Postharvest CO₂ and Ethylene Production and Quality Maintenance of Fresh-Cut Kiwifruit Slices

I. T. Agar, R. Massantini, B. Hess-Pierce and A. A. Kader

ABSTRACT

The quality attributes and gas production of fresh-cut kiwifruit slices (Actinidia deliciosa cv. Hayward) were studied to identify the optimum ranges of storage temperature, relative humidity, and atmospheric composition. Also the effects of wounding, C₂H₄ addition or removal, and chemical treatments (calcium, ascorbic acid, citric acid) on deterioration rate were investigated. Flesh softening was the major quality loss of stored fresh-cut kiwifruit slices. Fresh-cut kiwifruit slices had a shelf-life of 9-12 days if treated with 1% CaCl₂ or 2% Ca lactate, and stored at 0-2°C and >90% relative humidity in an C₂H₄-free atmosphere of 2 to 4 kPa O₂ and/or 5 to 10 kPa CO₂.

Key Words: ascorbic acid, controlled atmosphere, freshcut, kiwifruit, ethylene

INTRODUCTION

PHYSICAL DAMAGE OR WOUNDING CAUSED by slicing, peeling, and/or other mechanical injuries in minimally processed fruits results in increased rates of respiration and ethylene (C₂H₄) production within minutes (Abe and Watada, 1991). Increases occur in biochemical reactions related to changes in color, flavor, texture, nutritional quality and susceptibility to dehydration. During storage such products have a very limited shelf-life (Brackett, 1994; O’Connor-Shaw et al., 1994). These responses occur in disrupted tissues where cellular decompartmentation leads to intermixing of enzymes and substrates, as well as release of acids and hydrolyzing enzymes (Watada et al., 1990).

Minimally processed products should be refrigerated (0-5°C) to prolong their quality and safety (Watada et al., 1996). Removal of C₂H₄ from the storage environment of lightly processed fruits and vegetables can retard tissue softening (Abe and Watada, 1991). Controlled atmospheres can reduce the effects of C₂H₄ on fruit tissues and retard senescence (Kader, 1980), delay softening (Knee, 1980) and help extend the postharvest life (Kader, 1986; Huxsoll and Bolin, 1989). Exogenous treatments with calcium chloride (CaCl₂) dips have been reported to reduce browning (Drake and Spayd, 1983), delay ripening (Poovaiah, 1986) and retard flesh softening of whole kiwifruit slices (Bangerth et al., 1972; Garcia et al., 1996) and sliced fruits (Rosen and Kader, 1989) and vegetables (Izumi and Watada, 1995). However, CaCl₂ may also cause detectable off-flavors when used at >0.5% (Guzman, 1996). Kiwifruits are high in vitamin C (Mitchell, 1994). However, little has been reported about the physiological, microbiological and nutritional changes which may occur in fresh-cut kiwifruit slices (Varoquaux et al., 1990; Watada et al., 1990; Abe and Watada, 1991; O’Connor-Shaw et al., 1994; Massantini and Kader, 1995; Watada et al., 1996). Our objective was to determine the optimum ranges of storage temperatures, relative humidity, and concentrations of oxygen, carbon dioxide, and ethylene for maintaining appearance, texture, flavor, and nutritional quality of fresh-cut kiwifruit slices. Pre-storage dips of kiwifruit slices in calcium solutions, ascorbic acid and/or citric acid were also evaluated.

MATERIALS & METHODS

Material

Kiwifruits (Actinidia deliciosa (A. Chev.) C.-F. Liang et A.R. Ferguson var. deliciosa cv Hayward) were harvested from a commercial vineyard in Winters, CA, during 1996 and 1997 and transported to the Dept. of Pomology Postharvest Laboratory at the Univ. of California, Davis within 1h of harvest in an air conditioned vehicle. Initial firmness of whole kiwifruit was 53 to 66N. The average diameter and mass of the fruit were 40 mm and 70-85g, respectively. Kiwifruits were stored at 0°C and ventilated with 90-95% relative humidity, C₂H₄-free air for various durations before they were used in experiments.

Additionally, KMnO₄ impregnated on aluminum oxide was placed inside each storage tank to absorb C₂H₄.

Ripening

Kiwifruits were sorted to eliminate damaged or defective fruit and partially ripened at 20°C and 90-95% RH in air + 1 Pa C₂H₄ (10 µL·L⁻¹) in a flow through system. This provided whole fruit flesh firmness values of 15 to 20N. Fruits within this range were matched and used for experiments.

Slice preparation

Kiwifruits were peeled with a sharp vegetable peeler and sliced perpendicularly to the blossom end-stem scar axis with a meat slicer. From each kiwifruit 5 slices (7 mm thick) were obtained. For each treatment, 20 slices from 20 fruits were used for each replicate. Kiwifruit slices in colanders were dipped in 10-L solution containing chlorinated (1.3 mM NaOCl) distilled water at 4°C. Slices were drained, blotted dry with cheesecloth and placed in jars.

