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Quality characteristics of fresh-cut watermelon slices from non-treated and 1-methylcyclopropene- and/or ethylene-treated whole fruit

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Abstract

Maintaining the postharvest quality of fresh-cut fruit after processing and throughout distribution and marketing is a major challenge facing the fresh-cut fruit industry. Analytical quality characteristics of packaged fresh-cut watermelon slices from non-treated and 1-methylcyclopropene (1-MCP)- and/or ethylene-treated whole fruit were investigated. Freshly harvested seedless watermelon ('Sugar Heart') were stored 7–14 days in air before exposure to 0, 0.5 or 1.0 $\mu\text{L L}^{-1}$ 1-MCP for 18 h followed by 5 days exposure to 0 or 10 $\mu\text{L L}^{-1}$ ethylene, all at 20 °C. Following treatment, fruit were processed into wedge-shaped slices, packaged into rigid trays sealed with a high oxygen transmission rate film overlap and stored 1, 6 or 12 days at 5 °C. During storage, fresh-cut watermelon slices from non-treated and 1-MCP- and 1-MCP + ethylene-treated whole fruit maintained similar respiration rates and internal atmospheres of CO₂ and O₂ and were of similar quality with total aromatic volatile concentrations decreasing and puncture firmness, soluble solids content (SSC), cut surface pH and color remaining relatively stable. In contrast, fresh-cut slices from fruit treated with ethylene alone had higher respiration rates and modified package atmospheres containing more CO₂ and O₂; lower firmness, SSC and chromaticity values; higher pH and an altered volatile profile compared to those of slices from non-treated and 1-MCP- and 1-MCP + ethylene-treated fruit. The 22 most abundant volatiles were various aldehydes, alcohols and ketones. During storage, many individual volatiles decreased in concentration but some increased including (Z)-6-nonen-1-ol, a volatile having a pumpkin-like aroma. The results indicated that low dosage 1-MCP treatments prior to ethylene exposure of whole watermelons prevented ethylene-mediated quality deterioration in fresh-cut slices stored under modified atmosphere conditions at 5 °C.

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 Keywords: *Citrullus lanatus*; Ethylene; 1-Methylcyclopropene; Quality; Respiration rates; Volatiles

1. Introduction

The market for fresh-cut watermelon [*Citrullus lanatus* (Thunb. Matsum. and Nakai)] has increased at a rate of 20–30% annually (Fonseca et al., 2004), and the fresh-cut product now accounts for 46% of total watermelon sales and over 80% of total fresh-cut watermelon/melon sales (National Watermelon Promotion Board, 2005). Fresh-cut watermelon is marketed as halves, quarters and slices with rinds, or as rind-free chunks. Quality degradation has been associated

with decreased acceptability of texture, color and sweetness (Rushing et al., 2001), with shelf-life limited by water soaking, juice leakage (Cartaxo et al., 1997), off-odor development (Fonseca et al., 2004) and increased microbial growth and spoilage (Mao et al., 2006).

Uncut freshly harvested or stored watermelons normally produce ethylene at low (0.3 nL kg⁻¹ s⁻¹) rates (Elkashif and Huber, 1988; Rushing, 2004) and otherwise exhibit a non-climacteric pattern of ripening (Elkashif et al., 1989). Although production rates are normally low, fruit are sensitive to exogenously applied ethylene, exhibiting softening and water soaking of the flesh accompanied by off-odor development at ethylene concentrations as low as 1 $\mu\text{L L}^{-1}$ (Rissi and Hatton, 1982; Shimokawa, 1973). The response of watermelons to ethylene is not associated with fruit

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maturation (Karakurt and Huber, 2002) or normal ripening (Elkashif and Huber, 1988), but rather to a postharvest disorder in which phospholipid degradation and membrane deterioration are involved (Karakurt and Huber, 2004; Mao et al., 2004).

1-Methylcyclopropene, a potent inhibitor of ethylene action, maintains specific quality attributes and prolongs shelf-life of many fruits, especially climacteric fruit, but can also inhibit aromatic volatile production that contributes to the aroma (and flavor) of the fruit (Blankenship and Dole, 2003). In watermelon, 1-MCP has recently been shown to maintain the firmness of whole fruit stored in the presence or absence of added ethylene (Mao et al., 2004), but was not able to maintain firmness or extend shelf-life of fresh-cut placental pieces stored in air at 10 °C (Mao et al., 2006).

While whole melons and watermelons stored below 10 °C may develop rind and flesh damage, fresh-cut melon and watermelon products are not as chilling injury sensitive as the corresponding whole fruit (Beaulieu and Gorny, 2004). Temperatures near 0 °C generally provide optimal shelf-life by inhibiting growth of spoilage microorganisms. Fresh-cut watermelon has been stored for ≥ 9 days at 1–3 °C under modified atmosphere (MA) conditions (Fonseca et al., 2004). However, the flesh of chill sensitive fruit may still be chilling injured. No studies have indicated if quality-associated aromatic volatile profiles and concentrations in fresh-cut watermelon are affected by low temperature storage or by 1-MCP treatment of whole fruit.

