



Postharvest handling of plums (*Prunus salicina* Lindl.) at 10 °C to save energy and preserve fruit quality using an innovative application system of 1-MCP

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ABSTRACT

1-Methylcyclopropene (1-MCP) inhibits softening in plums, making it a candidate for a postharvest strategy of storing fruit at higher than normal storage temperatures to avoid chilling injury (CI) while providing energy and cost savings. This hypothesis was tested by exposing different Japanese plum (*Prunus salicina* Lindel.) cultivars to 0.5 $\mu\text{L L}^{-1}$ 1-MCP at 0 °C for 24 h. Following 1-MCP treatment, fruit were stored at 0 or 10 °C for 10, 20, or 30 d, respectively. A new application technology was tested by applying 1-MCP during forced-air cooling (FAC), reducing the application duration from 24 to 6 h without affecting treatment performance. This new 1-MCP application system is compatible with current postharvest handling, rendering it easily adopted by the tree fruit industry. 1-MCP had no detrimental effect on consumer acceptance of low-acid plums ripened properly prior to consumption, but it reduced the acceptance of high acidity plums. Thus, 1-MCP use on plums should avoid cultivars with high acidity and/or plums picked early when fruit have titratable acidity of 0.9% or more. 1-MCP–FAC treatment followed by storage at 10 °C is a promising new methodology to avoid chilling temperatures and provide considerable energy savings without reducing postharvest life and consumer quality of low-acid plums. Our results encourage testing this new technology at commercial scale to accurately quantify energy savings and consumer reactions for specific operations and markets.

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1. Introduction

Japanese plum (*Prunus salicina* Lindel.) is a highly perishable temperate fruit crop and cold storage at 0 °C is recommended to extend fruit postharvest life and maintain quality (Crisosto et al., 2004; Mitchell et al., 2008). Commercial storage and transportation conditions (0–5 °C and 80–95% relative humidity) delay softening and reduce weight loss and disease incidence, but may also lead to development of cold storage disorders such as chilling injury (CI) symptoms (Palou et al., 2003; Crisosto et al., 2009). Most plum cultivars are susceptible to express CI symptoms after prolonged cold storage and ripening at room temperature, evident as flesh browning, gel breakdown, mealiness, flesh translucency, red pigment accumulation (bleeding), and loss of flavor (Crisosto et al., 1999, 2004; Candan et al., 2008; Manganaris et al., 2008). The onset of these symptoms determines postharvest storage/shipping potential because CI development reduces consumer acceptance (Crisosto et al., 2004). Susceptibility of fruit to CI varies with genetic background and storage temperature (Crisosto et al., 1999, 2004, 2008). Plum storage or transport at temperatures higher than

7.5 °C to avoid CI has been tested in several cultivars and provided successful control of cold storage disorders, but the resulting over-ripening, senescence, and softening were equally damaging (Crisosto and Garner, 2008). Furthermore, a combined approach using controlled atmosphere (CA) to reduce softening in plums exposed to temperatures higher than 7.5 °C caused softening and 'off-flavor' problems due to low oxygen (3–5 kPa) and/or high CO₂ (10–15 kPa) toxicity after extended storage (Crisosto and Garner, 2008).

1-Methylcyclopropene (1-MCP) inhibits ethylene action and prevents ethylene-dependent responses such as softening and senescence of vegetative and fruit tissues (Sisler and Serek, 1997). Its ability to inhibit plum ripening is well documented (Abdi et al., 1998; Martinez-Romero et al., 2003; Candan et al., 2006), making it a promising candidate for plum storage above chilling temperatures without undesired softening. 1-MCP is registered as SmartFresh™ (AgroFresh Inc., Rohm and Haas, Spring House, PA, USA) for postharvest chemical fumigation in sealed rooms or tents on a number of fruit and vegetable crops including stone fruit (Watkins, 2006). The recommended application for stone fruit in California is 0.5 $\mu\text{L L}^{-1}$ at 0 °C for 24 h in a sealed room or tent (SmartFresh™, State of California, Department of Pesticide Regulation, Pesticide Registration, EPA: Registration No. 71297-2, 2010). Although postharvest 1-MCP application on plum shows promise in

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Table 1
Harvest quality of plum cultivars used for the three distinct experiments in this study. Values represent the mean of five replications of five fruits \pm standard deviation (SD).

Experiment	Cultivar	Harvest date	Firmness (N)	SSC (%)	TA (%)	Fruit weight (g)
1-MCP standard application and storage at 10 °C	'Blackamber'	July 7, 2010	27.1 \pm 5.3	12.4 \pm 0.1	0.66 \pm 0.0	122.6 \pm 6.1
	'Red Lane'	July 7, 2010	26.8 \pm 5.0	13.5 \pm 0.6	0.80 \pm 0.1	118.4 \pm 4.2
1-MCP application during the forced-air cooling (FAC) operation and storage at 10 °C	'Fortune'	July 26, 2010	29.5 \pm 5.7	15.8 \pm 0.4	0.60 \pm 0.1	121.5 \pm 10.1
	'Yummy Beaut'	June 21, 2011	24.3 \pm 2.2	12.2 \pm 0.4	0.53 \pm 0.0	98.2 \pm 4.4
	'Black Splendor'	June 21, 2011	29.5 \pm 4.0	11.5 \pm 0.4	1.09 \pm 0.1	116.2 \pm 5.1
In-store consumer test	'Yummy Beaut'	June 15, 2011	27.8 \pm 4.0	12.8 \pm 0.9	0.68 \pm 0.0	95.0 \pm 3.7
	'Black Splendor'	June 15, 2011	32.5 \pm 3.2	12.1 \pm 0.3	1.38 \pm 0.1	105.1 \pm 7.1

SSC, soluble solids concentration; TA, titratable acidity.

reducing softening during storage, transportation, and retail handling, it may interfere with the fruit's ability to ripen normally after storage and/or develop storage disorder symptoms (Dong et al., 2002). A potential barrier to use of 1-MCP is the 24-h application period recommended for stone fruit, which delays storage and packaging, interrupting the current operation flow.

Forced-air cooling (FAC) is a commercial practice used worldwide that allows perishable produce to be marketed over long distances by cooling it quickly after harvest (Thompson et al., 2002). It is the primary cooling method for stone fruit in California prior to cold storage (Thompson et al., 2002). We propose a 1-MCP application during FAC (6–9 h), which would not alter the current plum postharvest operation and thus should be easily adopted by the stone fruit industry. Cold storage operations and FAC are big energy consumers. It has been estimated that California's fresh market annually consumes \sim 3.6 million GJ of electricity for FAC and short-term storage (Thompson and Singh, 2008), which represents 5.5% of total electricity used by agriculture and 0.4% of the state's total consumption. Storing fruit at above-chilling temperatures of 7.5–10.0 °C after 1-MCP application could provide significant energy and cost savings while maintaining adequate post-storage plum quality.

Previous sensory studies indicated that 'Blackamber' plums should be harvested when they reach a minimum soluble solids concentration (SSC) of 10–12% and a titratable acidity (TA) < 0.70%, because consumers preferred low-acidity (TA \leq 0.6%) to high-acidity (TA \geq 0.9–1.0%) plums for the same range of SSC (Crisosto et al., 2004). So far, no sensory studies have been performed to investigate any potential effect of 1-MCP on consumer acceptance of plums.