Storage

Slices (20) were placed in 1.9-L jars which were ventilated with a flow of humidified air or a specified gas mixture at 20 mL·min⁻¹ to ensure that CO₂ concentrations in the air-control jars were maintained below 0.25 kPa. Gas mixtures were maintained ±10% of required concentrations throughout storage.

Flesh firmness

Firmness of whole fruit and slices was determined with a Univ. of California Firmness Tester (Western Industrial Supply Co., San Francisco, CA) by measuring force required for an 8-mm probe to penetrate the cut surface in two opposite locations in mesocarp tissue to a depth of 5 mm. Whole fruit firmness was determined by the force required for an 8-mm probe to penetrate the mesocarp of a whole fruit, with skin removed, to a depth of 10-mm.

Soluble solids (SSC), titratable acidity (TA) and mass loss

One wedge was cut from each slice, and all wedges from 20 slices were juiced together for a composite sample analyzed for SSC using a refractometer (Abbe model 10450;...
American Optical Corp, Buffalo, NY) and TA using an automatic titrator (Radiometer, Copenhagen, Denmark). Titration was conducted with 0.1N NaOH to pH 8.1 and percentage citric acid equivalents were determined. The mass of fruit slices in each replicate was recorded initially and after treatments and storage.

**Color and visual quality evaluation**

Color on opposite sides of each slice was measured with a Minolta Chromameter (Model CR-300, Minolta, Ramsey, NJ) in the CIE L*a*b* mode. Changes in hue angle (h°) were calculated to indicate color change during storage. The visual quality of each fruit slice was determined based on a hedonic scale: 1=inedible; 2=limit of usability; 3=limit of marketability; 4=very good; and 5=excellent. A color photograph of slices so-rated was used by 3 judges to score slices on color, visible structural integrity, and general visual appeal. A weighted average of 20 slice quality scores was calculated to determine the mean visual quality score for each replicate.

**Respiration and C2H4 production rates**

Carbon dioxide and C2H4 production rates were measured daily at 20°C and 101 kPa for each replicate and treatment. Slices (20) (200g) were sealed in a 1.9-L jar for 15-30 min and the headspace was sampled with a 10-ml syringe. An infrared CO2 analyzer (model PIR-2000R, Horiba Instruments, Irvine, CA) was used for CO2 measurements. A gas chromatograph (model 211 Carle Instruments, Anaheim, CA) with FID detector and alumina column was used to analyze for C2H4.

**Calcium content**

Fresh fruit samples were vacuum dehydrated at ~100 kPa at 70°C for 24h. Samples (0.5g) were weighed into 30 ml porcelain crucibles and ashed at 300°C for 1h followed by 500°C for 12h. Ashed samples were allowed to cool to room temperature, digested with 10 mL of 1M HNO3 at 80°C for 20 min, filtered through Whatman No.1, and made up to 50 mL with double deionized water. Samples were analyzed on a Techtron AA 120 Atomic Absorption Spectrophotometer. A Varian Techtron D 1-30 digital indicator was used; samples were compared to a standard curve and results were expressed as μg·g⁻¹ dry weight.

**Ethanol and acetaldehyde**

Juice from slices was immediately frozen in liquid N2 and stored at ~80°C until analysis. Samples were thawed and centrifuged in an Eppendorf (5,000 x g) for 2 min, and 1 μL of supernatant was injected directly to determine acetaldehyde and ethanol in each sample. A HP 5890 GC (Hewlett Packard, Palo Alto, Calif.) equipped with an autosampler, controller (Hewlett Packard model 7673), and FID detector fitted with a Carbopack glass column (2 mm x 1.8m containing 5% Carbowax on 60/80 Carbopack stationary phase; Supelco, Bellefonte, PA) was used. Injector and detector temperatures were 200 and 250°C, respectively. Oven temperature was 75°C for 2 min, followed by a gradient of 7.5°C/min to 100°C and a second gradient of 25°C/min to 160°C, held for 5 min at the final temperature. Compounds were quantified by comparison with known standard retention times and peak areas.

**Sugars and organic acids**

The method was based on van Gorsel et al. (1992) with some modifications. Juices were prepared by squeezing wedges of fresh slices through cheesecloth, filling vials and immediately freezing in liquid N2. Juice samples were stored at ~80°C until analyses were performed. Juice samples were thawed and centrifuged at 25,000 x g for 15 min at 4°C. The supernatant was adjusted to pH 8.9 with 58% NH4OH [16.5M], and 2 mL of sample was passed through a column with 2 g of anion-exchange resin (Bio-Rex 5 analytical grade, 100-200 mesh, chloride form). The column was rinsed with 2 × 4 mL double deionized water, and the eluate was collected, filtered through a 0.45-μm filter and 20 μL of the extract was injected into the HPLC system (Series 1050; Hewlett Packard, Palo Alto, CA).