The objective of this study was to examine the influence of 1-MCP, ethylene, and 1-MCP+ethylene applied to whole ‘Sugar Heart’ watermelon, on respiration and quality attributes, including aromatic volatile concentrations, of subsequently processed fresh-cut watermelon slices stored at 5 °C under modified atmosphere conditions.

2. Materials and methods

2.1. Plant material

Seedless watermelon (*C. lanatus* Thunb. Matsum. and Nakai, ‘Sugar Heart’) were harvested at the commercial maturity (fully ripe) stage as determined by a major grower/packer in central Delaware, placed in padded containers to avoid physical injury, and immediately transported to the ARS Agricultural Research Center in Beltsville, MD. Undamaged fruit weighing about 9 kg each were stored 7 or 14 days at 20 \pm 1 °C until used for experimentation.

2.2. 1-MCP and ethylene application and whole fruit storage

At both 7 and 14 days after harvest, sets of 20 fruit were treated with 0, 0.5 or 1.0 $\mu\text{L L}^{-1}$ 1-MCP (SmartFresh™,

Rohm and Haas Co., Spring House, PA) for 18 h at 20 \pm 1 °C as previously described (Saftner et al., 2003a). Subsets (10 fruit) of the control and the 1-MCP-treated watermelons were then treated with 0 or 10 $\mu\text{L L}^{-1}$ ethylene for 5 days at 20 \pm 1 °C. The watermelons were stored an additional day in air at 20 \pm 1 °C. Non-treated and 1-MCP- and/or ethylene-treated fruit were kept in separate treatment/storage areas to avoid possible contamination by 1-MCP or ethylene out-gassing.

2.3. Processing of watermelons and storage of fresh-cut slices

Non-treated and treated watermelons were rinsed with tap water followed by two 1-min dips with 100 $\mu\text{L L}^{-1}$ sodium hypochlorite (pH 6.5). With a sharp sanitized custom-made knife assembly, four 4-cm wide rings were latitudinally cut simultaneously from the center of the fruit. Each of the four rings was then processed into six equally sized wedge-shaped slices. The 24 slices from each watermelon were randomized and 18 were placed (two per container) into 13.5 cm \times 19 cm \times 4 cm rigid polypropylene trays (Pactiv Corporation, Lake Forest, IL, USA) and the trays sealed with a 29.2 $\text{pmol s}^{-1} \text{m}^{-2} \text{Pa}^{-1}$ oxygen transmission rate (OTR) film. Film OTR was determined by the film manufacturer (Package Concept Corporation, Salinas, CA, USA) at 23 °C using a MOCON apparatus to measure steady state rate of dry O₂ gas transmission through plastic films, i.e., according to ASTM International procedure D 3985-81 (ASTM International, 1986). At 5 °C in air, the film OTR was 10.5 $\text{pmol s}^{-1} \text{m}^{-2} \text{Pa}^{-1}$, as determined following an exponential decay method for determining OTRs through plastic films in a static cell (Moyle et al., 1992). The samples were stored at 5 \pm 1 °C and examined at 1, 6 and 12 days. Three packages (six slices) from each of five watermelons (replications) per treatment per evaluation time were evaluated. Three slices from each of four watermelons from each treatment also were placed in sealed 3.8-L glass jars and respiration, as evolved CO₂, and ethylene production rates were measured every 8 h during a 12-day period at 5 \pm 1 °C using an automated system (Izumi et al., 1996).

2.4. Quality assessments of packaged watermelon slices

The concentrations of O₂, CO₂ and ethylene in the atmosphere of the sealed trays on day 6 and 12 were measured using gas chromatography (GC) as previously described (Saftner et al., 1999). Gas concentrations are the means of 15 measurements (three trays per replicate \times 5 replicates) per treatment.

Texture, cut surface color and pH, SSC, and aromatic volatile concentrations were measured using six slices of each replicate sample from each treatment following 1, 6 and 12 days storage at 5 \pm 1 °C under modified atmosphere conditions.

The firmness of placental (curved inner mesocarp tissue around the ovules), heart (central core of inner mesocarp) and rind (white outer mesocarp, green hypoderm and epicarp) tissues of fresh-cut slices was determined using a texture analyzer (model TA.XTPlus; Stable Microsystems, Gomalming, Surrey, U.K.). Puncture firmness was measured with a 10-mm-diameter cylindrical probe to a deformation of 10 mm at 2.0 mm s^{-1} . For each tissue type, the force/deformation curves were analyzed for peak force and area under the entire curve as well as for overall curve profile. During punctures of placental tissue, care was taken to avoid vascular tissue strands and vestigial seeds.

