2H_4 in air during storage did not increase the softening rate. 1-MCP applied before cutting or both before and after cutting of the strawberries increased respiration rates but reduced C_2H_4 production rates. Exposure to 1-MCP had a synergistic effect when combined with $CaCl_2$ plus CA. The combined treatment of 1-MCP + $CaCl_2$ + CA slowed down softening, deterioration rates, TA and microbial growth. Compared to the control, which had a 6-day shelf life, the shelf life of fresh-cut strawberries subjected to the combination treatment was extended to 9 days at 5 °C.

Keywords: Quality; Firmness; Ethylene; Respiration rate; Fresh-cut strawberries; Microbial counts; Calcium

1. Introduction

Fresh strawberries are a good source of ascorbic acid and phenolic compounds but their quality declines rapidly after harvest. Wills and Kim (1995) reported that 0.01 μL L^{-1} ethylene reduced the storage life of whole strawberries at 0 °C. Fruit color development and softening were slightly accelerated by C_2H_4 (Tian et al., 2000). 1-Methylcyclopropene (1-MCP) inhibits ethylene action by blocking its receptor for extended periods (Blankenship and Dole, 2003). Ku et al. (1999) found that treatment with 5–15 nL L^{-1} 1-MCP extended the postharvest life of strawberry fruit through a delay in rotting. Jiang et al. (2001) found that exposure of strawberries to 0.01–1.0 μL L^{-1} of 1-MCP at 20 °C slowed loss of firmness, color changes and lowered ethylene production and increased anthocyanin and phenolic contents. Tian et al. (2000) also reported that 2.0 μL L^{-1} 1-MCP reduced softening, color changes, and respiration rates of early harvested strawberries, but had less effect on late harvested fruit; 1-MCP treatment had only a small effect on total storage life. Treating strawberries with 1-MCP is likely to be a cost-effective method of extending storage life (Bower et al., 2003).

The 1-MCP effect on fresh-cut fruit is variable. For example, the application of this compound in fresh-cut apples decreased the ethylene production, respiration, softening, color change and synthesis of aroma compounds (Jiang and Joyce, 2002; Bai et al., 2004; Calderón-López et al., 2005). In pineapple, 1-MCP decreased respiration, browning, loss of visual quality, lightness and ascorbic acid (Budu and Joyce, 2003). Vilas-Boas and Kader (personal communication) found different responses in firmness, color and CO_2 and C_2H_4 production depending on the timing

* Corresponding author. Tel.: +34 968 325750; fax: +34 968 325435.
E-mail address: encarna.aguayo@upct.es (E. Aguayo).

0925-5214/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.postharvbio.2006.01.016

of 1-MCP application to kiwifruit, persimmon, and mango before (whole fruit) and after cutting (slices).

Other treatments such as $CaCl_2$ dips or controlled atmospheres (CA) can help maintain firmness and visual quality resulting in a longer shelf life of the fresh-cut products. $CaCl_2$ dips retarded flesh softening in fresh-cut strawberry (Morris et al., 1985; Rosen and Kader, 1989), and elevated CO_2 atmospheres can slow down the softening rate of strawberries (Holcroft and Kader, 1999).

The aim of this study was to determine the potential of using 1-MCP (1 $\mu L\,L^{-1}$ for 24 h at 5 °C) before and/or after cutting for extending the shelf life of fresh-cut strawberries. Also, the combined effects of 1-MCP with $CaCl_2$ dips and atmospheric modification were investigated.

2. Material and methods

2.1. Material, slice preparation and treatments

In this study, three consecutive experiments were performed choosing the best treatments in each one. Strawberries ('Camarosa' or 'Seascape' cultivars) from Watsonville, California were obtained and used in the experiments within a day of harvest. The berries were sorted to remove damaged and defective fruit and those with less than 3/4 red surface color or over-ripe (dark red and soft).

In the first experiment, 'Camarosa' strawberries were treated with 1-MCP before cutting (bc), after cutting (ac) and, both before and after cutting (bc + ac). The calyx was cut off from the whole strawberry and fruit was cut vertically with a sharp knife into four wedges. The wedges were collected in a container and washed in cool (8 °C) water plus NaOCl (1.3 mM) for 2 min. A ratio of 5 L water per kilogram fresh-cut wedges was used. Then the wedges were drained in a colander, and dried with a cheesecloth and blotting paper. After that, wedges (100 g) were placed into 0.5 L glass jars. 1-MCP (1 $\mu L\,L^{-1}$ for 24 h at 5 °C) was applied to whole and/or fresh-cut fruit. Finally, all fresh-cut strawberries inside the jars were ventilated with humidified air flow (0.17–0.24 $mL\,s^{-1}$) with or without a 1 $\mu L\,L^{-1}$ C_2H_4 for 12 days at 5 °C.

In the second experiment, 1-MCP (1 $\mu L\,L^{-1}$ for 24 h at 5 °C) was applied to whole 'Seascape' strawberries before cutting into wedges as described in the first experiment. Calcium chloride (1%, w/v; Sigma–Aldrich) was added to the chlorinated water in which wedges were dipped for 2 min. All jars were ventilated with a humidified flow (0.17–0.24 $mL\,s^{-1}$) of air or a CA of 3 kPa O_2 plus 10 kPa CO_2 for 12 days at 5 °C.

In the third experiment, the best two treatments obtained from the second experiment ($CaCl_2$ + CA and 1-MCP + $CaCl_2$ + CA) were tested using 'Seascape' strawberries.

In all experiments, three replicates per treatment were used and evaluations were made every 3 days for up to 12 days at 5 °C. Rates of CO_2 and C_2H_4 production, firmness, color and visual quality were measured in the first two experiments. In the third experiment, firmness, skin color, taste and visual quality, soluble solids content (SSC), titratable acidity (TA) and microbial counts were determined.

2.2. Respiration and ethylene production rates

An infrared CO_2 analyzer (model PIR-2000R, Horiba Instruments, Irvine, CA) was used for CO_2 measurements in the exit air from the jars. A gas chromatograph (model 211 Carle Instruments, Anaheim, CA) with FID detector and alumina column was used to determine ethylene concentration in air samples taken from the exit air flow from the jars.

2.3. Quality evaluation

All quality evaluation procedures were performed at about 20 °C. Firmness of wedges was determined with a TA-XT Plus texture analyzer (Stable Micro System, Scarsdale, NY). Firmness of 12 wedges per replicate was determined, as the force required for a 3-mm tip to penetrate the widest part of the shoulder of the cut surface to a depth of 5 mm.