Individual sugars were separated with a 250 mm x 4 mm HPX-87C column (Bio-Rad) at 85°C and detected with a RI monitor. Double deionized water was used as the mobile phase at 0.6 mL·min⁻¹. Sucrose, glucose and fructose (Sigma Chemical Co.) were standards. Organic acids were separated with a reverse phase C8 Nucleosil column (150 mm x 4.6 mm, particle size 5 μm) at 25°C with a C18 guard column (Safeguard). All organic acids were determined with a photodiode array detector (DAD, Series II), at 210 nm. The mobile phase was 0.2N NH4H2PO4 (pH 3.5) at 1 mL·min⁻¹. Citric, malic and quinic acids (Sigma Chemical Co.) were standards.

**Ascorbic and dehydroascorbic acid**

The method was based on Zapata and Dufour (1992) with some modifications. Sub-samples of wedges were frozen in liquid N2 and stored at ~80°C for analysis of L-ascorbic acid and dehydroascorbic acid concentrations. Frozen samples (15g) were crushed with a pestle and homogenized in a 185 mL extraction solution of 0.1M citric acid and 0.05% ethylenediaminetetraacetic acid (EDTA) in 5% aqueous methanol (MeOH) for 2 min at high speed in an Oster Blender. An internal standard of isoascorbic acid was added at 50 mg·100 g⁻¹ of fruit. The homogenate was filtered through 4 layers of cheesecloth and centrifuged for 10 min at 11,950 x g at 2°C. After calibrating the pH meter with cold buffer solution, the pH of the supernatant was adjusted to 2.35-2.40 with HCl. The sample was passed through a Sep-Pak C18 cartridge (Waters Assoc.) which had been preconditioned with 10 mL HPLC grade methanol followed by 10 mL of ultrapure water. Before use, the residual water in the cartridge was expelled with air. The first 5 mL of eluent was discarded and the next 3 mL retained for analysis. We added 1 mL of 1.1-phenyldiamine (3.3 mg·mL⁻¹) in methanol-water (5:95, v/v) 37 min before injection. The mixture was immediately filtered through a 0.45-μm filter into an amber vial, sealed and stored in darkness at 20°C. After 37 min, 20 μL were injected into the HPLC system using a Waters µBonda pak C18 reverse-phase column (300 mm x 3.9 mm i.d. with a BioRad Biosil MicroGuard column (ODS-SS 30-mm x 4.6 mm i.d.). The eluent was methanol:water (5:95, v/v) containing hexadecyltrimethylammonium bromide (CTAB) and 50 mM potassium dihydrogen phosphate, with the pH adjusted to 4.55-4.60. The flow rate was 1.6 mL·min⁻¹ at 20°C. Prior to analysis, the column was equilibrated by pumping the eluent at 0.2 mL·min⁻¹ for 3h at 20°C and column function was reproducible from lot to lot. Detection was at 261 nm, and retention times were 7.3 and 8.3 min for reduced L-ascorbate and isoascorbate, respectively, and 4.2 min at 348 nm for L-dehydroascorbate. Solutions of standards were prepared in methanol:water (5:95, v/v). Standards of L-ascorbate and isoascorbate were supplied by Sigma and L-dehydroascorbate by Aldrich Chemical Co.

**Effects of storage temperature and wounding**

Kiwifruit slices were held at 0, 2, 5, and 20°C in the 1996 and at 0, 5, 10 and 20°C in the 1997 to study the effects of temperature on quality retention and physiology. To study the rate of mass loss and effects of wounding on CO2 and C2H4 production, whole peeled fruit, unpeeled slices and peeled slices were compared to whole fruit (control) kept at 2°C for 3 days or at 20°C for 6h.

**Effects of C2H4 in storage atmosphere**

The effects of C2H4 on slice firmness and titratable acidity were studied by storing slices in air, air + 0.1 Pa C2H4 (1 μl·L⁻¹), air + 1 Pa C2H4 (10 μl·L⁻¹), and air with/without C2H4 scrubbing with KMnO4 in a flow-through system at 2°C.

**Effects of chemical treatments**

Kiwifruit slices were dipped in aqueous solutions of 1% [0.068M] and 2% CaCl2 [0.136M] (m/v) at 4°C for 5 min and compared to controls (water). Calcium content of slices was analyzed with an Atomic Absorption Spectrophotometer. In a second test, slice-
es were dipped in aqueous solutions of 1 and 2% (m/v) CaCl₂, 1% (m/v) ascorbic acid [0.056 M], 1% (m/v) citric acid [0.0047 M] and 1% ascorbic acid + 1% citric acid, all at 4°C and compared to slices which had not been dipped (dry control) or had been dipped in distilled water (wet control) for 5 min. Firmness was evaluated initially and after 5 days at 2°C. In a third test, slices were dipped in aqueous solutions of 1% CaCl₂ [0.068 M] (m/v) and then stored at 2°C for 10 days in air with or without C₂H₄ scrubbing with KMnO₄, to determine how CaCl₂ treatment and C₂H₄ scrubbing affected firmness retention. In a fourth test, Ca lactate was used to replace CaCl₂ to prevent the off-flavor problems reported by Guzman (1996) at >0.5% in cantaloupes.