Flesh color (CIE L^* , a^* , b^*) was measured on the cut surface of heart tissue using a Minolta chroma meter (model CR-300, Tokyo, Japan) calibrated with a white tile. One reading was taken from each of six slices of each replicate sample. Color results were expressed as lightness (L^*), a^* and b^* chromaticity, chroma ($C^* = [(a^*)^2 + (b^*)^2]^{0.5}$) and hue angle ($h_{ab} = \tan^{-1}[(b^*)/(a^*)^{-1}]$). Surface pH was also measured on heart tissue from each of six slices of each replicate sample using three-dye pH indicator strips (pHIX pH 2.0–9.0 in 0.5 pH units; Mallinckrodt Baker Inc.; Phillipsburg, NJ, USA).

Soluble solids content from juice extracts (tissue purees) were analyzed using a digital temperature-compensated refractometer (model PR-101; Atago Co., Tokyo, Japan). Juice extracts were prepared by dicing 40 g of heart tissue with a razor blade and homogenizing the diced tissue with a polytron (model PT-10; Brinkmann Instruments, Westbury, NY, USA) for ~ 10 s at speed setting 4. The juice extracts were also used for aromatic volatile measurements. For volatile analyses, 1 mL of juice from each replicate sample was transferred to a 4-mL vial containing 0.3 mL of 3 M CaCl_2 (to inhibit enzymatic production of secondary volatiles), the vial capped with a Teflon-lined septum and the sample stored for up to 3 weeks at -20°C before being analyzed. Analysis of aromatic volatile concentration using a solid-phase microextraction (SPME; Suppelco Co., Bellefonte, PA, USA) technique for volatile collection over a 16-min sorption period and GC-flame ionization detector (FID) (model 6890; Agilent Technologies, Rockville, MD, USA) for volatile separation and quantification was performed as previously described (Saftner, 1999) except that the SPME fiber used for volatile collection was coated with $75 \mu\text{m}$ carboxen-polydimethylsiloxane. Constructing calibration curves for each volatile analyte in each watermelon juice sample is not feasible and thus total volatile and individual volatile concentrations are reported in detector response units of picoamps (pA) rather than absolute amounts (Saftner et al., 2002). For volatile identification, a GC–mass spectrometer (MS) procedure was used as previously described (Saftner et al., 2002). Identification of volatile components was confirmed by comparison of collected mass spectra with those of standards and spectra in the National Institute for Standards and Technology (NIST) mass spectral library, Search Version D.04.00 (Agilent Technologies, Rockville, MD, USA).

2.5. Statistical analyses

The experimental design was a split-plot in a randomized complete block with four (respiration and ethylene production data) or five (all other analytical data) replications. In the initial experiment, treatments were arranged in a 6×3 factorial: [control (non-treated), $0.5 \mu\text{L L}^{-1}$ 1-MCP, $0.5 \mu\text{L L}^{-1}$ 1-MCP + $10 \mu\text{L L}^{-1}$ ethylene, $1.0 \mu\text{L L}^{-1}$ 1-MCP, $1.0 \mu\text{L L}^{-1}$ 1-MCP + $10 \mu\text{L L}^{-1}$ ethylene and $10 \mu\text{L L}^{-1}$ ethylene] whole-plot \times [1, 6 and 12 days storage at 5°C] sub-plot. When the experiment was repeated, treatments were arranged in a 4×3 factorial since the two lower concentration 1-MCP treatments were not included.

Data were analyzed by repeated measures analysis of variance (ANOVA) using Proc MIXED[®] (SAS[®] Version 9.1.3, 2004) with compound symmetric (TYPE=CS) among-storage day covariance structure for responses measured on co-mingled wedges and unstructured (among wedges) \times compound symmetric (among storage days) (TYPE=UN@CS) covariance structure for responses measured on individual wedges. When effects were statistically significant, Sidak-adjusted LSD means comparisons were conducted to ensure an $\alpha = 0.05$ experiment-wise error rate. All differences mentioned were significant unless stated otherwise.

3. Results and discussion

3.1. Respiration and ethylene production rates and in-package atmospheric gas concentrations

The respiration rate, measured as evolved CO_2 , of fresh-cut watermelon slices decreased during the first 2 days after processing (Fig. 1) and was probably due to recovery from tissue wounding and to an excision-related decrease in resistance to CO_2 gas exchange from the tissue. A similar wound response has been reported for freshly cut muskmelon (Luna-

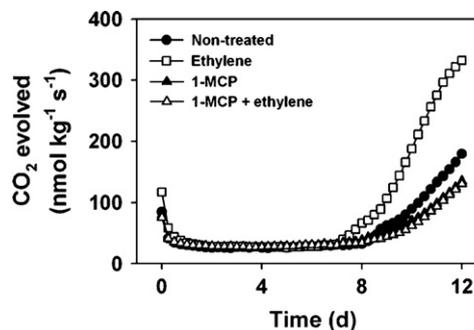


Fig. 1. Respiration rate, as evolved CO_2 , of fresh-cut watermelon slices during 12 days storage at 5°C following non-treatment or treatment of the whole fruit with $1.0 \mu\text{L L}^{-1}$ 1-MCP for 18 h at 20°C and/or $10 \mu\text{L L}^{-1}$ ethylene for 5 days at 20°C . One measurement from each of four replications ($n = 4$) were averaged to obtain a representative value at each 6-h storage time.