A Minolta Chroma Meter, model CR-200 (Minolta Corp, Ramsay, NJ), was used to evaluate color. It was calibrated with a white plate before use. The $L^*a^*b^*$ color space was used. Skin color was evaluated in the same location as the firmness measurements were made and flesh color was made in the center of the widest internal part. One side of each of 12 wedges per replicate was measured as skin or external color and 24 slices were taken for measuring the flesh or internal color.

A panel of three trained judges (two women and one man) scored the taste and visual quality of a representative sample on day 0 and after 3, 6, 9 and 12 days of storage. The samples were coded with three-digit numbers to mask the treatment identity in an effort to minimize the test subjectivity and ensure test accuracy. For each treatment a sample of 15 wedges was presented. Ratings were based on a 9-point hedonic scale, where 9 = excellent, freshly cut; 7 = very good; 5 = good, limit of marketability; 3 = fair, limit of usability; and 1 = poor, unusable.

Juice samples were obtained by squeezing half of the fruit slices from each replicate through four layers of cheesecloth with a hand juicer. Soluble solids content (SSC) of the juice was measured with an Abbé Refractometer, model 10450 (American Optical, Buffalo, NY) and expressed as a percentage. An automatic titrator (Radiometer, Copenhagen, Denmark) equipped with a PHM85 Precision pH meter, ABU80 Autoburette, PRS12 Alpha printer and a SAC80 sample changer was used to measure pH and titrable acidity (TA). A 4-g juice sample per replicate was diluted with 20 mL distilled water and titrated with 0.1N NaOH to pH 8.1. TA was calculated as percent citric acid (predominant acid in strawberries).

2.4. Microbial growth

To determine their microbial quality, random 10-g samples of strawberry wedges were homogenized for 2 min in 10 mL of sterile buffered peptone water (Difco, Sparks, MD), with a Seward 400 Lab Stomacher (Tekmar, Cincinnati, OH). Dilutions were made in 0.1% peptone water (Hardy Diagnostics, Santa Maria, CA) as needed for plating. The enumeration of particular microbial groups was performed by using the following media and culture conditions: Tryptic Soy Agar (Difco, Sparks, MD) for psychrotrophic aerobic bacteria, incubated at 7 °C for 7 days. Potato Dextrose Agar (Difco, Sparks, MD) with added streptomycin and acidified to pH 3.5 with 10% L-tartaric acid (Fisher, Fair Lawn, NJ), incubated at 29 °C for 2 and 5 days, respectively. All microbial counts were reported as log cfu g^{-1} (colony forming units per gram of sample).

2.5. Statistical analysis

A bifactorial model (time of storage × kind of treatment) ANOVA was applied and, when interactions were significant, the mean values were compared by an LSD multiple range test. The SigmaStat 2.0 statistical software was used.

3. Results and discussion

3.1. Experiment I. Effects of 1-MCP treatment before and/or after cutting and storage with or without 1 μL L^{-1} C_2H_4 in air

During the first 6 days, strawberry wedges in the 1-MCP (bc + ac) and 1-MCP (bc) treatments exhibited higher respiration rates compared to those in the control and 1-MCP (ac) treatments. However, from day 7 onward, no significant differences were found among treatments (Fig. 1). On the other hand, strawberry wedges from the control and the MCP (ac) treatments had higher C_2H_4 production rates than the 1-MCP (bc) and 1-MCP (bc + ac) treatments during the last 3 days of storage (Fig. 1). Control fruit produced the highest C_2H_4 levels on days 6 and 7, but remained below 250 nL kg^{-1} h^{-1}. Tian et al. (2000) found 1-MCP inhibited the C_2H_4-induced respiratory increase in early-harvested fruit, but not late-harvested whole strawberries. However, Bower et al. (2003) observed that 1-MCP treatment (0.01, 0.1 or 1.0 μL L^{-1}) reduced C_2H_4 production and the increased emission of CO_2 by 1-MCP treated whole strawberry was associated with the earlier onset of rots. In fresh-cut fruit, Vilas-Boas and Kader (personal communication) found a higher C_2H_4 production rate by persimmon slices made from 1-MCP-treated fruit than the control, and similar production rates between control and 1-MCP (ac)-treated slices. In kiwifruit and mango, 1-MCP treatments before or after cutting reduced the C_2H_4 production during the last 3 days in comparison with the control. Jiang and Joyce (2002) observed a slightly reduced respiration rate in response to 1-MCP treatment before and after cutting of apple slices compared to control slices, but a markedly reduced ethylene production when 1-MCP (1 μL L^{-1} for 6 h) was applied before cutting. Similar results were reported by Perera et al. (2003) in 'Braeburn' or by Rupasinghe et al. (2005) in 'Empire' and 'Crispin' apple slices made from 1-MCP-treated fruit. Budu and Joyce (2003) found that 1-MCP reduced respiration rate of pineapple slices. These results show no pattern when climacteric or non-climacteric fresh-cut fruit are 1-MCP treated. In agreement with our results, 1-MCP reduced C_2H_4 in fresh-cut kiwifruit, mango and apple as in whole strawberry when treated before cutting and a lower CO_2 production when fresh-cut apple and pineapple were 1-MCP treated after cutting.

There was no significant 1-MCP treatment effect on softening rates of strawberry wedges, as Budu and Joyce (2003) found in fresh-cut pineapple. It ranged between 2.2 and 2.8 N (data not shown). In contrast, Vilas-Boas and Kader (personal communication), Jiang and Joyce (2002) and Perera et al. (2003) observed that 1-MCP was effective in delaying the softening of fresh-cut persimmon and apple slices when applied on intact fruit before processing. Jiang et al. (2001) also found that exposure of whole strawberries to 0.01–1.0 μL L^{-1} 1-MCP at 20 °C slowed loss of firmness. In addition, 1-MCP delayed the softening of mango slices when applied after processing, and of kiwifruit slices when applied either before or after processing (Vilas-Boas and Kader, personal communication).

Exposure to a continuous flow of C_2H_4 (1 μL L^{-1}) in air did not increase the softening rate of strawberry wedges (data not shown). For example, in control wedges in air the firmness was 2.4 N compared to 2.5 N in control wedges stored in C_2H_4. Similarly, Tian et al. (2000) did not detect any difference in firmness between C_2H_4 or 1-MCP plus C_2H_4 treated whole strawberry fruit. They reported 1-MCP at 2 μL L^{-1} gave greater firmness loss than no treatment. Porat et al. (1999) found orange softening was not affected by 1-MCP or C_2H_4.