Therefore, we compared the efficacy of various concentrations of CaCl₂ with Ca lactate. Okuse and Ryugo (1981) reported how CaCl₂ treatment and C₂H₄ scrubbing affected firmness retention. In a fourth test, Ca lactate was used to replace CaCl₂ to prevent the off-flavor problems reported by Guzman (1996) at >0.5% in cantaloupes. Therefore, we compared the efficacy of various concentrations of CaCl₂ with Ca lactate on firmness retention. In order to have the equivalent amount of calcium in both treatments, Ca lactate was used at double the concentration of CaCl₂ (2% Ca Lac [0.064 M] m/v=1% CaCl₂ [0.068 M] m/v). Kiwifruit slices were dipped in aqueous solutions of 0.25, 0.5 and 1% (m/v) [0.017, 0.034, 0.068 M] CaCl₂, or 0.5, 1 and 2% (m/v) [0.016, 0.032, 0.064 M] Ca lactate, or distilled water at 4°C for 2 min. Treated kiwifruit slices were stored at 0 and 10°C. Firmness and color were evaluated immediately after dipping and after 3 and 6 days storage.

**Effects of atmospheric modification**

The quality and gas production of kiwifruit slices were evaluated after storage (0°C) in atmospheres of low O₂ (0.5, 1, 2 or 4 kPa, balance N₂) or elevated CO₂ (air + 2.5, 5, 10, or 20 kPa) concentrations. Subsequently, the following O₂/CO₂ combinations were tested: 2/5, 2/10, 4/5, 4/10 kPa (balance N₂). Slices were evaluated initially, and after 3, 6, 9, and 12 days at 0, 5, and 10°C. Slices were dipped in chlorinated (1.3 mM NaOCl) distilled water with 1% CaCl₂ at 4°C as a standard treatment.

**Statistical analysis**

Three replicates per treatment and 20 slices per replicate were used in the experiments. All data points represent the mean ± SD of the three replicates. Analysis of variance (ANOVA), followed by Duncan’s Multiple Range Test with a significance level of P<0.05, and correlation tests were performed on the data using CoStat Statistical Software, Ver. 5.01 (CoHort Software, Minneapolis, MN).

**RESULTS & DISCUSSION**

**Effects of storage temperature and relative humidity**

At 5°C and higher we noted rapid deterioration of slice quality. Softening increased as storage temperature and time increased (Fig. 1A). Slices kept at 0°C for 12 days exhibited a reduced rate of softening and were above 3N flesh firmness after 12 days. The L* value of kiwifruit slices (surface darkening) was greater at higher storage temperatures and longer durations (Fig. 1B). The cut surface darkening was due to induction of a translucent water-soaked tissue and not to enzymatic browning. Okuse and Ryugo (1981) reported that kiwifruit did not exhibit browning due to low tannin content, low polyphenoloxidase and high ascorbic acid.

Kiwifruit slices stored at 5 and 10°C exhibited a gradual decrease in ascorbic acid (AA) and an increase in dehydroascorbic acid (DHA) (Table 1). The total vitamin C (AA+DHA) was 8, 13 and 21% lower than initial values in slices kept at 0, 5, and 10°C, respectively, after 6 days storage. Mass loss of slices kept in 60% r.h. was 1.2% after 3 days at 2°C, double that of slices kept in 95% r.h.

**Effects of wounding**

Peeling and slicing caused an increase in mass loss (Fig. 2) which was highest in peeled slices and lowest in intact whole fruit stored 3 days at 2°C. Fresh-cut slices had more water loss than intact fruits because the protective epidermal cells were removed, and surface area/mass rate was increased. Physical tissue damage or wounding caused by slicing and/or peeling resulted in increased CO₂ and C₂H₄ production rates within 2 to 6h at 20°C (Fig. 3) and 1 to 3 days at 2°C (Fig. 4). The C₂H₄ and CO₂ production rates of peel were about 2 to 4 times higher than those of unpeeled slices, which were the next highest source.

Peeled fruit and slices had double the C₂H₄ and CO₂ production rates of whole fruit, which remained unchanged during 6h at 20°C or 3 days at 2°C. Respiration and CO₂ production rates increased with temperature. The C₂H₄ and CO₂ production rates were 5x higher in peeled slices at 20°C, than in those kept at 2°C (Fig. 3, 4).

**Effect of C₂H₄ in the storage atmosphere.**

All treatments resulted in loss of firmness of slices and lowest in intact whole fruit stored 3 days at 2°C. Fresh-cut slices had more water loss than intact fruits because the protective epidermal cells were removed, and surface area/mass rate was increased. Physical tissue damage or wounding caused by slicing and/or peeling resulted in increased CO₂ and C₂H₄ production rates within 2 to 6h at 20°C (Fig. 3) and 1 to 3 days at 2°C (Fig. 4). The C₂H₄ and CO₂ production rates of peel were about 2 to 4 times higher than those of unpeeled slices, which were the next highest source. Peeled fruit and slices had double the C₂H₄ and CO₂ production rates of whole fruit, which remained unchanged during 6h at 20°C or 3 days at 2°C. Respiration and CO₂ production rates increased with temperature. The C₂H₄ and CO₂ production rates were 5x higher in peeled slices at 20°C, than in those kept at 2°C (Fig. 3, 4).