Guzmán et al., 1999) and honeydew (Saftner et al., 2003b). Following wound recovery, the respiration rate was relatively stable for ~6 days in all slices from treated and non-treated fruit. However, the stable respiration rate was more than an order of magnitude lower than those reported in watermelon placental pieces stored in air at 10 °C (Mao et al., 2006). Differences in storage temperature as well as watermelon genotype, cultural conditions, degree of tissue wounding and tissues evaluated may have accounted for the large differences in respiration rates between this study and that of Mao and coworkers. After 8 days, CO₂ production increased continually, reaching rates as high as 335 pmol kg⁻¹ s⁻¹. Since whole watermelons do not go through a climacteric CO₂ production after harvest, at least part of the increased CO₂ production was probably due to increased microbial growth and/or to altered physiology of the fresh-cut product. During the last 4 days storage, slices from fruit treated with ethylene alone had both a higher CO₂ production rate (Fig. 1) and higher populations of bacteria and yeast and mold (Zhou et al., 2006) compared to slices from non-treated fruit which in turn generally had higher CO₂ production rates than slices from fruit treated with 1-MCP or 1-MCP + ethylene. Extending the time from harvest to 1-MCP treatment had no consistent effect on apparent respiration rates of fresh-cut slices (data not shown). Overall, 1-MCP treatment prevented the ethylene-induced increased production of CO₂, at least during the last 4 days storage.

We did not measure ethylene production rates of fresh-cut slices during storage since evolved ethylene was below the detection level (~40 pmol kg⁻¹ s⁻¹) for our automated flow through system. We also did not detect ethylene in the headspace of packaged slices during storage, a finding that is consistent with those of Mao et al. (2006) for watermelon slices stored in vented containers at 10 °C for 7 days. As suggested previously by Perkins-Veazie and Collins (2004), the modified atmospheres that develop in sealed packages of fresh-cut watermelon fruit might suppress [or prevent] ethylene production.

In this study, modified atmospheres variably developed within the packaged watermelon slices. During storage, the O₂ concentrations in the package atmosphere decreased and CO₂ increased, irrespective of treatment. By 12 days, the modified atmosphere for packaged slices from ethylene-treated fruit was 2.6 ± 1.3 kPa O₂ and 6.5 ± 0.1 kPa CO₂ while that for packaged slices from non-treated and 1-MCP-treated fruit (combined data) was less modified, containing 6.2 ± 0.8 kPa O₂ and 3.3 ± 0.1 kPa CO₂. Regardless of whether or not package atmospheres suppressed ethylene production, fresh-cut watermelon products in general have a low capacity to produce ethylene.

3.2. Puncture firmness analyses

The F_{max} of placental, heart and rind tissues of fresh-cut slices decreased during storage regardless of treatment, though the decrease was only significant for heart tissue of slices from fruit treated with ethylene alone (Fig. 2).

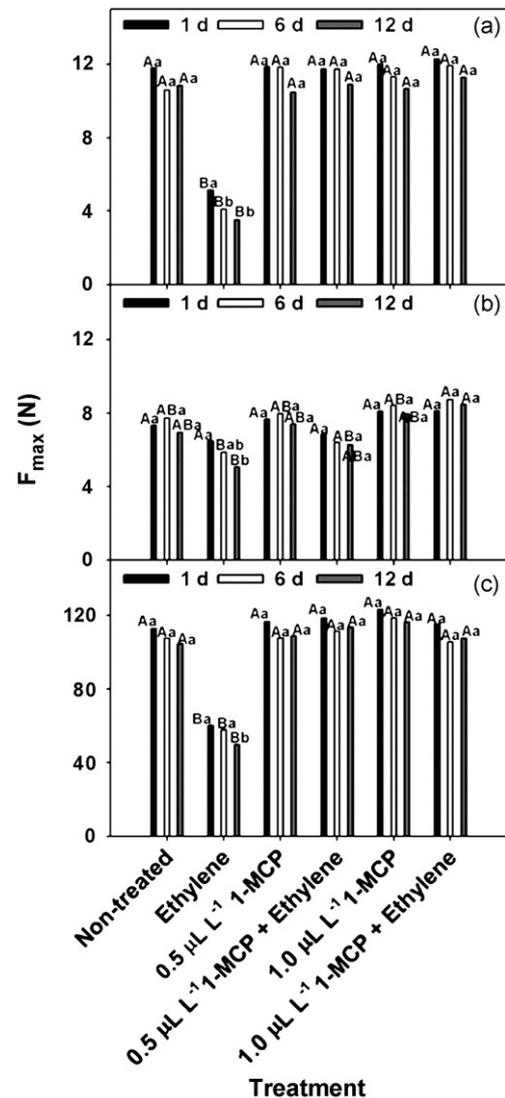


Fig. 2. Puncture (F_{max}) firmness of placental (panel a), heart (panel b) and rind (panel c) tissues of fresh-cut watermelon slices stored up to 12 days at 5 °C under modified atmosphere conditions following non-treatment or treatment of the whole fruit with 0.5 or 1.0 µL L⁻¹ 1-MCP for 18 h at 20 °C and/or 10 µL L⁻¹ ethylene for 5 days at 20 °C. Six measurements from each of five replications ($n=30$) were averaged to obtain a representative value at each storage time. Within time periods within panels, symbols labeled with the same A, B letters are not significantly different using Sidak-adjusted means comparison ($\alpha=0.05$). Within treatments within panels, symbols labeled with the same a, b letters are not significantly different using Sidak-adjusted means comparison ($\alpha=0.05$).