Our current study seeks to save energy and avoid cold storage disorders development during plum fruit storage by applying 1-MCP using a novel system that fits current industry postharvest handling. The ultimate goal of our work is to provide to the stone fruit industry a new and profitable postharvest technology that delivers flavorful plums to consumers.

2. Materials and methods

2.1. 1-MCP standard application and storage at 10 °C

Mid-season 'Blackamber' (black) and 'Red Lane' (red) plums of uniform size and maturity, free from visual blemishes and diseases, were commercially harvested at the California 'well-mature' stage according to the California Tree Fruit Agreement (CTFA) ground-color chips, packed in cardboard boxes, and delivered on the same day to the F. Gordon Mitchell Postharvest Lab at UC Kearney Agricultural Research and Extension Center, Parlier, CA. Immediately after arrival, five replicates of five fruit (defined here as 'fruit sample') were taken from each cultivar to evaluate fruit quality at harvest (Table 1). Fruit (1200 per cultivar) were randomized and divided into two postharvest treatments: (1) untreated (control); and (2) treated with 0.5 μ L L⁻¹ 1-MCP, released from SmartFresh™

tabs provided by AgroFresh Inc. (Spring House, PA, USA), at 0 °C for 24 h in sealed 330-L aluminum tanks (1-MCP treatment). Immediately after treatment, fruit were split into two sub-groups and stored at (1) 0 °C or (2) 10 °C for up to 10, 20 and 30 d. After each storage period at 0 or 10 °C, one third of the fruit was transferred to room temperature (20 °C, RH 90%) to ripen (simulated conditions of a retail market), and the postharvest quality of a fruit sample per treatment evaluated at 0, 2, 4 and 6 d of ripening. The experimental set up is presented in Supplementary Fig. S1.

2.2. 1-MCP application during forced-air cooling (FAC) and storage at 10 °C

Early season 'Yummy Beaut' (red) and 'Black Splendor' (black) and mid-season 'Fortune' (red) plums were commercially harvested, packed and delivered to the lab. Immediately after arrival, a fruit sample was taken from each cultivar and used to determine fruit quality at harvest (Table 1). Fruit (2400 per cultivar) were randomized and divided into three treatments: (1) untreated (control); (2) treated with 0.5 μ L L⁻¹ 1-MCP at 0 °C for 24 h in sealed 330-L aluminum tanks (1-MCP treatment); and (3) treated with 0.5 μ L L⁻¹ 1-MCP at 0 °C for 6 h in a forced-air cooler (1 L s⁻¹ kg⁻¹) fitted in a sealed 4000-L tent (1-MCP-FAC treatment). Thereafter, fruit were split into two groups and stored at (1) 0 °C or (2) 10 °C for up to 10–20 d. After each storage period at 0 or 10 °C, one half of the fruit were transferred to 20 °C (RH 90%) to ripen, and the postharvest quality of a fruit sample per treatment evaluated at 0 d and every 2 d until ripe (fruit firmness < 10 N). The experimental set up is presented in Supplementary Fig. S2.

2.3. Fruit quality evaluation

Ethylene production, respiration rate, flesh firmness, soluble solids concentration (SSC), titratable acidity (TA), and skin and flesh color of fruit were monitored during ripening at 20 °C after removal from cold storage. Ethylene production and respiration rate were measured in five fruit sampled from each treatment. Single fruit were sealed in 1.8-L airtight jars for 1 h at 20 °C. Ethylene production was calculated by ethylene concentration in the gas phase of the jars, determined by withdrawing a 10-mL headspace gas sample from each jar and injecting it into a 2-mL fixed sample volume valve of a gas chromatograph (model Carle AGC-211, EG&G Chandler Engineering, Tulsa, OK, USA) equipped with two stainless steel columns (1.22 m and 0.305 m) packed with 8% NaCl on Alumina F-1 80/100 DV (EG&G Chandler Engineering, Tulsa, OK, USA) and a flame ionization detector. Nitrogen (N₂) was used as the carrier gas at a flow rate of 0.5 mL s⁻¹ while O₂ and H₂ were used to create the flame of the detector at flow rates of 5 and 0.5 mL s⁻¹, respectively. Injector, oven and detector temperatures were 80 °C. Respiration rate was calculated by carbon dioxide concentration in the gas phase of the jars, determined by withdrawing a 10-mL headspace gas sample from each jar and injecting it into a 2-mL fixed sample volume valve of an infrared gas analyzer (Horiba