A slight red color darkening (higher *a*/*b* ratio) was significantly greater in control wedges kept in air which had highest C_2H_4 levels on days 6 and 7 in storage (Fig. 1), than those from the treatments with 1-MCP (bc) kept in air with or without C_2H_4 and 1-MCP (bc + ac) kept in air (Table 1). Exogenous C_2H_4 did not accelerate red color development as reported by Tian et al. (2000) on whole strawberries. Skin luminosity (L^*) increased with time of storage (data not shown). It ranged between 33.90 and 37.50. 1-MCP with or without C_2H_4 treatments did not influence these color changes. Changes in *a*/*b* ratio and L^* values of flesh color were not correlated consistently with internal browning. Nevertheless, the interaction of time and 1-MCP treatment was significant for both the *a*/*b* ratio and L^* color parameters (Table 1). Other authors reported that 1-MCP reduced color changes in fresh-cut apple, pineapple,

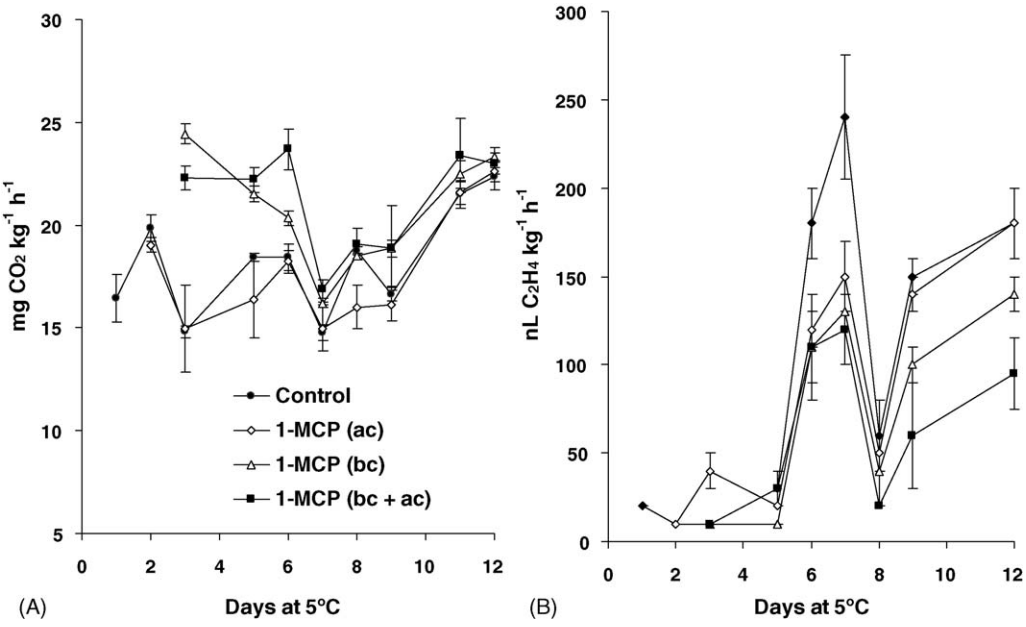

Fig. 1. Respiration rates (A) and ethylene production (B) of fresh-cut 'Camarosa' strawberries treated with 1-MCP (1 μL L^{-1} for 24 h at 5 °C) before (bc) and/or after (bc + ac, ac) cutting and kept under a continuous flow of humidified air at 5 °C. Means of three replicates ± S.E.

persimmon and mango (Jiang and Joyce, 2002; Budu and Joyce, 2003; Perera et al., 2003; Vilas-Boas and Kader, personal communication) but did not affect the color (L^*) of kiwifruit slices (Vilas-Boas and Kader, personal communication).

Visual qualities of strawberry wedges decreased with time of storage and no effects of 1-MCP treatments with or without C_2H_4 were observed. In contrast, Able et al. (2003) found 1-MCP (1 μL L^{-1}) treatment significantly protected minimally processed leafy Asian vegetables in the presence of C_2H_4. Ku et al. (1999) and Tian et al. (2000) reported that when strawberry fruit were treated with 1-MCP and then exposed to an exogenous application of C_2H_4, the effects were dependent on fruit maturity and 1-MCP concentration. However, 1-MCP was also found to extend strawberry postharvest life in the absence of exogenous C_2H_4 (Jiang et al., 2001). In this experiment, highest visual quality after 9 days at 5 °C was observed in the 1-MCP (bc) strawberry wedges kept in air (Table 1). That treatment and 1-MCP (ac) in air were the only ones scored above the limit of marketability. After 12 days at 5 °C, strawberry wedges in all treatments were scored under the limit of marketability, indicating a shelf life shorter than 12 days.

No clear advantages were found when strawberries were 1-MCP-treated before, after or both before and after cutting. A lower C_2H_4 emission, red color darkening and a higher but not significant appearance quality was found in 1-MCP-treated strawberries before cutting. In addition, it is more practical to treat whole strawberries on a commercial scale. This timing of 1-MCP application was chosen for the next experiment.

3.2. Experiment II. Effect of combined treatments with $CaCl_2$, CA and/or 1-MCP (before cutting)

Strawberry wedges in the control, 1-MCP, and $CaCl_2$ treatments showed similar respiration rates, but the combination of 1-MCP and $CaCl_2$ dip slowed down the CO_2 production (Fig. 2). C_2H_4 production rates were similar among all treatments during the first 5 days at 5 °C. Subsequently, the control and $CaCl_2$ treated wedges had higher C_2H_4 production rates than wedges exposed to 1-MCP, with or without a $CaCl_2$ dip (Fig. 2). This may have been due in part to possible microbial growth and general deterioration of the tissue due to senescence in these treatments. As in our results, lower ethylene production rates and a firmer tissue was obtained in apple slices prepared from whole 1-MCP (1 μL L^{-1} for 24 h) treated 'Delicious', 'Empire' and 'Idared' fruit (Calderón-López et al., 2005) or 'Gala' apples (1-MCP; 1 or 0.625 μL L^{-1} for 18 h) (Bai et al., 2004).

The best four treatments for getting good firmness retention of strawberry wedges were (lower to higher) 1-MCP + $CaCl_2$, $CaCl_2$ + CA, CA, and, particularly those treated with 1-MCP plus $CaCl_2$ plus CA (Table 2). The synergistic effect among 1-MCP, $CaCl_2$, and CA on firmness retention was similar to what has been reported for kiwifruit slices (Vilas-Boas and Kader, personal communication).