As storage time before processing of whole watermelons increased, the F_{max} of all three tissues evaluated in correspondingly treated fruit decreased but not significantly (data not shown). Among treatments, all three tissues of watermelon slices from whole fruit treated with ethylene alone were softer than those from all other treatments (Fig. 2). Low (both 0.5 and 1.0 µL L⁻¹ for 18 h) dosage 1-MCP treatments prevented ethylene-induced softening in all tissues evaluated. However, 1-MCP by itself did not increase or otherwise affect F_{max} in fresh-cut slices from 1-MCP-treated whole

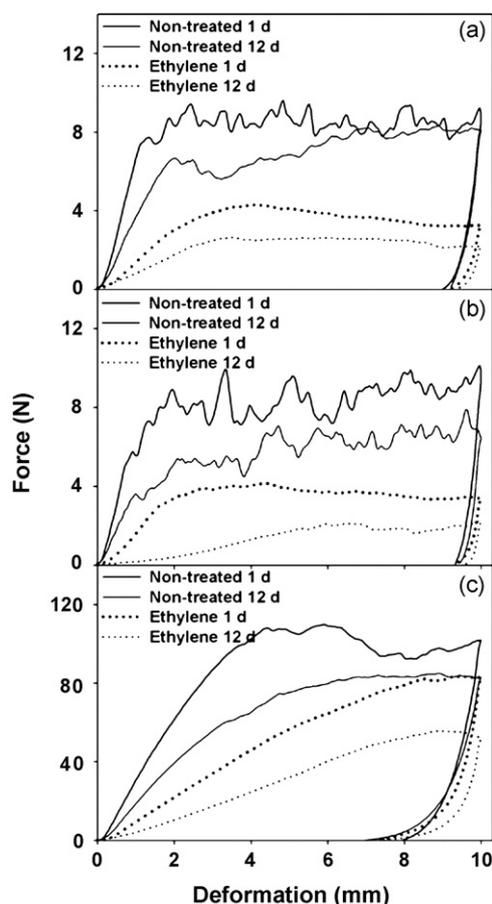


Fig. 3. Firmness measurements on placental (panel a) and rind (panel c) tissues of fresh-cut watermelon slices stored up to 12 days at 5 °C under modified atmosphere conditions following non-treatment or treatment of the whole fruit with 10 $\mu\text{L L}^{-1}$ ethylene for 5 days at 20 °C. Each curve is a representative sample of a single tissue puncture of fresh-cut watermelon slices stored up to 12 days at 5 °C under modified atmosphere conditions.

watermelon, suggesting that at least part of the softening of watermelon tissue during storage at 5 °C is a consequence of ethylene independent ripening and/or chilling injury effects. Extending the time from harvest to 1-MCP treatment consistently led to slightly lower puncture firmness measurements in tissues of freshly cut watermelon slices, but the changes in firmness were not significant. Interestingly, heart tissue was considerably less sensitive to ethylene-induced softening than placental or rind tissues (Fig. 2). The same softening patterns were observed when area under the force/deformation curve, which approximates the energy required to penetrate the tissue, was used as the measurement parameter for firmness (data not shown).

During storage of fresh-cut watermelon slices, the shape of the puncture force/deformation curves changed for placental, heart and rind tissues (Fig. 3). The placental (Fig. 3a) and heart (Fig. 3b) force/deformation curves of slices from whole fruit treated with ethylene alone were much smoother, specifically lacking the numerous secondary peaks around 2–10 mm deformation. Ethylene treatment also changed the

shape of rind force/deformation curves by delaying and sometimes even preventing tissue fracturing (Fig. 3c). During storage of fresh-cut slices processed from non-treated fruit, curve shapes became more attenuated and less complex but never to the degree observed in tissues treated with ethylene alone (Fig. 3). 1-MCP and 1-MCP + ethylene treatments maintained curve shapes similar to those of corresponding non-treated tissues (data not shown). The effect on textural quality of the shape of the initial peak or of multiple secondary peaks has not been established. We speculate that watermelon tissues having an early tissue fracture followed by many well defined secondary fractures might be perceived as crisp whereas ones with a late maximum lacking secondary peaks or otherwise having secondary peaks with lower force profiles would be tough. Such detailed textural attributes can only be investigated using extensively trained sensory panels. In this study, however, informal tasting of watermelon slices (placental and heart tissues) from non-treated fruit and fruit treated with ethylene alone confirmed that ethylene had severely modified the textural quality of the slices. We also observed that rind tissue pieces felt rubbery and could be bent more severely in the hands before fracturing when excised from watermelon slices of whole fruit treated with ethylene alone compared to those excised from slices of non-treated or 1-MCP-treated whole fruit. Overall, these results and informal observations suggest that 1-MCP can essentially prevent ethylene-mediated softening in fresh-cut watermelon but cannot appreciably counteract softening associated with storage of packaged slices under modified atmospheric conditions in the absence of any detectable ethylene accumulation at 5 °C. Mao et al. (2004, 2006) have previously shown that 1-MCP (10 $\mu\text{L L}^{-1}$ for 18 h at 20 °C) can prevent ethylene-mediated softening of placental pieces but not softening associated with storage in air at 10 °C of non-ethylene-treated pieces.