![Fig. 1—Effect of storage conditions on firmness (A) and L* value= brightness (B) of fresh-cut kiwifruit slices as related to storage conditions (means ± SD of three replicates)](image)

![Fig. 2—Effect of wounding on mass loss of whole kiwifruit, whole-peeled fruit, peeled slices and unpeeled slices stored at 20°C for 3 days.](image)

![Fig. 3—Effect of wounding on the C₂H₄ (A) and CO₂ (B) production rates of whole kiwifruit, whole-peeled fruit, peel, peeled and unpeeled fruit slices stored at 20°C for 6h.](image)
CHEMISTRY/BIOCHEMISTRY

Fresh-Cut Kiwifruit Slices

Table 2—Effects of CaCl₂-C₂H₄ scrubbing (with KMnO₄), controlled atmosphere, and their combinations on reduced ascorbic acid (AA) content of kiwifruit slices stored at 2°C (means ± SD of three replicates)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>0</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>55±6</td>
<td>34±5</td>
<td>30±3</td>
<td>20±2</td>
<td>6±4</td>
</tr>
<tr>
<td>Air + 1% CaCl₂</td>
<td>34±4</td>
<td>28±2</td>
<td>29±4</td>
<td>23±5</td>
<td></td>
</tr>
<tr>
<td>Air + KMnO₄</td>
<td>35±4</td>
<td>22±8</td>
<td>22±2</td>
<td>20±4</td>
<td></td>
</tr>
<tr>
<td>1% CaCl₂ + KMnO₄</td>
<td>38±3</td>
<td>36±3</td>
<td>28±3</td>
<td>22±3</td>
<td></td>
</tr>
<tr>
<td>CA (2 kPaO₂ + 5 kPaCO₂)</td>
<td>45±7</td>
<td>30±6</td>
<td>32±6</td>
<td>31±4</td>
<td></td>
</tr>
<tr>
<td>CA + 1% CaCl₂</td>
<td>40±5</td>
<td>40±7</td>
<td>38±3</td>
<td>38±2</td>
<td></td>
</tr>
<tr>
<td>LSDₜreat 0.05≈ 3.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LSDₜype 0.05≈ 4.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

and TA. Removal of C₂H₄ from the storage atmosphere reduced the rates of firmness (Fig. 5A) and TA (Fig. 5B) losses of fresh-cut slic-
es stored at 2°C for 5 days. The softening rate was increased by storage in air + 1 Pa (10 µL·L⁻¹) C₂H₄, whereas storage in air + 0.1 Pa (1 µL·L⁻¹) C₂H₄ had no effect after 5 days at 2°C. When C₂H₄ was removed, slices were 62%, 27% and 18% firmer than those kept in air + 1 Pa C₂H₄, air + 0.1 Pa C₂H₄ and air (control) treatments, respectively. TA was 18% lower in air (control) and in ethylene-
treated slices than in those kept in ethylene-
free atmospheres. Slices stored in ethylene-
free air contained 3-fold more ascorbic acid 
than controls (Table 2). When dipped in 1% 
CaCl₂ after cutting and kept in an ethylene-
free atmosphere, slices had a slightly higher ascorbic acid content than those treated with 1% CaCl₂ only. Results confirmed those of Watada et al. (1990) and Abe and Watada (1991), that the softening rate of kiwifruit slic-
es was reduced by C₂H₄ scrubbing (charcoal
Table 3—Changes in reduced ascorbic acid (AA), dehydroascorbic acid (DHA), and total ascorbic acid (vitamin C) contents of fresh-cut kiwifruit slices as related to O2 and CO2 concentrations at 0°C (means±SD of three replicates)

<table>
<thead>
<tr>
<th></th>
<th>mg 100g⁻¹ FW after 6 days</th>
<th>mg 100g⁻¹ FW after 12 days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AA</td>
<td>DHA</td>
</tr>
<tr>
<td>Initial</td>
<td>55.0±2.6</td>
<td>6.8±1.2</td>
</tr>
<tr>
<td>Air</td>
<td>44.6±5.5</td>
<td>8.7±2.6</td>
</tr>
<tr>
<td>0.5% O₂</td>
<td>50.7±4.9</td>
<td>7.8±0.6</td>
</tr>
<tr>
<td>0.25% O₂</td>
<td>47.7±5.5</td>
<td>12.9±0.8</td>
</tr>
<tr>
<td>2% O₂</td>
<td>51.6±8.6</td>
<td>9.8±1.8</td>
</tr>
<tr>
<td>Air + 5 kPa CO₂</td>
<td>49.4±2.1</td>
<td>11.1±1.3</td>
</tr>
<tr>
<td>Air + 10 kPa CO₂</td>
<td>41.1±3.1</td>
<td>10.5±0.8</td>
</tr>
<tr>
<td>Air + 20 kPa CO₂</td>
<td>36.0±0.4</td>
<td>10.2±0.6</td>
</tr>
</tbody>
</table>