Firmness was improved by the $CaCl_2$ dip. Calcium dips have been used as firming agents to extend postharvest shelf life in whole and in fresh-cut fruit. Rosen and Kader (1989) found that the $CaCl_2$ treated slices of strawberries resulted in higher calcium content and they were firmer than water-dipped slices. Luna-Guzmán and Barret (2000) also found $CaCl_2$ maintained the firmness throughout storage and less

Table 1
Firmness, color and appearance quality (means of three replicates) of fresh-cut 'Camarosa' strawberries treated with 1-MCP (1 μL L^{-1} for 24 h at 5 °C) and stored in air or air + 1 μL L^{-1} C_2H_4 at 5 °C

Days at 5 °C	1-MCP treatment	Skin color	Flesh color		Appearance score
		a/b	L^*	*a/b*	(1–9)
0		1.73	50.14	1.06	8.5
3	Control + air	1.74	51.87	1.07	5.7
	1-MCP (bc) + air	1.61	53.22	1.02	5.3
	1-MCP (ac) + air	1.70	51.71	1.07	6.0
	1-MCP (bc + ac) + air	1.62	50.72	1.06	6.3
	Control + C_2H_4	1.71	52.03	1.06	4.3
	1-MCP (bc) + C_2H_4	1.50	52.60	1.07	7.0
	1-MCP (ac) + C_2H_4	1.81	52.54	1.08	5.3
	1-MCP (bc + ac) + C_2H_4	1.71	51.68	1.06	7.3
6	Control + air	1.75	52.24	1.09	5.7
	1-MCP (bc) + air	1.62	51.03	1.08	5.3
	1-MCP (ac) + air	1.69	53.82	1.04	6.0
	1-MCP (bc + ac) + air	1.56	49.16	1.05	5.0
	Control + C_2H_4	1.63	54.15	0.98	6.7
	1-MCP (bc) + C_2H_4	1.63	52.47	1.06	6.0
	1-MCP (ac) + C_2H_4	1.60	52.54	1.02	5.3
	1-MCP (bc + ac) + C_2H_4	1.67	52.04	1.04	7.0
9	Control + air	1.81	51.43	1.12	4.7
	1-MCP (bc) + air	1.67	51.51	1.10	5.7
	1-MCP (ac) + air	1.70	53.17	1.03	5.0
	1-MCP (bc + ac) + air	1.66	52.27	1.02	3.0
	Control + C_2H_4	1.83	51.16	1.12	3.7
	1-MCP (bc) + C_2H_4	1.73	51.46	1.12	3.7
	1-MCP (ac) + C_2H_4	1.71	50.89	1.13	3.0
	1-MCP (bc + ac) + C_2H_4	1.60	51.33	1.07	4.3
12	Control + air	1.83	51.66	1.11	3.3
	1-MCP (bc) + air	1.58	51.57	1.09	4.0
	1-MCP (ac) + air	1.80	52.14	1.11	4.7
	1-MCP (bc + ac) + air	1.67	50.48	1.07	4.0
	Control + C_2H_4	1.62	53.14	1.03	3.3
	1-MCP (bc) + C_2H_4	1.72	52.83	1.07	4.7
	1-MCP (ac) + C_2H_4	1.80	51.67	1.10	3.3
	1-MCP (bc + ac) + C_2H_4	1.83	52.81	1.10	3.7
Time		(0.08)[b]	(1.1)[c]	(0.03)[c]	(1.2)[c]
1-MCP treatment		(0.10)[b]	(1.0)[b]	(0.03)[a]	NS
Time × 1-MCP		NS	(2.33)[b]	(0.07)[b]	NS

NS: not significant. LSD values are in brackets.
[a] $P < 0.05$.
[b] $P < 0.01$.
[c] $P < 0.001$.

softness in kiwifruit slices dipped in 0.5 or 1% $CaCl_2$ was obtained by Agar et al. (1999). The rate of fruit softening depends on fruit calcium status (Poovaiah, 1986). Firming and resistance to softening resulting from addition of calcium have been attributed to the stabilization of membrane systems and the formation of Ca-pectates, which increase rigidity of the middle lamella and cell wall to increased resistance to polygalacturonase attack and to improve turgor pressure (Poovaiah, 1986; Mignani et al., 1995). In this experiment, calcium treatments played an important role in firmness that even increased after treatment, in particular from day 6 onwards (Table 2). In agreement with Glenn and Poovaiah (1990), a calcium gradient remained in the stored wedges after calcium treatment.

Calcium chloride dips and the CA had a similar effect on keeping firmness in the strawberry wedges (Table 2). CO_2 enriched atmospheres are effective in retaining flesh firmness in whole strawberry but the extent of benefit is cultivar-dependent (Holcroft and Kader, 1999). However, the firmness in fresh-cut 'Selva' strawberries increased over the day 7 storage in air and CA treatments, with no clear difference among treatments (Wright and Kader, 1997).

The combination of calcium dips plus CA storage had no significant additional effect in firmness retention compared to these treatments when they were provided alone. As in the first experiment, no effect on firmness retention was observed when 1-MCP was applied alone. However, Jeong et al. (2004) found fresh-cut tomato slices prepared from light-

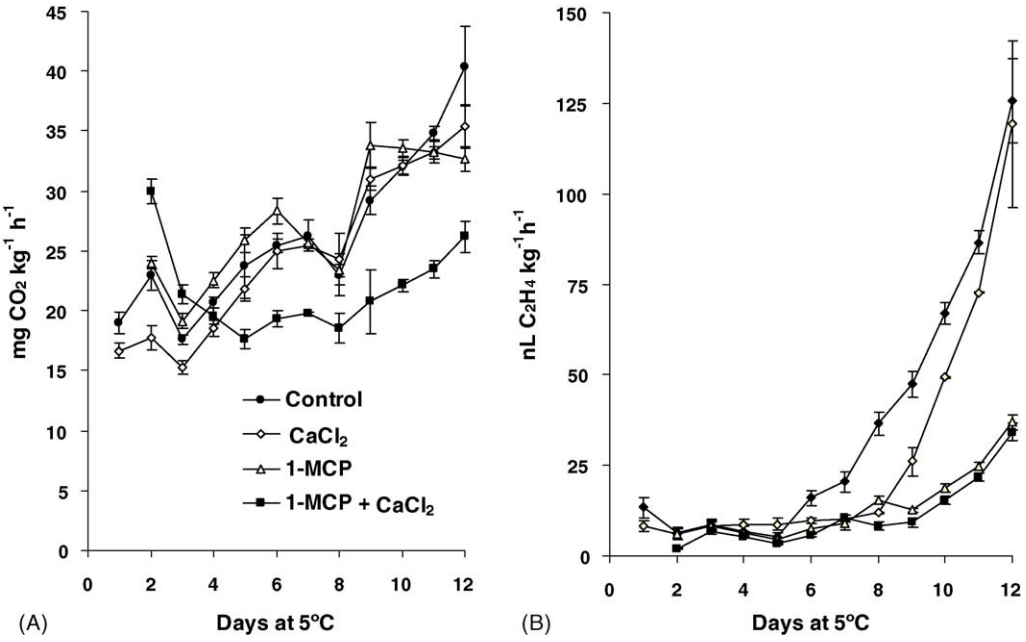

Fig. 2. Respiration rates (A) and ethylene production (B) in fresh-cut 'Seascape' strawberries treated with 1-MCP (1 μL L^{-1} for 24 h at 5 °C) before cutting (bc), dipped in $CaCl_2$ (1%, 2 min), and kept under a continuous flow of humidified air at 5 °C. Means of three replicates ± S.E.