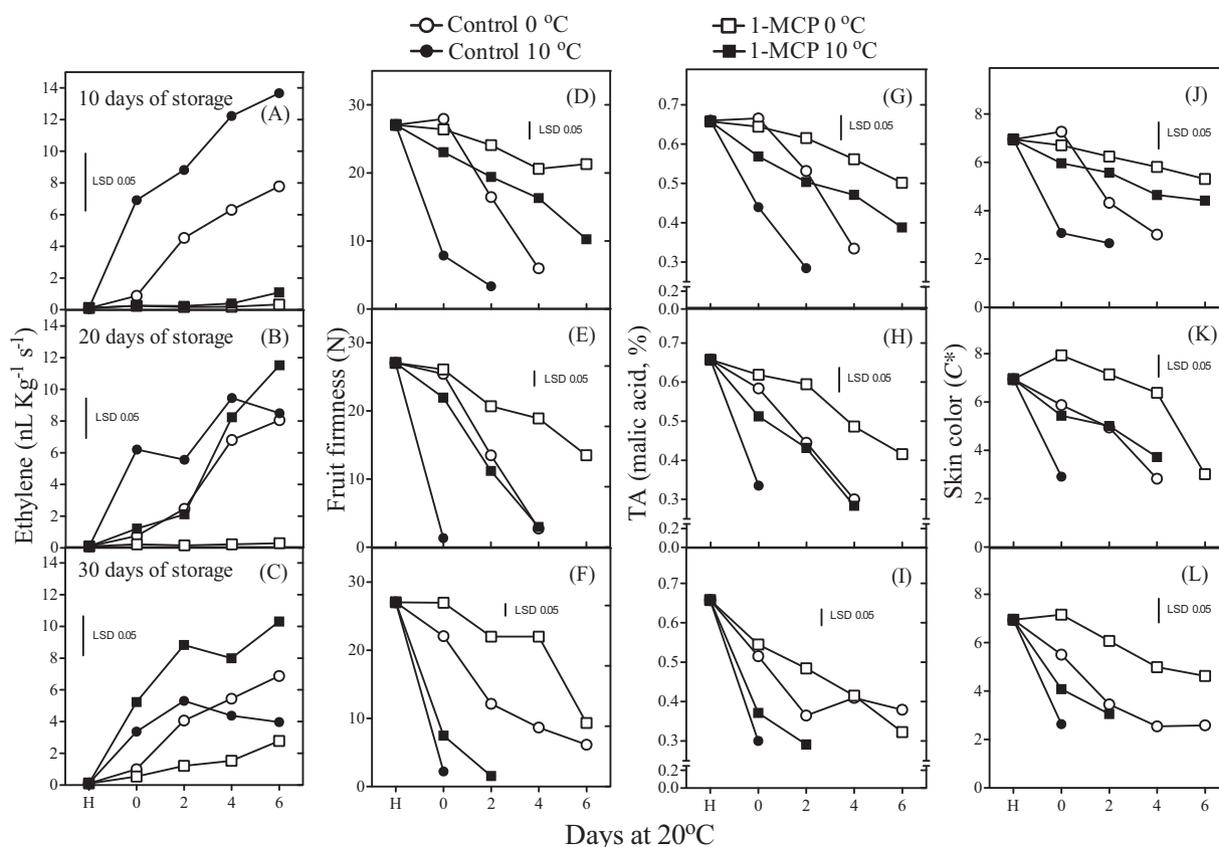


Fig. 1. Postharvest changes in ethylene production (A–C), fruit firmness (D–F), titratable acidity (G–I), and skin color (J–L) of ‘Blackamber’ plums measured during ripening at 20 °C on fruit treated or untreated with 0.5 $\mu\text{L L}^{-1}$ 1-MCP at 0 °C for 24 h before storage, after 10 (A, D, G and J), 20 (B, E, H and K), or 30 (C, F, I and L) days of storage at 0 or 10 °C. Each value represents the mean of five replicates of one (ethylene) or five fruit (fruit firmness, TA, skin color) analyzed at each ripening stage after storage. The bar in each particular figure represents the least significant difference (LSD, $P=0.05$). Abbreviations. H, harvest; TA, titratable acidity.

PIR-2000R, Horiba Instruments Inc., Irvine, CA, USA). Nitrogen was used as the carrier gas at a flow rate of 0.33 mL s^{-1} . Ethylene production was expressed as C_2H_4 $\text{nL kg}^{-1} \text{s}^{-1}$ and respiration rate as CO_2 $\text{mL kg}^{-1} \text{s}^{-1}$. Volumes are relative to total pressure of 101 kPa and 20 °C.

Flesh firmness was measured on the two opposite cheeks of each fruit after removal of peel (1 mm thick) using a fruit texture analyzer (FTA, model GS, Güss Manufacturing Ltd., Strand, South Africa) fitted with a 8.0-mm probe. Data were calculated as the mean of measurements from a fruit sample and expressed in Newtons (N). The number of days to reach the ‘ready to buy’ and ‘ready to eat’ thresholds was estimated from the flesh firmness loss rate per day for each replicate based on previous studies (Crisosto et al., 2001; Valero et al., 2007).

A fruit sample was used to analyze soluble solids concentration (SSC) and titratable acidity (TA). A longitudinal wedge (from the stem end to the blossom end) was removed from each fruit, pooled to form a composite sample, and pressed through cheesecloth using a juicer. The juice SSC was measured with a temperature-compensated digital refractometer (PR 32 α , Atago, Tokyo, Japan). TA was measured using an automatic titrator (model TitraLab 850, Radiometer Analytical SAS, Lyon, France) connected to a sample changer (model SAC80, Radiometer Analytical SAS, Lyon, France), titrated with 0.1 mol L^{-1} NaOH to endpoint pH 8.2 and expressed as percentage of malic acid (%).

Fruit skin and flesh color were measured with a portable colorimeter (Minolta CR-300, Minolta, Osaka, Japan). Two measurements on two opposite equatorial sides of the fruit were taken, using a fruit sample per treatment. The colorimeter was calibrated using the manufacturer’s standard white plate. Skin color changes

were expressed using chroma (C^*) and hue angle (h°) values for the black and the red plums, respectively (Crisosto et al., 1997).

2.4. In-store consumer test

Early season ‘Yummy Beaut’ (red) and ‘Black Splendor’ (black) plums were commercially harvested, packed, and delivered as described above. Immediately after arrival, a fruit sample from each cultivar was used to measure fruit quality at harvest (Table 1). Thereafter, fruit were randomized and divided into two groups: (1) untreated (control) and (2) treated with 0.5 $\mu\text{L L}^{-1}$ 1-MCP at 0 °C for 24 h in sealed 330-L aluminum tanks (1-MCP treatment). Following treatments, fruit were stored at 0 °C for 5 d, then ripened at 20 °C (RH 90%), until a subsample of five fruit for each treatment and cultivar reached a flesh firmness of 22 ± 2 N (‘ready to buy’) or 13 ± 2 N (‘ready to eat’) as described previously (Crisosto et al., 2001; Valero et al., 2007), following the ripening protocol (Crisosto and Crisosto, 2005). Once the desired flesh firmness was reached, the fruit were immediately stored at 0 °C until used for the consumer test.

On the day of the consumer test, on each ripened fruit to be tested, a 2-cm diameter piece of skin was removed from one cheek and the flesh firmness was measured with a UC firmness tester (Western Industrial Supply, San Francisco, CA, USA) equipped with an 8-mm probe. If the fruit was within the desired ripening stages (‘ready to buy’ or ‘ready to eat’), a numerical code was written on the tip of the fruit and the flesh firmness was recorded. A sample consisted of one longitudinal slice cut from the stem end to the blossom end on the cheek opposite to the flesh firmness measurement of the fruit to be tested, following our single fruit in-store consumer test protocol (Crisosto and Crisosto, 2005).