3.3. Surface color, SSC and surface pH analyses

Surface color (L^* , a^* , b^* , C^* and h_{ab}) of heart tissue did not change appreciably across trials or during storage of fresh-cut slices; however, fresh-cut slices from whole watermelon treated with ethylene alone were darker (lower L^* ; 38.2 ± 0.8 versus 45.8 ± 0.4), less red (lower a^* ; 22.2 ± 0.3 versus 26.3 ± 0.2), more blue (lower b^* ; 13.3 ± 0.7 versus 16.6 ± 0.3) and had lower C^* (24.7 ± 0.5 versus 31.3 ± 0.2) and h_{ab} (29.8 ± 0.7 versus 32.2 ± 0.3) values than those from slices of all other treatments combined. In fresh-cut watermelon, a^* , b^* and C^* values are directly correlated to lycopene and β -carotene concentrations of stored tissue (Penelope Perkins-Veazie, personal communication). In this study, the lower chromaticity values in slices from whole watermelon treated with ethylene alone might indicate an ethylene-induced decrease in carotenoid concentrations and therefore an ethylene-mediated decrease in nutritive value. Consistent with the chromameter results, we consistently observed that placental and heart tissues of watermelon slices from ethylene-treated fruit had a dark, dull red hue with a blue tint

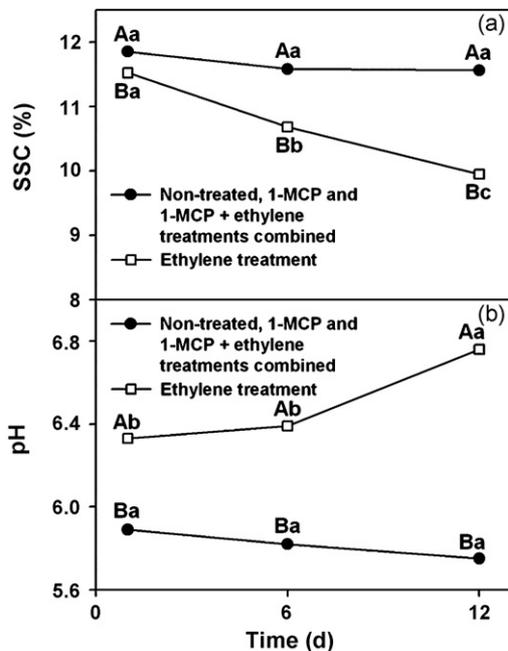


Fig. 4. Soluble solids content (panel a) and surface pH (panel b) of heart tissue from fresh-cut watermelon slices stored up to 12 days at 5 °C under modified atmosphere conditions following non-treatment or treatment of the whole fruit with 1.0 $\mu\text{L L}^{-1}$ 1-MCP for 18 h at 20 °C and/or 10 $\mu\text{L L}^{-1}$ ethylene for 5 days at 20 °C. Data from 1-MCP-, 1-MCP+ethylene-treated and non-treated fruit for each quality characteristic were combined since differences among those treatments were not significant. For each quality characteristic, one measurement from each of five replications ($n=5$ for ethylene treatment and $n=25$ for combined treatments) were averaged to obtain a representative value at each storage time. Within time periods within panels, symbols labeled with the same A, B letters are not significantly different using Sidak-adjusted means comparison ($\alpha=0.05$). Within treatments within panels, symbols labeled with the same a, b, c letters are not significantly different using Sidak-adjusted means comparison ($\alpha=0.05$).

and a water soaked appearance. Water soaking in ethylene-treated fruit is thought to occur as a result of increased lipid metabolism (Karakurt and Huber, 2002, 2004), and is consistent with the finding that electrolyte leakage, an indicator of membrane damage, is increased in ethylene-treated watermelon (Elkashif and Huber, 1988). On the basis of available data, it seems plausible that ethylene-induced membrane damage subsequently led to tissue water soaking and modifications in surface color, whereas low dosage 1-MCP treatments prevented these ethylene-mediated changes to fresh-cut watermelon tissues. Surface color remained relatively stable as the time from harvest to 1-MCP treatment increased.