red fruit that had been exposed to 1-MCP (1 μL L^{-1} for 24 h) retained significantly higher pericarp firmness during storage at 5 °C, but no effect was found when slices were obtained from red tomatoes. The lack of effect on firmness retention could be due to the low temperature of storage. Mir et al. (2001) found that a given concentration of 1-MCP had less effect on apple firmness as storage temperature was lowered, and it was hypothesized that lower temperatures might lower the affinity of the binding site for 1-MCP. These authors found 1-MCP treatment maintained apple firmness better than CA storage. Watkins et al. (2000) found in whole apples that the combination of 1-MCP and CA was better than either alone. In our case, the combination of 1-MCP plus $CaCl_2$ provided a higher firmness than 1-MCP plus CA (Table 2). Mao et al. (2004) held whole seedless watermelon in 10 μL L^{-1} 1-MCP and the fresh-cut cylinders obtained were rinsed with 2% $CaCl_2$. These authors found that the combination of 1-MCP and $CaCl_2$ retarded the ripening process, as indicated by higher firmness and lower activities of lipolytic enzymes relative to the control. However, $CaCl_2$ alone was not sufficient to maintain quality of fresh-cut watermelon, and would even exert negative effects by stimulating lipolytic enzymes. In contrast, Rupasinghe et al. (2005) showed that a post-cut dipping treatment of Nature Seal (6% calcium ascorbate) was much more effective than 1-MCP in maintaining firmness of the cut-surface of 'Empire' and 'Crispin' apple slices.

Skin and flesh red color darkening increased with storage duration at 5 °C. Initially, the *a*/*b* ratios were 1.76 for skin and 0.98 for flesh, and reached 1.89 and 1.11, respectively, after 12 days at 5 °C (Table 2). Strawberries treated with 1-MCP and stored with or without CA also had increased *a*/*b* ratios. In contrast, Tian et al. (2000) found the *a*/*b* color ratio was reduced in 1-MCP treated whole strawberries when compared with the control. Jiang et al. (2001) found that 1-MCP maintained fruit color in strawberries; however, it inhibited phenylalanine ammonia lyase activity and lowered anthocyanin production. In sweet cherries there was no influence of 1-MCP on postharvest color changes or stem browning (Gong et al., 2002). Other examples in climacteric fruit are in apricots when 1-MCP-treated fruit were greener and exhibited less color change than untreated controls (Fan et al., 2000). This was also found to be true in peaches (Kluge and Jacomino, 2002). Others researchers found that apricots and plum color changes were not affected by 1-MCP (Dong et al., 2002). Fresh-cut strawberries under CA maintained a lower flesh *a*/*b* ratio (Table 2). Wright and Kader (1997) reported a decrease in the flesh a values when fresh-cut strawberries were stored under the air + 12 kPa CO_2 and 2 kPa O_2 + 12 kPa CO_2. Holcroft and Kader (1999) found that skin and flesh of whole strawberries stored at 5 °C in air became darker red and accumulated higher anthocyanin levels, than those kept in CO_2 enriched atmospheres.

Wedges stored in CA exhibited an increase in skin L^*, from day 3 onwards, compared to the 1-MCP treatment where a reduction of this color parameter was noted (Table 2). On the other hand, the internal or flesh luminosity (L^*) for strawberry wedges in the combined 1-MCP + CA treatment was lower than the rest of the treatments on days 3, 6 and 9. However, there was no consistent relationship between L^* values and visual quality of the wedges. By day 7, Wright and Kader (1997) also found that the cut surface of strawberries stored under the air + 12 kPa CO_2 and 2 kPa O_2 + 12 kPa CO_2 atmospheres had lightened and appeared bleached, while the sliced fruit stored under air or 2 kPa O_2 darkened.

Table 2
Firmness, color and appearance quality (means of three replicates) of fresh-cut 'Seascape' strawberries treated or not with 1-MCP before cutting (1 μL L^{-1} for 24 h at 5 °C) and/or dipped in calcium chloride (1% for 2 min), and stored in air or controlled atmosphere, CA (10 kPa CO_2 + 3 kPa O_2) at 5 °C

Days at 5 °C	Treatment	Firmness	Skin color		Flesh color		Appearance score
		(N)	L^*	*a*/*b*	L^*	*a*/*b*	(1–9)
0		1.66	36.65	1.76	52.51	0.98	8.5
3	Control	1.45	36.63	1.90	48.75	1.10	7.7
	$CaCl_2$	1.55	36.71	1.86	48.75	1.10	7.0
	1-MCP	1.52	34.49	1.88	48.46	1.11	7.7
	CA	1.59	35.68	1.88	49.14	1.09	8.0
	1-MCP + $CaCl_2$	1.54	35.51	1.77	50.01	1.09	7.3
	$CaCl_2$ + CA	1.66	35.01	1.73	49.27	1.09	7.7
	1-MCP + CA	1.54	33.37	2.00	47.51	1.13	8.0
	1-MCP + $CaCl_2$ + CA	1.89	35.33	1.80	49.89	1.09	7.0
6	Control	1.57	36.05	1.93	48.79	1.12	6.0
	$CaCl_2$	1.79	35.85	1.91	49.36	1.11	6.0
	1-MCP	1.57	34.82	1.95	47.95	1.16	5.7
	CA	1.89	37.36	1.81	50.32	1.07	6.3
	1-MCP + $CaCl_2$	1.69	36.89	1.82	49.57	1.13	6.0
	$CaCl_2$ + CA	1.73	35.79	1.92	47.62	1.16	5.7
	1-MCP + CA	1.67	36.36	1.90	47.84	1.18	5.3
	1-MCP + $CaCl_2$ + CA	2.14	36.39	1.89	50.67	1.11	6.0
9	Control	1.57	35.82	1.91	49.81	1.08	4.7
	$CaCl_2$	1.70	35.32	1.88	48.96	1.10	6.0
	1-MCP	1.44	34.79	1.93	48.35	1.16	5.3
	CA	1.89	38.30	1.78	49.57	1.08	5.3
	1-MCP + $CaCl_2$	1.89	34.66	1.87	48.53	1.14	6.0
	$CaCl_2$ + CA	1.83	36.78	1.87	49.13	1.11	5.3
	1-MCP + CA	1.50	36.33	1.96	47.80	1.19	5.3
	1-MCP + $CaCl_2$ + CA	2.07	36.42	1.91	49.04	1.12	6.3
12	Control	1.51	34.57	1.88	50.02	1.07	3.0
	$CaCl_2$	1.89	34.95	1.88	48.28	1.10	3.0
	1-MCP	1.30	34.70	1.94	46.62	1.15	4.3
	CA	1.88	37.06	1.86	49.55	1.07	4.7
	1-MCP + $CaCl_2$	1.84	34.38	1.91	47.09	1.18	4.3
	$CaCl_2$ + CA	1.85	37.79	1.80	49.44	1.11	5.0
	1-MCP + CA	1.58	35.51	1.97	48.16	1.16	4.0
	1-MCP + $CaCl_2$ + CA	1.97	35.33	1.91	48.15	1.13	5.0
Time		(0.13)[c]	(0.76)[c]	(0.09)[c]	(0.93)[c]	(0.03)[c]	(0.6)[b]
Treatment		(0.17)[c]	(0.96)[c]	(0.07)[a]	(1.17)[c]	(0.04)[c]	NS
Time × treatment		(0.30)[b]	(2.15)[c]	NS	(2.06)[b]	(0.05)[a]	(1.29)[a]