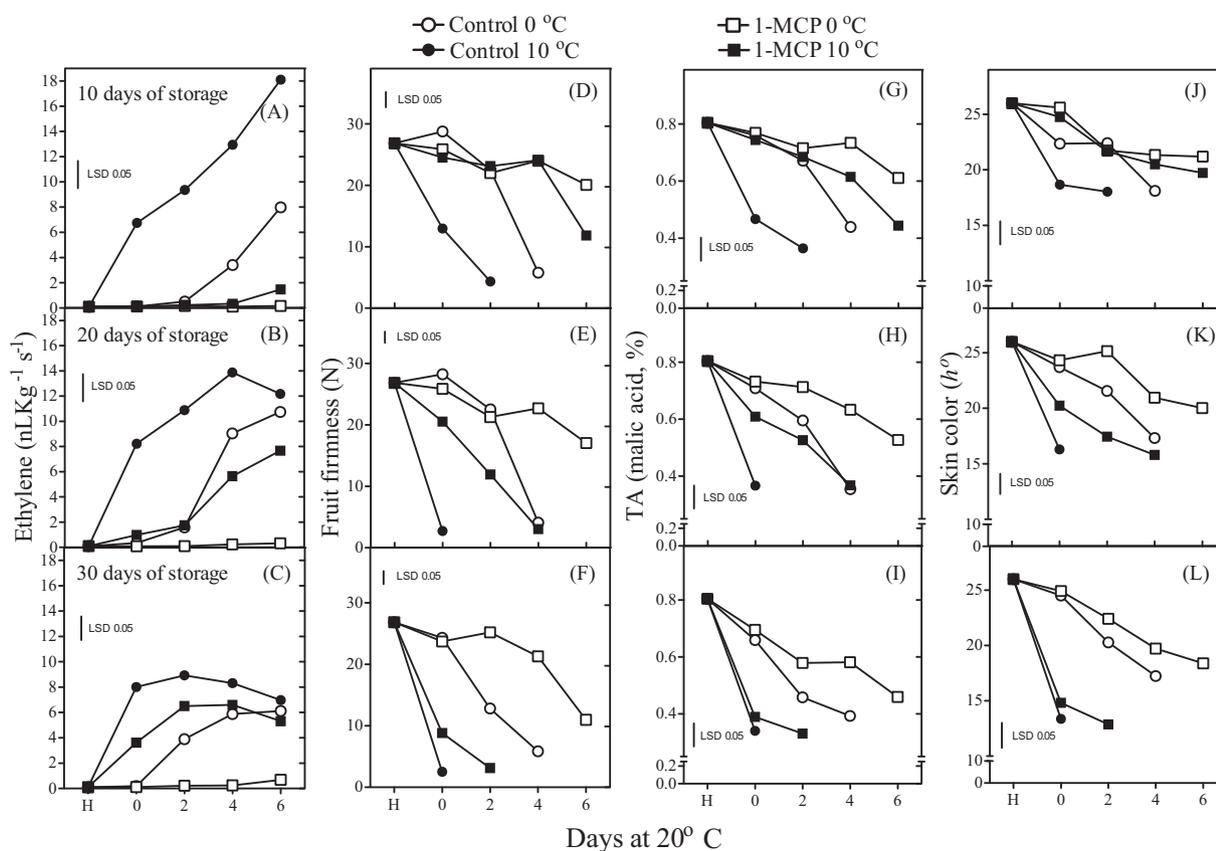


Fig. 2. Postharvest changes in ethylene production (A–C), fruit firmness (D–F), titratable acidity (G–I), and skin color (J–L) of ‘Red Lane’ plums measured during ripening at 20 °C on fruit treated or untreated with 0.5 $\mu\text{L L}^{-1}$ 1-MCP at 0 °C for 24 h before storage, after 10 (A, D, G and J), 20 (B, E, H and K), or 30 (C, F, I and L) days storage at 0 °C or 10 °C. Each value represents the mean of five replicates of one (ethylene) or five fruit (fruit firmness, TA, skin color) analyzed at each ripening stage after storage. The bar in each particular figure represents the least significant difference (LSD, $P=0.05$). Abbreviations. H, harvest; TA, titratable acidity.

A total of 140 consumers participated in the test, based on availability and their response that they had no sensitivity or allergies to plum or similar food products. The experiment was conducted at the Robert Mondavi Institute (RMI) Sensory lab at UC Davis on June 29, 2011. Each consumer evaluated eight samples. The presentation order of the samples was randomized using a Williams Latin square design provided by the FIZZ software and one longitudinal slice of plum of approximately 2 cm per cultivar per treatment per ripening stage was evaluated by each consumer (Lawless and Heymann, 2010). Consumers rated their overall impression for each sample on a 9-point hedonic scale (degree of liking: 1 = dislike extremely; 2 = dislike very much; 3 = dislike moderately; 4 = dislike slightly; 5 = neither like nor dislike; 6 = like slightly; 7 = like moderately; 8 = like very much; 9 = like extremely) and their perception of firmness, sweetness, and sourness using a Just Right (JAR) Scale (Lawless and Heymann, 2010). Consumer acceptance was measured as both degree of liking (1–9) and percentage acceptance. Percentage acceptance was calculated as the number of consumers liking the fruit sample (score > 5.0) divided by the total number of consumers within that sample (Lawless and Heymann, 2010; Crisosto et al., 2004). In a similar way the percentage of consumers disliking and/or indifferent to that sample was calculated. The experimental set up is presented in Supplementary Fig. S3.

2.5. Statistical analysis

Data were subjected to analysis of variance and least significant differences (LSD) at the 5% level were used for comparing means

using SPSS 17.0 for Windows (SPSS, Chicago, IL, USA). Graphs were created using Prism v5.01 (Graph Pad Inc., San Diego, USA).

3. Results

3.1. 1-MCP standard application and storage at 10 °C

Pre-storage application of 1-MCP delayed the onset of ethylene production or decreased its production during ripening after 10 and 20 d of storage at 0 °C or 10 °C ($P \leq 0.05$), respectively, compared to untreated ‘Blackamber’ and ‘Red Lane’ plums (Figs. 1 and 2). The suppression in ethylene production was more evident in fruit stored at the lower temperature (0 °C) and for shorter duration. 1-MCP-treated ‘Blackamber’ and ‘Red Lane’ plums showed no ethylene production during 6 d ripening at 20 °C after 10 or 20 d cold storage at 0 °C, while decreased ethylene production was exhibited after 30 d (60% and 89% less ethylene production for ‘Blackamber’ and ‘Red Lane’, respectively), in contrast to the higher concentration of ethylene measured in untreated fruit. 1-MCP-treated ‘Blackamber’ and ‘Red Lane’ plums stored at 10 °C exhibited no ethylene production during ripening at 20 °C after 10 d cold storage, while ethylene production was lower than in untreated fruit after 20 d storage plus 0 d at 20 °C (80 and 88% less ethylene production for ‘Blackamber’ and ‘Red Lane’, respectively). In addition, 1-MCP treated fruit of both cultivars stored at both temperatures exhibited reduced respiration rates compared to the control (data not shown).

Pre-storage 1-MCP significantly delayed softening and skin color darkening during ripening after 10, 20, and 30 d storage at 0 °C compared to untreated fruit, in both ‘Blackamber’ and ‘Red Lane’ plums (Figs. 1 and 2). In general, the delay in softening extended

Table 2

Estimation of days needed by 'Blackamber' and 'Red Lane' plums, untreated or treated with 1-MCP ($0.5 \mu\text{L L}^{-1}$ at 0°C for 24 h), to reach the minimum fruit firmness threshold to be 'ready to buy' ($\leq 22 \text{ N}$) and 'ready to eat' ($\leq 13 \text{ N}$) during retail display at 20°C after 10, 20, and 30 d storage at 0°C or 10°C .

Treatment	Cultivar/ripening stage			
	'Blackamber'		'Red Lane'	
	'Ready to buy'	'Ready to eat'	'Ready to buy'	'Ready to eat'
10 d storage				
Control 0°C	1b*	3c	2c	3c
1-MCP 0°C	3a	13a	5a	13a
Control 10°C	na	na	na	na
1-MCP 10°C	1b	5b	4b	6b
20 d storage				
Control 0°C	1a	2b	2b	3b
1-MCP 0°C	1a	6a	5a	7a
Control 10°C	na	na	na	na
1-MCP 10°C	0b	2b	0c	2b
30 d storage				
Control 0°C	0b	2b	0b	2b
1-MCP 0°C	2a	5a	4a	6a
Control 10°C	na	na	na	na
1-MCP 10°C	na	na	na	na

na, not applicable (fruit was already below the specific firmness threshold for the ripening stage at the end of storage prior to ripening at 20°C).