**Effect of atmospheric modification**

The firmness of slices, initially about 7-8 N, decreased rapidly during the first 3 days storage to about 4 N irrespective of atmosphere. Thereafter, rates of softening were slower. Treatments with 2 kPa or 4 kPa O₂ (balance N₂) atmospheres (Fig. 9A), as well as air + 5 kPa and air + 10 kPa CO₂ (Fig. 9B), resulted in higher firmness than controls. Slices stored in 4 kPa O₂ tended to have a slightly higher firmness than those kept in 2 kPa O₂. Slices stored in air + 10 kPa CO₂ resulted in slightly higher firmness than in air + 5 kPa CO₂. However, we noted a slight brown discoloration in slices exposed to 10 kPa or higher CO₂ in the first year but not in the second year. Firmness levels were slightly higher for up to 6 d storage in two CA combinations than for those in only low O₂ or only elevated CO₂ atmospheres. However, we did not observe a clear additive effect of low O₂ and elevated CO₂ concentrations on firmness retention (Fig. 9C). Kiwifruit slices stored in low O₂, elevated CO₂ or their combinations tended to retain their initial SSC and TA, while control slices exhibited an increase in SSC and decline in TA during 12 days storage (data not shown).

The visual quality of air (control) stored slices deteriorated (appeared water soaked and macerated around the edges) faster than did those from the other treatments during 12 days storage (Fig. 9 D, E, F). The 2 and 4 kPa O₂ and air + 5 and 10 kPa CO₂ atmospheres resulted in better visual quality (no differences among treatments) of slices compared to controls. Slices stored in low O₂ plus elevated CO₂ atmospheres were similar in visual quality to those held in either low O₂ or elevated CO₂ treatments alone (Fig. 9F).

Ethylene production of slices stored in air was 3-4 fold higher than for those kept in low O₂ or elevated CO₂ (Fig. 10). The 2 kPa O₂ (balance N₂) or air + 10 kPa CO₂ atmospheres generally resulted in lower C₂H₄ production compared to 4 kPa O₂ (balance N₂) or air + 5 kPa CO₂. Storage in 2 kPa O₂ + 5 kPa CO₂ (balance N₂) resulted in the lowest C₂H₄ production rate.

The major plant fermentative metabolism products in fruits are ethanol and acetaldehyde and their accumulation has correlated well with off-flavor development (Ke et al., 1991). The acetaldehyde and ethanol contents with palladium chloride) and enhanced by 2 and 20 µL·L⁻¹ C₂H₄. Arpaia et al. (1986) determined that C₃H₄ levels of air + 0.005-0.5 Pa accelerated kiwifruit softening, and the response was accelerated by increasing temperatures.

**Effect of chemical treatments**

Ca concentrations of the slices which had been dipped in 1 and 2% CaCl₂ were at levels of 2967±16 µg·g⁻¹ and 3907±13 µg·g⁻¹ Ca, respectively, as compared to 2000±16 µg·g⁻¹ of slices which were 25% firmer than controls after dipping and after 3 and 6 days at 0°C. CaCl₂ and C₂H₄ fruit which were 25% firmer than controls had higher ascorbic acid after 3-5 days at 2°C and their combination treatments did not affect firmness retention.

Kiwifruit slices treated with 1% CaCl₂ and then stored in C₂H₄-free air were firmer and had higher ascorbic acid content than treatments of 1% CaCl₂ or ethylene scrubbing alone (Fig. 7, Table 2). CaCl₂ and C₂H₄ scrubbing treatments had an additive effect on firmness and ascorbic acid content until 5 days at 2°C.

Slices treated with 0.5 or 1% CaCl₂ and 1 or 2% C₂H₄ lactate immediately after cutting had a higher flesh firmness than those treated with 0.25% CaCl₂ or 0.5% Ca lactate and controls (Fig. 8). Firmness in all treatments declined after 3 d at 0°C. Slices treated with 0.25 and 0.5% CaCl₂ were firmer after 3 days at 0°C than those treated with 0.5 and 1% C₂H₄ lactate, although the solutions had equivalent amounts of Ca. The greatest firmness loss occurred between 0 and 3 days, whereas differences between 3 and 6 d were minimal. The two higher concentrations of CaCl₂ (0.5 and 1%) and C₂H₄ lactate (1 and 2%) resulted in similar firmness. The L* values decreased less rapidly in Ca-treated slices than in untreated slices, and there was no visible cut surface browning in fresh-cut slices (data not shown).