NS: not significant. LSD values are in brackets.
[a] $P<0.05$.
[b] $P<0.01$.
[c] $P<0.001$.

Visual quality decreased with time of storage depending on the treatment (Table 2). From the initial time to day 6, no difference among treatments was found. On day 9, only the control treatment scored under the limit of marketability, and the best treatment was the combination of 1-MCP + $CaCl_2$ + CA, followed by $CaCl_2$ with or without 1-MCP. After 12 days of storage at 5 °C, only the following two treatments did not fall below the limit of marketability: $CaCl_2$ + CA and 1-MCP + $CaCl_2$ + CA, indicating a potential shelf life of 12 days at 5 °C.

Due to lower CO_2 and C_2H_4 production, very good firmness retention and appearance was found in the 1-MCP + $CaCl_2$ treatment and 1-MCP + $CaCl_2$ + CA, and these treatments were chosen for the next evaluation.

Comparing control treatments between the cultivars 'Camarosa' (experiment I) and 'Seascape' (experiment II), a higher respiration rate (17–40 mg CO_2 kg^{-1} h^{-1} compared to 15–22 mg CO_2 kg^{-1} h^{-1}) and lower C_2H_4 production (13–125 nL C_2H_4 kg^{-1} h^{-1} compared to 20–240 nL C_2H_4 kg^{-1} h^{-1}) were found in 'Seascape'. In addition, softer wedges were obtained from 'Seascape' (1.5–1.6 N) than from 'Camarosa' (2.2–2.5 N). However, a similar shelf life (shorter than 9 days at 5 °C) was obtained in both cultivars.

Treating strawberries with 1-MCP decreased C_2H_4 production more in 'Seascape' (13–125 to 6–37 nL C_2H_4 kg^{-1} h^{-1}) than in 'Camarosa' (20–240 to 10–130 nL C_2H_4 kg^{-1} h^{-1}) although no effect on firmness retention and a similar shelf life of 9 days was reached in both cultivars.

Table 3
Firmness, appearance, taste, color, SSC and TA (means of 3 replicates) of fresh-cut 'Seascape' strawberries treated with 1-MCP before cutting (1 μL L^{-1} for 24 h at 5 °C) and dipped in calcium chloride (1% for 2 min), and stored in air or in a controlled atmosphere, CA (10 kPa CO_2 + 3 kPa O_2) at 5 °C

Days at 5 °C	Treatment	Firmness	Flesh color		Appearance score	Taste score	SSC	TA
		(N)	L^*	*a*/*b*	(1–9)	(1–9)	%	%
0		1.5	50.84	1.08	8.7	8.7	8.6	1.00
3	Control	1.7	50.21	1.08	7.3	7.7	8.4	1.05
	1-MCP + $CaCl_2$	1.6	49.62	1.11	7.7	7.8	8.5	1.03
	1-MCP + $CaCl_2$ + CA	1.6	48.32	1.14	8.3	7.8	8.7	1.03
6	Control	1.6	47.63	1.15	5.7	7.0	8.2	0.95
	1-MCP + $CaCl_2$	1.8	48.22	1.16	6.7	6.7	8.5	1.01
	1-MCP + $CaCl_2$ + CA	1.8	48.36	1.17	7.3	7.0	8.4	1.03
9	Control	1.7	49.12	1.11	3.7	4.3	8.0	0.90
	1-MCP + $CaCl_2$	1.6	46.26	1.20	5.0	5.0	8.3	0.96
	1-MCP + $CaCl_2$ + CA	1.9	46.94	1.21	5.0	5.0	8.0	0.99
12	Control	1.2	50.39	1.08	2.0	–	8.1	0.87
	1-MCP + $CaCl_2$	1.7	50.38	1.10	3.7	–	8.0	0.97
	1-MCP + $CaCl_2$ + CA	1.9	51.43	1.14	3.0	–	8.3	0.98
Time		(0.22)[c]	(1.31)[c]	(0.04)[c]	(1.81)[c]	(1.17)[c]	(0.39)[c]	(0.08)[c]
1-MCP treatment		(0.17)[c]	NS	(0.03)[c]	(0.79)[a]	NS	NS	(0.04)[a]
Time × 1-MCP		(0.38)[c]	(2.28)[c]	(0.05)[c]	NS	NS	NS	NS

NS: not significant. LSD values are in brackets.
[a] $P < 0.05$.
[c] $P < 0.001$.

3.3. Experiment III. Further evaluation of the best treatments (MCP + $CaCl_2$, 1-MCP + $CaCl_2$ + CA) from prior experiments

For the first 6 days at 5 °C, no effect on firmness retention of strawberry wedges was observed among treatments. However, on days 9 and 12, the combinations of 1-MCP + $CaCl_2$ + CA and 1-MCP + $CaCl_2$ were firmer than those in the control (Table 3).

From day 9 onwards, the flesh color of fresh-cut strawberries treated with 1-MCP + $CaCl_2$ + CA was slightly redder than those in the control treatment (Table 3). The internal luminosity in the control was lower on day 6, but on day 9 it was the combination 1-MCP + $CaCl_2$ with a lower L^*. It was very difficult to determine severity of the internal browning by measuring this parameter.