* For each ripening stage after cold storage, means within the same column followed by the same letter are not significantly different by the LSD test at $P=0.05$.

the shelf life of 'Blackamber' and 'Red Lane' plums after storage at 0 or 10°C , expressed as number of days to reach 'ready to buy' fruit firmness (22 N, minimum bruising threshold for existing packaging and transportation), and to be 'ready to eat' (13 N) during ripening after 10 and 20 d of storage (Table 2). The exception to this rule was the fruit from 'Blackamber' 'ready to buy' after 20 d storage at 0°C . 1-MCP treated fruit stored at 10°C retained firmness comparable to that of untreated fruit stored at 0°C for up to 20 d, but they were over-ripe after 30 d of storage. In contrast, untreated fruit stored at 10°C had unacceptable fruit firmness for marketing after less than 10 d storage for both cultivars tested. 1-MCP-treated 'Blackamber' plums had fruit firmness three to seven times greater than untreated fruit by the fourth day of ripening after 10, 20, or 30 d storage at 0°C . Similarly, 1-MCP-treated 'Red Lane' plums had fruit firmness four to six times greater than untreated fruit. 1-MCP-treated 'Blackamber' fruit stored at 10°C retained firmness up to sixteen times greater than untreated fruit after 10, 20, and 30 d storage, while 'Red Lane' firmness was two to eight times greater.

1-MCP did not affect SSC during storage or ripening of plums (data not shown), but it significantly delayed the decrease in TA during ripening for both 'Blackamber' and 'Red Lane' fruit (Figs. 1 and 2). Color changes, measured as chroma (C^*) and hue angle (h°), were significantly delayed by 1-MCP in both cultivars, respectively. Loss of TA and skin color darkening (C^* or h°) followed the fruit softening pattern during ripening after storage at 0°C and 10°C for both cultivars. The effect of 1-MCP on softening and on skin and flesh color development during ripening at both storage temperatures (0°C and 10°C) was visually observed for both 'Blackamber' and 'Red Lane' plums (Fig. 3). In general, 1-MCP-treated fruit stored at 10°C exhibited delayed or similar ripening behavior compared to untreated fruit stored at 0°C after 10 and 20 d of storage, respectively (Figs. 1 and 2 and Table 2).

3.2. Application of 1-MCP during forced-air cooling (FAC) and storage at 10°C

Both the standard 1-MCP treatment (applied for 24 h) and the novel methodology of applying 1-MCP during FAC (applied for 6 h) delayed ripening changes at both storage temperatures in 'Yummy

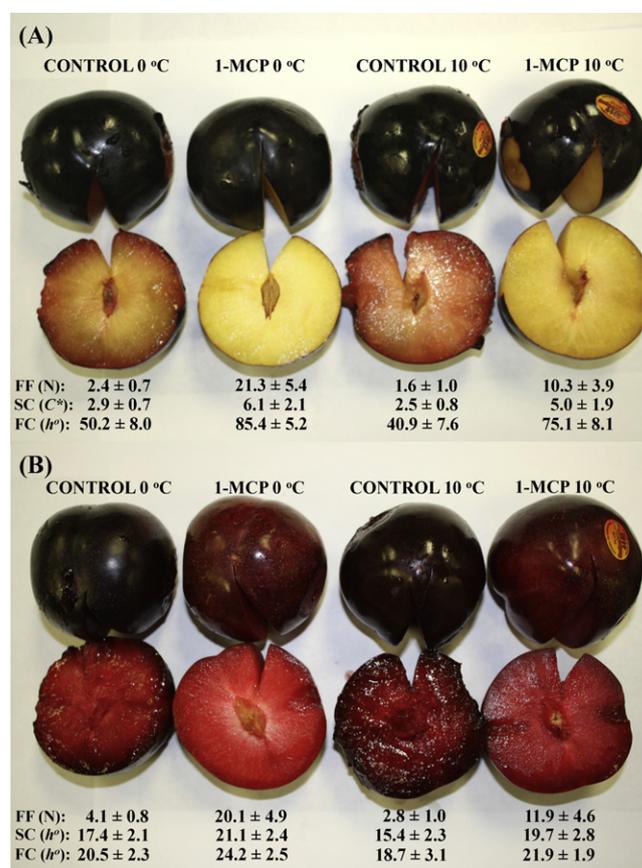


Fig. 3. Skin and flesh color appearance of 'Blackamber' (A) and 'Red Lane' (B) plums untreated or treated with $0.5 \mu\text{L L}^{-1}$ 1-MCP at 0°C for 24 h, after ten days of storage at 0 or 10°C , plus six additional days of ripening at 20°C . Values represent the mean of five replicates of five fruit \pm standard deviation (SD). Abbreviations. FF, fruit firmness (N); SC, skin color (chroma value, C^*); FC, flesh color (hue angle, h°); SC, skin color (hue angle, h°). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Beaut', 'Fortune', and 'Black Splendor' plums. 'Yummy Beaut' and 'Fortune' plums responded similarly to all treatments and storage temperatures; therefore, hereafter only 'Yummy Beaut' and 'Black Splendor' ripening patterns are presented (Figs. 4 and 5). In general, 1-MCP application following the standard 24 h protocol or during FAC for 6 h had similar and significant effect, delaying the onset of ethylene production and decreasing its production compared to untreated fruit after 10 and 20 d of storage at 0°C or 10°C . Interestingly, fruit treated using both 1-MCP application protocols and stored at 10°C had significantly lower ethylene production than untreated fruit stored at 0°C , for all cultivars tested. The efficacy of 1-MCP applied during FAC was similar to the standard 24 h application on 'Yummy Beaut' and 'Fortune' plums, but more effective on 'Black Splendor' plums. On 'Yummy Beaut' plums, the standard 1-MCP treatment (24 h) suppressed ethylene production by 30–35% below that of untreated fruit during ripening at 20°C after 10 and 20 d cold storage (0°C), while a reduction of ~25% was observed when applied during FAC (6 h). On 'Black Splendor' plums, the suppression of ethylene production by FAC-6 h 1-MCP application during ripening at 20°C was greater (66 and 82% after 10 and 20 d storage at 0°C , respectively) than that accomplished by the standard 24-h 1-MCP application (41 and 49% suppression after 10 and 20 d storage, respectively) compared to untreated fruit. During ripening at 20°C , the standard 1-MCP treatment (24 h) showed no significant ethylene suppression in either 'Yummy Beaut' or 'Black Splendor' (24 and 26%, respectively), or for both cultivars with the 6-h FAC application (19 and 18%, respectively) compared