Varoquaux et al. (1990) reported that the most obvious change in kiwifruit slices was a rapid loss of firmness, which was noticeable after a few hours. They hypothesized that texture loss during storage was due to enzymatic hydrolysis of cell wall components. Calcium chloride treatments firm fruit tissue by reacting with pectinic acid to form calcium pectate (King and Bolin, 1989). Bangerth et al. (1972) and Poovaiah (1986) hypothesized that the main effect of Ca was maintaining the structural integrity of membranes and cell walls. Retention of ascorbic acid levels in kiwifruit slices treated with calcium was similar to results reported for apples (Bangerth, 1976; Drake and Spayd, 1983).
of fresh-cut kiwifruit slices increased during 12 days storage at 0°C (Fig. 11). Higher acetaldehyde and ethanol concentrations were found in slices stored under low O$_2$ atmospheres compared to those stored in air (control). Generally, the lower the O$_2$ level, the higher the acetaldehyde and ethanol concentration although the slices stored in 1 and 2 kPa O$_2$ did not differ in acetaldehyde. An atmosphere of 0.5 kPa O$_2$ (balance N$_2$) resulted in 40% higher fermentative metabolism products compared to 1 kPa O$_2$ (data not shown). Fresh-cut slices stored in air + 20 kPa CO$_2$ resulted in higher acetaldehyde and ethanol contents compared to air + 5 or air + 10 kPa CO$_2$ or air. Slices stored under low O$_2$ atmospheres accumulated higher acetaldehyde and ethanol concentrations compared to those from elevated CO$_2$ treatments. Combinations of low O$_2$ and elevated CO$_2$ atmospheres did not show any additive effect. The concentration of O$_2$ in the storage atmosphere was the key factor in accumulation of fermentative products.

The ascorbic acid (AA) content of fresh-cut slices dipped in 1% CaCl$_2$ and stored under 2 kPa O$_2$ + 5 kPa CO$_2$ (CA) at 2°C declined from 55 to 38 mg·100g$^{-1}$ FW during 9 days storage but resulted in the highest AA retention among 6 treatments (Table 2). Slices contained 61.8 mg·100g$^{-1}$ FW of vitamin C (AA+DHA) when freshly cut. During 12 days storage slices stored under low O$_2$ retained higher vitamin C compared to those under the highest CO$_2$ atmospheres: air + 10 and air + 20 kPa CO$_2$ (Table 3). Vitamin C content of the fresh-cut slices under 0.5, 2, and 4 kPa O$_2$ (balance N$_2$) decreased by 7, 12 and 18%, respectively, after 12 days storage. Vitamin C content in slices kept in air + 5, 10 and 20 kPa CO$_2$ decreased by 14, 22 and 34%, respectively, of their initial vitamin C contents. Slices kept in air lost 18% of their vitamin C within the same period.

Ascorbic acid (AA) at 55 mg·100g$^{-1}$ FW accounted for 88% of the vitamin C (AA+DHA) content of freshly cut slices (Table 2). Those kept in lower O$_2$ were higher in AA, whereas those from higher CO$_2$ were lower in AA content than air-control slices. Kiwifruit slices kept in air lost 34% AA and reached about 36 mg·100g$^{-1}$ FW AA after 12 d storage. Slices stored under 0.5, 2, or 4 kPa O$_2$ (balance N$_2$) lost 10, 20 or 28% of their original AA, respectively, after 12 days storage. Slices held in air + 5, 10 or 20 kPa CO$_2$ decreased by 26, 33 or 39% of initial AA content.

Over time the AA contents of slices decreased irrespective of storage treatment. A concomitant increase in DHA, from 6.8 to

---

### Table 4—Concentrations of sugars and organic acids in kiwifruit slices stored in air or in controlled atmospheres* at 0°C (means±SD of three replicates)

<table>
<thead>
<tr>
<th>Storage period (days)</th>
<th>Sugars (g/100mL juice)</th>
<th>Organic Acids (mg/100mL juice)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sucrose</td>
<td>Glucose Fructose</td>
</tr>
<tr>
<td></td>
<td>Citric Malic Quinic</td>
<td></td>
</tr>
<tr>
<td>Initial 0</td>
<td>1.11±0.06 5.37±0.23 5.61±0.17</td>
<td>964±56 523±21 475±28</td>
</tr>
<tr>
<td>Air 6</td>
<td>1.63±0.20 7.43±0.63 8.24±0.63</td>
<td>886±36 366±21 398±49</td>
</tr>
<tr>
<td>12</td>
<td>1.76±0.35 6.24±0.24 7.45±0.26</td>
<td>818±56 372±44 388±61</td>
</tr>
<tr>
<td>2 kPa O$_2$+5 kPa CO$_2$ 6</td>
<td>1.38±0.07 6.29±0.15 6.89±0.16</td>
<td>880±31 377±13 392±27</td>
</tr>
<tr>
<td>12</td>
<td>1.40±0.20 5.15±0.13 6.10±0.20</td>
<td>1116±146 529±68 470±34</td>
</tr>
<tr>
<td>2 kPa O$_2$+10 kPa CO$_2$ 6</td>
<td>1.33±0.09 6.35±0.24 7.10±0.32</td>
<td>922±74 386±27 442±66</td>
</tr>
<tr>
<td>12</td>
<td>1.15±0.36 5.85±0.35 5.20±0.30</td>
<td>810±68 338±16 294±43</td>
</tr>
<tr>
<td>4 kPa O$_2$+5 kPa CO$_2$ 6</td>
<td>1.27±0.01 6.35±0.25 6.70±0.09</td>
<td>1164±84 528±27 393±44</td>
</tr>
<tr>
<td>12</td>
<td>1.23±0.19 5.36±0.37 5.97±0.66</td>
<td>1010±82 501±57 454±26</td>
</tr>
<tr>
<td>4 kPa O$_2$+10 kPa CO$_2$ 6</td>
<td>1.13±0.16 5.80±0.30 6.27±0.42</td>
<td>1080±120 503±36 378±28</td>
</tr>
<tr>
<td>12</td>
<td>1.31±0.28 5.95±0.43 5.60±0.50</td>
<td>998±84 466±43 418±13</td>
</tr>
</tbody>
</table>