Visual quality and the taste scores decreased with time in storage (Table 3). By treating strawberry with 1-MCP + $CaCl_2$ with or without CA, it was possible to reach a shelf life of 9 days at which time the control strawberry wedges were not marketable. A storage period of 12 days was too long for maintaining good appearance and taste in spite of adding 1-MCP, $CaCl_2$ and/or CA. The appearance was always better in 1-MCP + $CaCl_2$ + CA and 1-MCP + $CaCl_2$ treatments than in the controls, but no significant difference was found between those two treatments.

In general, SSC and TA decreased with time of storage ranging from 8.6 to 8.2% and 1.00 to 0.94 g citric acid per 100 mL of juice. 1-MCP treatments did not affect SSC but there was an influence on TA; 1-MCP + $CaCl_2$ + CA and 1-MCP + $CaCl_2$ treatments showed a higher TA than controls (Table 3). Neither Jiang and Joyce (2002) and Perera et al. (2003) in fresh-cut apples nor Porat et al. (1999) in whole oranges found any significant effects of 1-MCP on SSC. However, SSC were higher in 1-MCP-treated pineapple (Selvarajah et al., 2001) or reduced in 1-MCP-treated strawberries regardless of the presence or absence of exogenous ethylene (Tian et al., 2000).

Time of storage increased the microbial growth, in particular, in control strawberry wedges (Table 4). 1-MCP + $CaCl_2$ had a very slight effect on reducing the microbial counts.

Table 4
Microbial counts (log cfu g^{-1}) of fresh-cut 'Seascape' strawberries treated with 1-MCP before cutting (1 μL L^{-1} for 24 h at 5 °C) and dipped in calcium chloride (1% for 2 min), and stored in air or in a controlled atmosphere, CA (10 kPa CO_2 + 3 kPa O_2) at 5 °C

Days at 5 °C	Control	1-MCP + $CaCl_2$	1-MCP + $CaCl_2$ + CA
Psychotropic			
0		1.47[a] ± 0.25	
6	4.15 ± 0.02	3.93 ± 0.08	3.22 ± 0.14
9	5.00 ± 0.07	4.52 ± 0.02	3.84 ± 0.24
12	6.23 ± 0.06	6.26 ± 0.04	5.45 ± 0.12
Yeast			
0		1.10 ± 0.10	
6	3.31 ± 0.07	2.97 ± 0.32	2.24 ± 0.14
9	3.86 ± 0.05	4.09 ± 0.23	2.48 ± 0.24
12	5.30 ± 0.15	5.19 ± 0.12	4.88 ± 0.10
Mold			
0		<1	
6		<1	
12	<3	<3	<2

[a] Values are means ($n = 3$) ± S.E.

Total microbial growth were decreased by 1-MCP (1 $\mu L\,L^{-1}$ for 24 h) in 'Empire' apples but the influence on 'Crispin' apple slices was marginal (Rupasinghe et al., 2005). Budu and Joyce (2003) did not find any effect on microbial load of treating pineapple slices with 1-MCP. This compound promoted decay development on the cut surface in apple slices prepared from whole 'Gala' fruit which reduced the shelf life (Bai et al., 2004). In whole strawberries 1-MCP concentrations greater than 15 $nL\,L^{-1}$ are associated with increased decay of fruit (Ku et al., 1999). Jiang et al. (2001) also found an increase in disease with high 1-MCP concentrations on strawberries due to a lower phenolic content. Exposure of whole strawberries to 0.01, 0.1 or 1.0 $\mu L\,L^{-1}$ 1-MCP slightly increased the rate of rot development (Bower et al., 2003). According to these authors, blocking ethylene perception interferes with disease resistance, but there was only a small effect on total storage life. 1-MCP may inhibit a beneficial metabolic response or stimulate an undesirable characteristic, possibly relating to a natural defense mechanism (Ku et al., 1999).

The storage under CA had an important and strong effect slowing down psychotropic and yeast growth (Table 4). For the first 9 days of storage, the reduction in levels between 1-MCP + $CaCl_2$ + CA and control was 1–1.3 log cfu g^{-1}. At the end of storage, these differences between those treatments were smaller, 0.5–0.8 log cfu g^{-1}. No differences among treatments were found in mold growth. Nguyen-the and Carlin (1994) reported that CO_2 enriched atmospheres with or without low O_2 levels reduced e molds, mesophilic and psychotropic growth in fresh-cut endive. In addition, the high CO_2 effect is greater with a reduction in O_2 levels as found by Portela and Cantwell (1998) in fresh-cut cantaloupe, Qi et al. (1999) in honeydew melon, and Rattanapanone et al. (2001) in mango.

4. Conclusions

The 1-MCP applied before cutting (in the whole product) and also both before and after cutting (in the whole and wedges of strawberry) reduced C_2H_4 production. The application of only 1-MCP before and/or after cutting did not have a significant effect on firmness and appearance quality. The exposure to a continuous flow of air + 1 $\mu L\,L^{-1}$ C_2H_4 flow did not increase the rate of softening. 1-MCP had a synergistic effect when combined with $CaCl_2$ plus CA. This treatment (1-MCP + $CaCl_2$ + CA) slowed down the softening, loss of appearance quality, changes in TA, and microbial growth of strawberry wedges, resulting in a shelf life of strawberry wedges of 9 days (versus 6 days for the control) at 5 °C.

Acknowledgement

E. Aguayo thanks the Technical University of Cartagena for supporting her sabbatical leave at UC Davis.

References

Able, A.J., Wong, L.S., Prasad, A., O'Hare, T.J., 2003. The effect of 1-methylcyclopropene on the shelf life of minimally processed leafy Asian vegetables. Postharvest Biol. Technol. 27, 157–161.

Agar, I.T., Massantini, R., Hess-Pierce, B., Kader, A.A., 1999. Postharvest CO_2 and ethylene production and quality maintenance of fresh-cut kiwifruit slices. J. Food Sci. 64, 433–440.

Bai, J., Baldwin, E.A., Soliva Fortuny, R.C., Matthesis, J.P., Stanley, R., Perera, C., Brecht, J.K., 2004. Effect of pretreatment of intact 'Gala' apple with ethanol vapor, heat, or 1-methylcyclopropene on quality and shelf life of fresh-cut slices. J. Am. Soc. Hort. Sci. 129, 583–593.

Blankenship, S.M., Dole, J.M., 2003. 1-Methylcyclopropene: a review. Postharvest Biol. Technol. 28, 1–25.

Bower, J.H., Biasi, W.V., Mitcham, E.J., 2003. Effects of ethylene and 1-MCP on the quality and storage life of strawberries. Postharvest Biol. Technol. 28, 417–423.

Budu, A.S., Joyce, D.C., 2003. Effect of 1-methycyclopropene on the quality of minimally processed pineapple fruit. Aust. J. Exp. Agric. 43, 177–184.