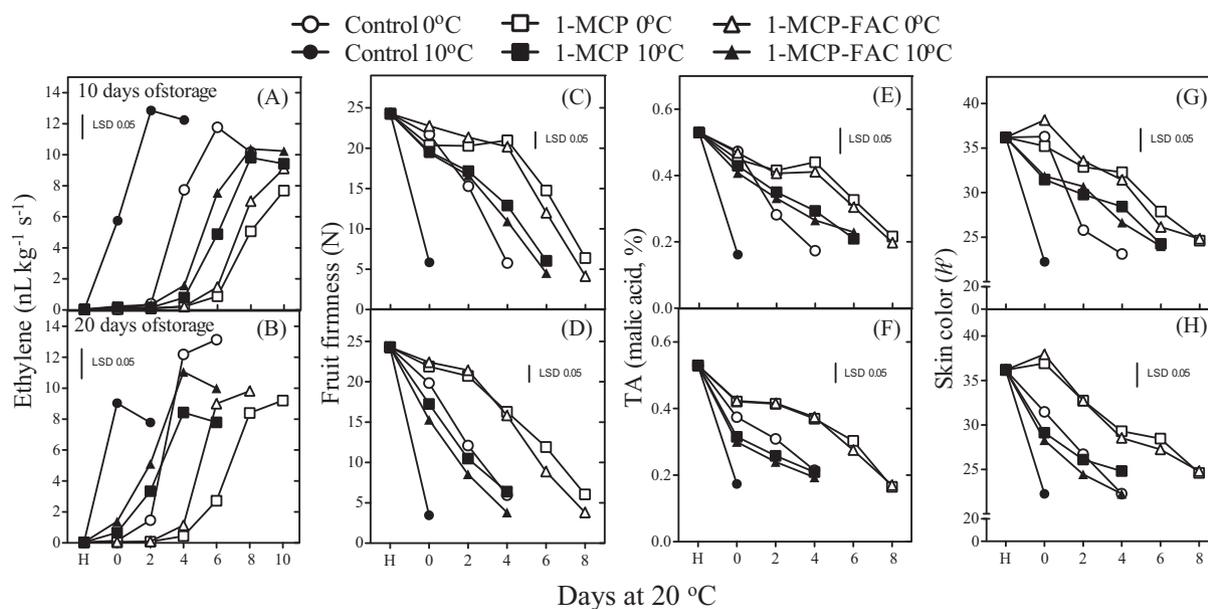


Fig. 4. Postharvest changes in ethylene production (A and B), fruit firmness (C and D), titratable acidity (E and F), and skin color (G and H) of 'Yummy Beaut' plums measured during ripening at 20 °C on fruit treated or untreated with 0.5 μL^{-1} 1-MCP at 0 °C before storage for 24 h (1-MCP) or 6 h (1-MCP-FAC) after 10 (A, C, E and G) and 20 (B, D, F and H) days storage at 0 °C or 10 °C. Each value represents the mean of five replicates of one (ethylene) or five fruit (fruit firmness, TA, skin color) analyzed at each ripening stage after storage. The bar in each particular figure represents the least significant difference (LSD, $P=0.05$). Abbreviations. H, harvest; TA, titratable acidity.

to untreated fruit after 10 d storage at 10 °C. Additionally, 1-MCP treated fruit of all cultivars stored at both temperatures exhibited reduced respiration rates compared to untreated fruit (data not shown).

Both 1-MCP application systems (24-h standard and 6-h FAC) were effective in protecting all cultivars from rapid softening during ripening after 10 or 20 d storage at 0 °C or 10 °C ($P \leq 0.05$). It must be emphasized that the application system of 1-MCP-FAC, when combined with storage at 10 °C, effectively inhibited softening of the three cultivars tested. They exhibited greater or similar firmness

retention compared to untreated, cold-stored (0 °C) fruit during ripening after 10 or 20 d storage. In general, both 1-MCP application protocols extended the shelf life (days to reach 'ready to eat' ≤ 13 N firmness) of 'Yummy Beaut' fruit by 4–6 d longer than untreated fruit stored 10 or 20 d at 0 or 10 °C. However, the 6-h FAC application was more effective in extending the market life of 'Black Splendor' plums than the 24-h standard application, resulting in 1–3 d longer market life after both storage periods and temperatures tested. The standard 1-MCP-treated 'Black Splendor' fruit reached the 'ready to eat' stage firmness (≤ 13 N) 4–6 d later than untreated fruit, while

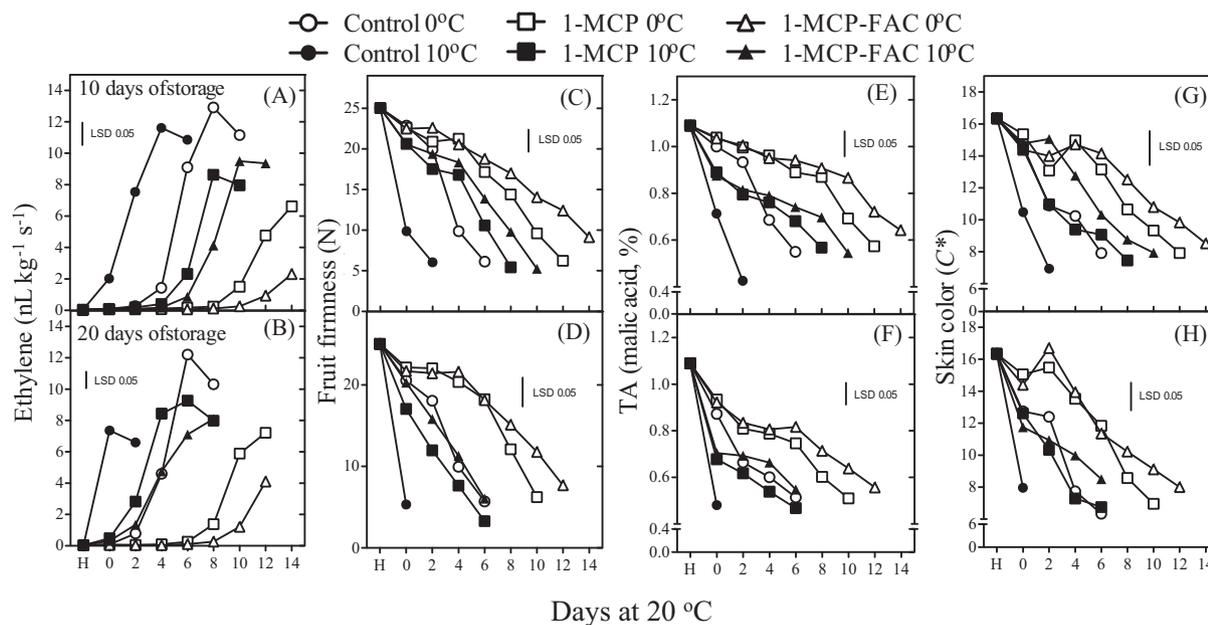


Fig. 5. Postharvest changes in ethylene production (A and B), fruit firmness (C and D), titratable acidity (E and F), and skin color (G and H) of 'Black Splendor' plums measured during ripening at 20 °C on fruit treated or untreated with 0.5 μL^{-1} 1-MCP at 0 °C before storage for 24 h (1-MCP) or 6 h (1-MCP-FAC) after 10 (A, C, E and G) and 20 (B, D, F and H) days storage at 0 °C or 10 °C. Each value represents the mean of five replicates of one (ethylene) or five fruit (fruit firmness, TA, skin color) analyzed at each ripening stage after storage. The bar in each particular figure represents the least significant difference (LSD, $P=0.05$). Abbreviations. H, harvest; TA, titratable acidity.

the fruit treated during FAC reached the 'ready to eat' stage 6–9 d later than control fruit.