Across all trials, the soluble solids content (SSC) in freshly cut heart tissue was 11 to 12% and decreased appreciably during 5 °C storage only in watermelon slices from whole fruit treated with ethylene alone (Fig. 4a). This is in contrast to the findings of Mao et al. (2006) who found that SSC decreased during storage of placental pieces in vented containers at 10 °C, irrespective of treatment. Most of the difference in stored tissue SSC profiles between the two studies is likely due to differences in storage temperature although

differences in cultivar selection, tissue handling and storage may have also contributed to the contrasting results.

Across all trials, the surface pH of freshly cut heart tissue was 5.8–6.4 and increased appreciably during 5 °C storage only in watermelon slices from whole fruit treated with ethylene alone (Fig. 4b). The surface pH of freshly cut heart tissue from whole fruit treated with ethylene alone was about a 0.5 pH unit higher than that of slices from whole fruit treated otherwise (combined data) (Fig. 4b). During storage, pH increased only on the surface of heart tissue from whole fruit treated with ethylene alone. The high surface pH in heart tissue from whole fruit treated with ethylene alone corresponded to and may have been caused by increased microbial populations (Zhou et al., 2006) in both freshly cut and stored slices from whole fruit treated with ethylene alone. Increased pH and SSC in watermelon tissue are generally considered as indicators of fruit ripening (Corey and Schlimme, 1988). However, the finding that pH, but not SSC, increased in fresh-cut tissue from whole fruit treated with ethylene alone would argue that factor(s) other than ripening were involved. Our results demonstrate that color, SSC and pH of watermelon tissue from whole fruit treated with ethylene alone were adversely affected before fresh-cut processing and/or during the 12-day storage period of fresh-cut slices at 5 °C and that low dosage 1-MCP treatments of whole watermelon can prevent these ethylene-mediated changes in quality of the fresh-cut product.

3.4. Aromatic volatile analyses

SPME-recovered aromatic volatiles evolved from extracts of watermelon heart tissue were mostly aldehydes and alcohols along with two ketones (Table 1). Many of these volatiles have distinctive aldehydic, alcoholic, green, fruity and/or floral odor attributes. Most of the volatiles listed in Table 1 have been previously identified in extracts of watermelon (Beaulieu and Lea, 2005; Kemp, 1975; Yajima et al., 1985) and other cucurbit fruit (Beaulieu, 2006; Buttery et al., 1982; Kreck et al., 2004). To our knowledge, this is the first time that β -cyclocitral has been identified in watermelon. Due to their low odor thresholds, unsaturated C₉ aldehydes and alcohols are considered to be major contributors to melon aroma (Buttery et al., 1982).

Across all trials, treatment \times storage interactions occurred for total and for a number of individual aromatic volatile concentrations. While the reason(s) for non-treated and treated watermelon tissue behaving differently relative to one another in volatile profiles during storage is not known, two possible explanations are fruit to fruit (maturity, pre-harvest factor) variations and qualitative and quantitative differences in microbial contamination of watermelon slices within and among treatments. Microbial populations on fresh-cut watermelon slices varied within and among treatments especially for slices from whole fruit treated with ethylene alone (Zhou et al., 2006). During storage of fresh-cut watermelon slices from all treatments, total volatiles decreased (Fig. 5a)

Table 1
SPME-recovered volatiles from headspace of watermelon extracts and their attributes

Peak	Compound	RI	Attributes
1	Acetaldehyde	525	Sharp, aldehydic, orange, coffee, wine
	Ethanol	537	Sweet, alcoholic, fruit flavoring agent
2	(E)-2-Pentenal	621	Pungent, green, apple, orange, tomato
	(Z)-2-Penten-1-ol	661	Fresh, alcoholic, fruity green, citrus
3	Pentan-1-ol	760	Alcoholic, sweet, balsamic, fusel-like odor
4	Hexanal	800	Green, grassy, floral
5	Heptanal	907	Green, grassy, floral
6	(E)-2-Heptenal	940	Pungent, green, fruity
7	6-Methyl-5-hepten-2-one	996	Oily green, fruity, herbaceous odor
	6-Methyl-5-hepten-2-ol	1000	Sweet, oily green, coriander-like odor
8	Octan-1-ol	1071	Fatty, citrus
9	(Z)-6-Nonenal	1107	Citrus, melon
10	Nonanal	1116	Citrus, rose, green
11	(Z)-3-Nonen-1-ol	1170	Citrus, melon
	(E, Z)-2,6-Nonadienal	1171	Cucumber, violet, green, melon
	(Z, Z)-3,6-Nonendien-1-ol	1173	Fresh, fruity, watermelon, cucumber
12	(E)-2-Nonenal	1177	Penetrating, fatty
	(Z)-6-Nonen-1-ol	1178	Melon-pumpkin, green
13	Nonan-1-ol	1186	Rose, citrus
14	β -Cyclocitral	1250	Minty, fruity, green
15	Geranyl acetone	1450	Rose, fresh, green, magnolia
16	β -Ionone	1504	Floral, violet, woody