Calderón-López, B., Bartsch, J.A., Lee, C.Y., Watkins, C.B., 2005. Cultivar effects on quality of fresh cut apple slices from 1-methylcyclopropene (1-MCP)-treated apple fruit. J. Food Sci. 70, 114–118.

Dong, L., Lurie, S., Zhou, H., 2002. Effect of 1-methylcyclopropene on ripening of 'Canino' apricots and 'Royal Zee' plums. Postharvest Biol. Technol. 24, 135–145.

Fan, X., Argenta, L., Matthesis, J.P., 2000. Inhibition of ethylene action by 1-methylcyclopropene prolongs storage life of apricots. Postharvest Biol. Technol. 20, 135–142.

Glenn, G.M., Poovaiah, B.W., 1990. Calcium-mediated postharvest changes in texture and cell wall structure and composition in 'Golden Delicious' apples. J. Am. Soc. Hort. Sci. 115, 962–968.

Gong, Y., Fan, X., Mattheis, J.P., 2002. Responses of 'Bing' and 'Rainier' sweet cherries to ethylene and 1-methylcyclopropene. J. Am. Soc. Hort. Sci. 127, 831–835.

Holcroft, D.M., Kader, A.A., 1999. Controlled atmosphere-induced changes in pH and organic acid metabolism may affect color of stored strawberry fruit. Postharvest Biol. Technol. 17, 19–32.

Jeong, J., Brecht, J.K., Huber, D.J., Sargent, S.A., 2004. 1-Methylcyclopropeno (1-MCP) for maintaining texture quality of fresh-cut tomato. HortScience 39, 1359–1362.

Jiang, Y., Joyce, D.C., 2002. 1-Methycyclopropene treatment effects on intact and fresh-cut apple. J. Hort. Sci. Biotechnol. 77, 19–21.

Jiang, Y., Joyce, D.C., Terry, L.A., 2001. 1-Methylcyclopropene treatment affects strawberry fruit decay. Postharvest Biol. Technol. 23, 227–232.

Kluge, R.A., Jacomino, A.P., 2002. Shelf life of peaches treated with 1-methylcyclopropene. Scientia-Agricola 59, 69–72.

Ku, V.V.V., Wills, R.B.H., Ben-Yehoshua, S., 1999. 1-Methylcyclopropene can differentially affect the postharvest life of strawberries exposed to ethylene. HortScience 34, 119–120.

Luna-Guzmán, I., Barret, D.M., 2000. Comparison of calcium chloride and calcium lactate effectiveness in maintaining shelf stability and quality of fresh-cut cantaloupes. Postharvest Biol. Technol. 19, 61–72.

Mao, L.C., Que, F., Donald, H.J., 2004. 1-Methylcyclopropene and $CaCl_2$ treatments affect lipolytic enzymes in fresh-cut watermelon fruit. Acta Botanica Sinica 46, 1402–1407.

Mignani, I., Greve, L.C., Ben-Arie, R., Stotz, H.U., Li, C., Shackel, K., Labavitch, J., 1995. The effects of GA_3 and divalent cations on aspects of pectin metabolism and tissue softening in ripening tomato pericarp. Physiol. Plant. 93, 108–115.

Mir, N.A., Curell, E., Khan, N., Whitaker, M., Beaudry, R.M., 2001. Harvest maturity, storage temperature, and 1-MCP application frequency alter firmness retention and chlorophyll fluorescence of 'Redchief Delicious' apples. J. Am. Soc. Hort. Sci. 126, 618–624.

Morris, J.R., Sistrunk, W.A., Sims, C.A., Main, G.L., Wehunt, E.J., 1985. Effects of cultivar, postharvest storage, preprocessing dip treatments

and style of pack on the processing quality of strawberries. J. Am. Soc. Hort. Sci. 110, 172–177.

Nguyen-the, C., Carlin, F., 1994. The microbiology of minimally processed fresh fruits and vegetables. CRC Crit. Rev. Food Sci. Nutr. 34, 371–401.

Perera, C.O., Balchin, L., Baldwin, E., Stanley, R., Tian, M., 2003. Effect of 1-methylcyclopropene on the quality of fresh-cut apple slices. J. Food Sci. 68, 1910–1914.

Poovaiah, B.W., 1986. Role of calcium in prolonging the storage life of fruits and vegetables. Food Technol. 40, 86–89.

Porat, R., Weiss, B., Cohen, L., Daus, A., Goren, R., Droby, S., 1999. Effects of ethylene and 1-methylcyclopropene on the postharvest qualities of 'Shamouti' oranges. Postharvest Biol. Technol. 15, 155–163.

Portela, S.I., Cantwell, M.I., 1998. Quality changes of minimally processed honeydew melons stored in air or controlled atmosphere. Postharvest Biol. Technol. 14, 315–357.

Qi, L., Wu, T., Watada, A.E., 1999. Quality changes of fresh-cut honeydew melons during controlled atmosphere storage. J. Food Qual. 22, 513–521.

Rattanapanone, N., Lee, Y., Wu, T., Watada, A.E., 2001. Quality and microbial changes of fresh-cut mango cubes held in controlled atmosphere. HortScience 36, 1091–1095.

Rosen, J.C., Kader, A.A., 1989. Postharvest physiology and quality maintenance of sliced pear and strawberry fruits. J. Food Sci. 54, 656–659.

Rupasinghe, H.P.V., Mur, D.P., DeEll, J.R., Odumeru, J., 2005. Influence of 1-methylcyclopropene and Natureseal on the quality of fresh-cut 'Empire' and 'Crispin' apples. J. Food Qual. 28, 289–306.

Selvarajah, S., Bauchot, A.D., John, P., 2001. Internal browning in cold-stored pineapples is suppressed by a postharvest application of 1-methylcyclopropene. Postharvest Biol. Technol. 23, 167–170.

Tian, M.S., Prakash, S., Elgar, H.J., Young, H., Burmeister, D.M., Ross, G.S., 2000. Responses of strawberry fruit to 1-methylcyclopropene (1-MCP) and ethylene. Plant Growth Regul. 32, 83–90.

Watkins, C.B., Nock, J.F., Whitaker, B.D., 2000. Responses of early, mid and late season apple cultivars to postharvest application of 1-methylcyclopropene (1-MCP) under air and controlled atmosphere storage conditions. Postharvest Biol. Technol. 19, 17–32.

Wills, R.B.H., Kim, G.H., 1995. Effect of ethylene on postharvest life of strawberries. Postharvest Biol. Technol. 6, 249–255.

Wright, K.P., Kader, A.A., 1997. Effect of slicing and controlled-atmosphere storage on the ascorbate content and quality of strawberries and persimmons. Postharvest Biol. Technol. 10, 39–48.