In agreement with our previous results for 'Blackamber' and 'Red Lane', SSC was not affected by either 1-MCP application method (data not shown). However, TA loss and color development, measured as hue angle (h°) and chroma (C^*), were significantly delayed by 1-MCP in 'Yummy Beaut' and 'Black Splendor' plum fruit, respectively (Figs. 4 and 5). Also, as found for 'Blackamber' and 'Red Lane', TA loss and color development followed the fruit softening patterns during ripening after storage at 0 °C or 10 °C in 'Yummy Beaut' and 'Black Splendor' fruit. In general, and consistent with the previous experiment, 1-MCP-treated fruit of all cultivars and for both application methods that were stored at 10 °C showed delayed or similar ripening behavior compared to untreated fruit stored at 0 °C for 10 or 20 d, respectively (Figs. 4 and 5).

3.3. In-store consumer test

For both cultivars, degree of liking was significantly affected by the treatments. For 'Yummy Beaut', a low-acid cultivar, consumers liked moderately (6.5–6.8 on a scale from 1=dislike extremely to 9=like extremely) plums from control 'ready to eat', 1-MCP 'ready to eat', and control 'ready to buy' ripening stages, but only liked slightly (6.1) fruit from the 1-MCP 'ready to buy' treatment (Table 3). For fruit from all treatments, acceptance varied from 70% for fruit from 1-MCP 'ready to buy' to near 80% for fruit from the other treatments. 'Ready to buy', 1-MCP treated or untreated plums were disliked by almost 20% of consumers in this low-acid cultivar. For 'Black Splendor', a high-acid cultivar, consumers liked plums from control 'ready to eat' (6.7) more than the other treatment-ripening stages. Plums from 1-MCP 'ready to eat' (6.2) were liked more than control 'ready to buy' (5.5) and 1-MCP 'ready to buy' (5.3) plums. For fruit from all treatments, acceptance varied from 51% for fruit from 1-MCP 'ready to buy' to nearly 80% for fruit from control 'ready to eat'. 1-MCP treated and untreated 'Ready to buy' plums were disliked by nearly 40% of consumers. For both cultivars, there was a significant difference in fruit firmness between 'ready to buy' (~20 N) and 'ready to eat' (~11 N), indicating that ripening to reach the 'ready to buy' and 'ready to eat' stages (22 and 13 N, respectively) was successful.

Our sensory test indicated that 1-MCP treatment had no detrimental effect on consumer acceptance of the low-acid 'Yummy Beaut' plums that were completely ripe ('ready to eat') prior to consumption. For the low-acid 'Yummy Beaut' plums, liking of the incompletely ripened ('ready to buy') fruit treated with 1-MCP was less than for the completely ripened ('ready to eat') fruit (1-MCP treated or untreated), but these fruit were still accepted by 70% of consumers. In contrast, for the high-acid 'Black Splendor' plums, 1-MCP treatment with incomplete ripening prior to consumption significantly reduced acceptance. For ripe ('ready to eat'), high-acid 'Black Splendor' plums, 1-MCP decreased liking from moderately (6.7) for untreated fruit to slightly (6.2.), with a loss of about 12% of consumers. There were no significant differences in liking between 1-MCP 'ready to buy' and control 'ready to buy' fruit: in both cases approximately 40% of consumers disliked this type of fruit.

4. Discussion

In this work, pre-storage 1-MCP application resulted in a significant, consistent decrease and delay of ethylene production during the ripening of several plum cultivars after several storage periods compared to untreated fruit, as in previous studies (Abdi et al., 1998; Martinez-Romero et al., 2003; Valero et al., 2003; Candan et al., 2006; Manganaris et al., 2008). It is noteworthy that a significant reduction in ethylene production, with inhibition of

ripening triggered by ethylene, was also observed when the fruit were treated with 1-MCP and subsequently stored at 10 °C. As a result, ethylene-dependent ripening processes such as softening were delayed, extending shelf life of the treated fruit. In previous studies on different plum cultivars (Martinez-Romero et al., 2003; Valero et al., 2003; Salvador et al., 2003; Menniti et al., 2004), 1-MCP-treated fruit retained higher firmness during ripening than untreated fruit ($P \leq 0.05$), extending its shelf life. The slower softening observed in 1-MCP-treated fruit may be due to the low ethylene production and fewer available receptors induced by the 1-MCP treatment, since flesh softening and skin and flesh color changes are ethylene-dependent processes (Lelievre et al., 1997). Moreover, ethylene participates in the development of cold storage and CI symptoms in climacteric plums and 1-MCP effectively reduces CI symptoms, not only due to its action on ethylene, but also by directly affecting the antioxidant potential (Larrigaudiere et al., 2004; Menniti et al., 2006; Candan et al., 2008, 2011). However, we observed that ethylene affects specific cold storage disorder symptoms such as translucency and flesh browning, but not typical CI symptoms such as mealiness (Crisosto, unpublished).

In this work, fruit skin and flesh color development were delayed by 1-MCP during ripening, as observed previously in other Japanese and European plum cultivars (Dong et al., 2002; Salvador et al., 2003; Menniti et al., 2004; Candan et al., 2011). 1-MCP reduced red flesh color development, coinciding with observations made in 'Laetitia' (Argenta et al., 2003) and 'Blackamber' (Candan et al., 2006) plums. This color change inhibition was more effective on cold-stored (0 °C) fruit than on fruit stored at 10 °C. 1-MCP did not affect SSC, but delayed the metabolism of TA during fruit ripening, as previously reported (Dong et al., 2002; Argenta et al., 2003; Salvador et al., 2003; Khan and Singh, 2009). 1-MCP-treated fruit stored at 10 °C retained less acidity than treated fruit stored at 0 °C. This retention of acidity after 1-MCP application may be due to the decreased respiration, as observed in other cultivars (Dong et al., 2002; Argenta et al., 2003; Salvador et al., 2003).

Plums treated with 1-MCP and subsequently stored at 10 °C exhibited similar storage performance and ripening behavior compared to untreated fruit stored at the recommended 0 °C for up to 20 d. Furthermore, with this protocol, fruit may have an extra 2–3 d of market life and would be less likely to suffer damage from bruising during postharvest retail handling (Crisosto et al., 2001). Previous studies by our group (Palou and Crisosto, unpublished data) have shown that 10 °C for up to 2 weeks does not trigger cold storage disorders, including CI symptoms. Combining 1-MCP treatment with storage at 10 °C offers a solution to potentially avoid CI symptoms and improve consumer acceptance.

Cold storage is the main postharvest tool used for stone fruit. While it slows down ripening and preserves fruit quality, it is an important energy consumer and the main economic investment during postharvest handling of plums in California (Thompson et al., 2010). 1-MCP may provide a useful tool for energy savings during plum storage without a consumer-noticeable reduction in fruit quality and storability. Pre-storage 1-MCP treatment followed by storage at 10 °C would cost an estimate 126.0 versus the 194.4 kJ kg⁻¹ needed for storage at 0 °C for up to 20 d in the California climate (Thompson and Singh, 2008). Thus, our proposed new protocol would reduce energy use by 35%, reducing fresh fruit costs from \$8.10 to \$5.25 per ton (Thompson et al., 2010). Reduced energy consumption and/or more efficient energy use are current challenges towards reducing CO₂ output and costs.