RI=retention index based on retention times of identified compounds, calculated from linear equation between each pair of straight chain hydrocarbons (C₅–C₁₆). Attribute is the organoleptic property of individual purified compounds. Co-eluting volatile compounds are listed together by GC peak number.

along with many individual volatiles, but (Z)-6-nonen-1-ol (Fig. 5b), 6-methyl-5-hepten-2-one, 6-methyl-5-hepten-2-ol, (Z)-6-nonenal, nonanal, (E)-2-nonenal, nonan-1-ol, β -cyclocitral and geranyl acetone (data not shown) concentrations remained stable or increased at least transiently. The increase in (Z)-6-nonen-1-ol during storage of fresh-cut slices may be particularly important since this volatile has pumpkin- and squash-like odors (Leffingwell and Associates, 1999) that might at least partially contribute to the pumpkin-like off-odors and squash-like off flavors often attributed to overripe whole watermelon (Penelope Perkins-Veazie, personal communication) and long-stored, 1-MCP-treated whole watermelon (Donald Huber, personal communication). A further indication that (Z)-6-nonen-1-ol might be involved in off-odors and off flavors was the development of higher (Z)-6-nonen-1-ol concentrations in extracts of heart tissue from 1-MCP-treated whole fruit than those from fruit

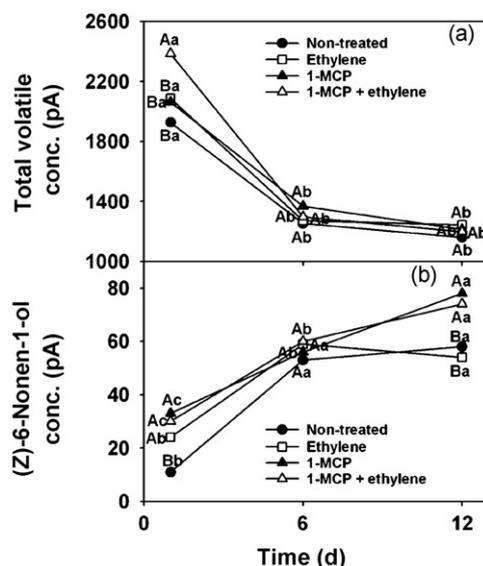


Fig. 5. Total aromatic volatile (panel a) and (Z)-6-nonen-1-ol (panel b) concentrations evolved from extracts of heart tissue from fresh-cut watermelon slices stored up to 12 days at 5 °C under modified atmosphere conditions following non-treatment or treatment of the whole fruit with 1.0 $\mu\text{L L}^{-1}$ 1-MCP for 18 h at 20 °C and/or 10 $\mu\text{L L}^{-1}$ ethylene for 5 days at 20 °C. One summation (panel a) or individual (panel b) volatile measurement from each of five replications ($n=5$) were averaged to obtain a representative value at each storage time. Within time periods within panels, symbols labeled with the same A, B letters are not significantly different using Sidak-adjusted means comparison ($\alpha=0.05$). Within treatments within panels, symbols labeled with the same a, b, c letters are not significantly different using Sidak-adjusted means comparison ($\alpha=0.05$).

treated with ethylene alone or from non-treated fruit (Fig. 5b). (Z)-6-nonen-1-ol has recently been identified in juice extracts of pumpkin fruit (Kreck et al., 2004). How (Z)-6-nonen-1-ol and other aromatic volatiles specifically impact aroma and flavor attributes of fresh-cut watermelon during storage can best be investigated using a GC–MS–olfactory approach and extensively trained sensory panels.

Among treatments, tissue extracts of stored watermelon slices from whole fruit treated with ethylene alone had the lowest concentration of hexanal, a major SPME-recovered volatile evolved from watermelon extracts, throughout storage and the highest concentrations of acetaldehyde and ethanol, (E)-2-pentenal and (Z)-2-penten-1-ol, and pentan-1-ol after 12 days storage (data not shown). 1-MCP had no consistent stimulatory or inhibitory effect on aromatic volatile evolution from extracts of fresh-cut slices other than to prevent ethylene-induced changes in specific volatile concentrations. This probably indicates that low dosage 1-MCP treatments would prevent ethylene-induced adulterations of watermelon aroma and volatile-associated flavor but not the off-odors and off flavors that might otherwise develop during 5 °C storage of packaged fresh-cut watermelon. Extending the time from harvest to 1-MCP treatment consistently led to decreased total aromatic volatile and hexanal concentrations in heart tissue extracts from freshly cut watermelon

slices, but the changes were not always significant among treatments.

4. Conclusions

Results of this study demonstrate that fresh-cut watermelon slices from whole fruit treated with ethylene alone had altered respiration rates, puncture firmness and puncture force/deformation curves, aromatic volatile concentrations, SSC and cut surface color and pH compared to slices from non-treated or 1-MCP-treated fruit. Treatment of watermelons prior to ethylene exposure with 0.5 or 1.0 $\mu\text{L L}^{-1}$ 1-MCP for 18 h prevented ethylene-mediated quality deterioration in fresh-cut watermelon slices stored under modified atmosphere conditions at 5 °C.

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