LSD treatment 0.05 = 0.25 0.21 0.35 122 44 51
LSD time 0.05 = 0.25 0.21 0.35 122 44 51

* Nitrogen was the balance gas in controlled atmospheres.
14.1 mg·100 g⁻¹ FW (207% increase) occurred in air-stored kiwifruit slices (Table 2). Those stored in 4 kPa O₂ (balance N₂) and air + 10 kPa CO₂ had a 164% increase in DHA after 12 days (Table 3). However, not all AA degradation was due to conversion of AA to DHA, since a loss of total vitamin C occurred in slices after 12 days. The lowest DHA was in slices stored in 0.5 kPa O₂ (balance N₂) and air + 20 kPa CO₂ which contained the highest and lowest vitamin C, respectively, after 12 days.

Our results confirmed results of Rosen (1987) that ‘G3’ strawberries stored under 2% O₂ for 7 days at 2.5°C had a higher AA content than fruit stored in air. Reducing the O₂ concentration in elevated CO₂ had little effect on vitamin C content. Similar results have been reported by Bangerth (1977) and Agar et al. (1997) on berries. Generally all 3 increased the first 6 days of storage and declined thereafter. The increase in sugars in air (control) stored slices was greater than for all 4 CA treatments. The total of the 3 sugars increased from 12.1 g·100 mL⁻¹ to 17.5 g·100 mL⁻¹ and then declined to 15.5 g·100 mL⁻¹ after 6 days and 12 days, respectively, in air-stored slices. Kiwifruit slices stored in CA contained 13.2 to 14.8 g·100 mL⁻¹ total sugars after 6 days storage and 12.2 to 12.9 g·100 mL⁻¹ after 12 days storage. The increase in SSC, especially in air stored slices, appear to correlate with the increase in total sugars (data not shown), which was probably due to continued ripening. The CA treatments, particularly 2 kPa O₂ + 10 kPa CO₂ delayed ripening during storage and also resulted in lower sugar content.

Citric, malic and quinic acid were respectively 49%, 26% and 24% of the organic acids determined in fresh-cut slices (Table 4). Total organic acid content of air (control) stored slices decreased by 21% after 12 days storage. Slices stored in CA treatments, with exception of 2 kPa O₂ + 10 kPa CO₂, either retained or had slightly increased organic acid concentrations. Slices stored in 2 kPa O₂ + 5 kPa CO₂ and 4 kPa O₂ + 5 kPa CO₂ treatments had the highest citric, malic and quinic acid contents after 12 days, which may have been due to the low respiration rates.

**CONCLUSIONS**

**STORAGE TEMPERATURE, DEGREE OF TISSUE DAMAGE AND MICROATMOSPHERIC GAS COMPOSITION WAS IMPORTANT FACTORS FOR QUALITY RETENTION OF FRESH-CUT KIWIFRUIT SLICES.** The shelf-life of slices held at 0-2°C was longer com-
pared to slices at 5°C or 10°C, which had accelerated softening, mass loss, and AA degradation. Physical damage or wounding caused by slicing and/or peeling resulted in increased CO₂ and C₂H₄ production and caused higher mass loss. Peel contributed to total CO₂ and C₂H₄ production. Removal of C₂H₄ from the storage atmosphere increased retention of firmness and TA, and the rate of softening was increased by exposure to air + 1 Pa C₂H₄. Treatments of CaCl₂ (1%) or Ca lactate (2%) were equally effective in firmness retention. No visible cut surface browning was observed in stored slices. Atmospheres of 0.5 and 1 kPa O₂ (balance N₂) did not extend the shelf-life of slices compared to 2 and 4 kPa O₂ (balance N₂). Atmospheres of 2 or 4 kPa O₂ or air + 5 or 10 kPa CO₂ were the most effective in extending shelf-life. Low O₂ helped maintain vitamin C content of fresh-cut slices. A CO₂ concentration of 5 kPa in air helped retain AA but CO₂ concentrations of 10 and 20 kPa in air increased losses of AA. The shelf-life range of fresh-cut kiwifruit slices was 9–12 days if treated with 1% AA. The shelf-life range of fresh-cut kiwifruit slices was 9–12 days if treated with 1% AA. The shelf-life range of fresh-cut kiwifruit slices was 9–12 days if treated with 1% AA.

REFERENCES


Ms received 7/10/98; revised 11/30/98; accepted 12/13/98.

Research supported in part by USDA research agreement no. 95–37500–910, NRI Competitive Grants Program. We thank Sarah Cathcart, Erica Mandle and Carolyn Menke for their excellent technical assistance.