The ability of 1-MCP applied during FAC to decrease and delay ethylene production and, therefore, extend plum shelf life, reduced the application duration from 24 to 6 h. This is a promising and innovative outcome from our study. The reduced time required would allow this technology to be adopted easily by growers because it does not add an extra step to the current postharvest

Table 3
Consumer acceptance (140 consumers) and quality attributes of different ripening stages of 'Yummy Beaut' and 'Black Splendor' plum samples previously untreated or treated with 1-MCP (0.5 $\mu\text{L L}^{-1}$ at 0 °C for 24 h).

Cultivar/treatment-ripening stage	Degree of liking (0–9) ^a	Acceptance (%)	Neither like nor dislike (%)	Dislike (%)	Firmness (N)	SSC (%)	TA (%)	SSC:TA	Days to reach firmness ^b
'Yummy Beaut'									
Control 'ready to eat'	6.8a [*]	79.3	5.7	15.0	10.6c	12.5b	0.4b	39.1a	5
1-MCP 'ready to eat'	6.7a	82.9	5.7	11.4	10.9c	12.4b	0.3b	40.7a	9
Control 'ready to buy'	6.5ab	76.4	5.0	18.6	19.2b	13.3a	0.5a	30.6b	3
1-MCP 'ready to buy'	6.1b	70.0	10.0	20.0	20.1a	13.0a	0.5a	27.3b	7
'Black Splendor'									
Control 'ready to eat'	6.7a	79.3	7.9	12.9	11.1c	13.1a	0.9b	14.7a	7
1-MCP 'ready to eat'	6.2b	67.1	8.6	24.3	11.8c	13.0a	1.0b	13.8a	13
Control 'ready to buy'	5.5c	55.7	6.4	37.9	19.3b	13.1a	1.2a	11.8b	4
1-MCP 'ready to buy'	5.3c	51.4	7.8	40.7	20.2a	12.9a	1.1a	11.9b	9

^a Degree of liking: 1 = dislike extremely; 2 = dislike very much; 3 = dislike moderately; 4 = dislike slightly; 5 = neither like nor dislike; 6 = like slightly; 7 = like moderately; 8 = like very much; 9 = like extremely.

^b Days to reach firmness ≤ 22 N ('ready to buy') and ≤ 13 N ('ready to eat').

^{*} For each cultivar, means within the same column followed by the same letter are not significantly different by the LSD test at $P=0.05$.

handling of plums. Forced-air cooling is a rapid cooling method (75–90% faster than conventional room cooling) widely used for stone fruit and other packaged fresh commodities in California (Wills et al., 1998; Thompson et al., 2002). Besides the energy savings mentioned above, the proposed new application system would also require less time to cool fruit to the higher suggested storage temperature (10 °C). Depending on climatic conditions, the desired temperature could be reached in 3 h rather than 8 h. This would allow more than double the quantity of fruit that could be processed by a facility per unit time, providing a more efficient use of the FAC equipment. Moreover, no additional special facilities are needed to treat fruit with 1-MCP.

When 1-MCP was applied at low temperature (0 °C), the treatments were less effective at preventing ethylene responses than when applied at 20 °C in several fruit species including apples, peaches, nectarines, and pears (DeEll et al., 2002; Blankenship and Dole, 2003; Liguori et al., 2004; Villalobos-Acuña et al., 2011). Lower temperatures may decrease 1-MCP affinity or interaction with ethylene receptors, decrease solubility, and affect enzymatic metabolism of 1-MCP in the cytoplasm (Mir et al., 2001; Huber et al., 2010). However, 1-MCP treatment applied during FAC is very efficient. Almost 80–100% adsorption efficiency has been reported for gases like sulfur dioxide with this application system (Cantín et al., 2011). It is possible that 1-MCP gas can penetrate fruit tissues more rapidly during FAC than in a conventional cold room, where the air moves passively around the containers. Thus, 1-MCP mobility and flow into fruit tissues to interact with ethylene receptors may be greater during FAC. Further studies would clarify the role of temperature and FAC in the solubility and movement of 1-MCP in cytoplasm and its interactions with ethylene receptors. Ethylene competing with 1-MCP to bind receptor sites modulated 1-MCP responses in several plant species (Sisler et al., 2003). Ethylene produced by the fruit at the onset of ripening has been proposed as one reason for variations in 1-MCP response among cultivars, times after harvest, and different maturity stages in some climacteric fruits that produce high ethylene concentrations during ripening (Zhang et al., 2009; Villalobos-Acuña et al., 2011). Here, differences in responses of several cultivars to different 1-MCP application protocols could be due to different ethylene production rates during the 1-MCP application.

Besides the beneficial effects of 1-MCP on slowing fruit ripening, it is critical that fruit treated with 1-MCP reach high quality prior to consumption. For this reason, fruit were presented to consumers at the same ripening stage regardless of treatment to ensure that any differences detected were due to treatment with 1-MCP and not to the different fruit ripening stages. The sensory data of

the current study confirmed our ongoing tree fruit sensory work indicating that ripening is necessary to maximize potential flavor perception (Crisosto et al., 2004). The number of days needed to reach the 'ready to eat' stage was longer for 1-MCP-treated fruit than for untreated fruit; it took 4 and 6 d longer to reach the 'ready to eat' stage for 'Yummy Beaut' and 'Black Splendor', respectively. Thus, 1-MCP treatment has the potential to extend postharvest life during warm display (15–25 °C) and still reach the 'ready to eat' stage. This also points out the need for a longer ripening period prior to consumption on 1-MCP treated plums.

Perception of sweetness by consumers is directly related to acceptance and is a response to the ratio SSC:TA. In previous sensory studies performed on plums, consumer acceptance was reduced in high-acid plums probably because consumers preferred sweet plums when acidities were higher than 0.9% (Crisosto et al., 2004). 1-MCP had no detrimental effect on consumer acceptance of low-acid plums ripened completely ('ready to eat') prior to consumption. Consumer acceptance was significantly reduced in untreated and treated high-acid 'Black Splendor' plums, compared to the low-acid 'Yummy Beaut' plums, probably due to the low SSC:TA recorded (11.9–14.7 and 27.3–40.7 for the high- and the low-acid cultivar, respectively). Ripe, 1-MCP-treated plums with high acidity were liked less than untreated plums, but were still accepted by consumers. These results support the recommendation that 1-MCP use in plum should be integrated into a holistic strategy that considers both its beneficial effect on ripening inhibition and factors affecting consumer acceptance. This SSC:TA balance is particularly important in old released early cultivars and/or cultivars harvested prior to be ripened on the tree (early maturity) when they have high acidity.

5. Conclusions

Considerable energy can potentially be saved by cooling and storing 1-MCP-treated plums at 10 °C, without reducing postharvest life or fruit quality. The proposed 1-MCP application protocol during the forced-air cooling operation reduced the application duration to 6 h without affecting postharvest performance of plums or interrupting handling operations. Thus, this novel 1-MCP-FAC application method can replace the currently recommended 24 h application and would be easily adopted by the tree fruit industry.

1-MCP treatment had no detrimental effect on consumer acceptance of properly ripened, low-acid plums, but significantly reduced acceptance of high-acid or early-harvested plums. Our results are sufficiently encouraging to justify large-scale

commercial testing to accurately quantify energy savings and consumer reactions for specific operations and markets.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.postharvbio.2012.08.013>.

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