EFFECT OF ELECTROLYZED OXIDIZING WATER AND CHLORINATED WATER TREATMENTS ON STRAWBERRY AND BROCCOLI QUALITY

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ABSTRACT

*Strawberries and broccoli were treated for 5 min with 4C tap water, chlorinated water or electrolyzed oxidizing water (55 and 100 mg/L chlorine, respectively) with or without ultrasonication. Several quality parameters (weight loss, shear force, color, pH, titratable acidity, soluble solids and decay) were evaluated to estimate the effect of treatments on consumer acceptability during storage at 4C. Strawberries were examined on the initial day of experiments and at 3, 6, 9 and 13 days of storage, and broccoli on the initial day as well as at 5, 10, 14 and 21 days of storage. On each day of analysis, weight loss, decay and color (*L* a* b* *values, chroma, hue angle, total color difference) were evaluated. On the last day of storage, texture was measured as force (Newton) needed to shear each sample. For strawberry, samples were also tested for pH, titratable acidity (%) and soluble solids content. No significant differences in quality were detected among strawberries and broc-*

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coli subjected to different treatments, and between treated samples and control at any of the sampling times. However, quality of strawberries treated with chlorinated water was significantly affected with respect to weight loss and decay, whereas only decay was significantly affected when broccoli was treated with chlorinated water.

PRACTICAL APPLICATIONS

Electrolyzed oxidizing (EO) water has been demonstrated to inactivate *Escherichia coli* O157:H7 on strawberries and broccoli during a washing treatment. This study found no significant differences in quality among strawberries and broccoli subjected to EO water treatments when compared with the tap water washing treatment or the control (no washing).

INTRODUCTION

Fruits and vegetables are an important component of the human diet as primary sources of essential vitamins and minerals. Fruits and vegetables also add variety to the diet and are highly favored for their pleasing colors, aromas, textures and flavors. To supply the current strong demand for fresh produce, producers are challenged to deliver safe and high quality products (Pangloli *et al*. 2009).

Strawberries are the fourth most valuable fruit produced in the United States and are one of the most delicate and perishable of all fruits, being very susceptible to water loss, decay and physiological deterioration (Eaves and Leefe 1962; Lillard 1993; Udompijitkul *et al*. 2007). Broccoli is a cruciferous vegetable that is thought to have anticarcinogenic properties and is rich in vitamins A, C and folic acid (Berrang *et al*. 1990). The increase in produce consumption has led to an increase in food-borne illnesses associated with raw fruits and vegetables (Nguyen-The and Carlin 1994; Brackett 1999; Rangel *et al*. 2005). Treatments with water-based sanitizers, including chlorine, have been introduced to enhance the safety of fruits and vegetables.

Chlorinated water, in the form of OCl^-, Cl_2 and HOCl, is widely used to wash fresh fruits and vegetables shortly after harvesting and at various stages of handling and processing (Nagawara *et al*. 1998; Sapers and Simmons 1998; Nunes and Edmond 1999; Xu 1999; Park *et al*. 2001). A new nonthermal treatment using electrolyzed oxidizing (EO) water has been reported to have strong bactericidal effects on most pathogenic bacteria (Venkitanarayanan *et al*. 1999; Kim *et al*. 2000). Bactericidal effects are due to an electrolyzed acidic aqueous solution with a low pH (*c.* 2.5), high oxidation-reduction potential (ORP; *c.* 1050 mV), and contains hypochlorous acid (from 10 to 100 ppm). The concentration of chlorine in EO water can be controlled by adjusting the amperage setting of the EO water generator (Ezeike and Hung 2004). Chemical methods can also be combined with a physical–mechanical method such as ultrasonication, for enhancing the disinfection of fresh fruits and vegetables (Maas 1971; Peterson and Pitt 1999; Hua and Thompson 2000; Kim *et al.* 2003).

Although several scientists have reported that EO water washes can be used as an alternative nonthermal process to chlorine water in eliminating food-borne pathogens on food material (Kim *et al.* 2000, 2005; Park *et al.* 2001, 2002, 2005; Huang *et al.* 2005, 2006), few studies have reported the effects of EO water treatment on the quality of fresh produce (Koseki and Itoh 2001; Park *et al.* 2001; Rico *et al.* 2008). Quality may consist of many properties within a food product. Abbott (1999) reported that appearance is one of the major factors consumers use to evaluate the quality of fresh fruits and vegetables and many products are routinely sorted for color. She also indicated that the measurement of optical properties has also been one of the most successful technologies used for assessing food quality. In addition, when mechanical properties and chemical constituents of fresh fruits and vegetables are combined, they may provide an estimate of consumer acceptability.

A previous study of lettuce treated with electrochemically activated water (Park *et al.* 2001) and on fresh cut vegetables treated with EO water (Koseki and Itoh 2001) indicated no significant effect on quality attributes. Kim *et al.* (2003) also found that EO water treatment with up to 84 mg/L chlorine did not affect the germination rate of alfalfa seeds. A related study on washing fresh-cut iceberg lettuce with chlorinated water (Delaquis *et al.* 2004) found that warm chlorinated water (50C) treatment significantly reduced aroma development during storage but not by the chilled (4C) chlorinated water. Simmons *et al.* (2006) reported the appearance, color, aroma, texture and overall quality of fresh-cut lettuce treated with different hypochlorite solutions were only affected by storage time but not by different treatments.

A companion study to this article evaluated the efficacy of EO water in combination with ultrasonication for the inactivation of *E. coli* O157:H7 on strawberries and broccoli (Hung *et al.* 2010). They found that combining EO water and ultrasonication treatments reduced *Escherichia coli* O157:H7 by 1.9 and 2.2 log CFU/g for strawberries and broccoli, respectively. The present study was conducted to investigate the quality attributes of strawberries and broccoli treated with EO water and chlorinated water in combination with ultrasonication at the conditions most effective in killing *E. coli* O157:H7 found in our companion study.

MATERIALS AND METHODS

Materials

Produce selected for quality evaluation were strawberries (*Fragaria xananassa*, Naturipe™, CA, USA) at the same ripening stage (three-quarter to full red) and broccoli (*Brassica oleracea* var. *italica*). Produce used for this study were purchased from a local grocery store in Griffin, GA.

The strawberries were graded for uniformity of size and sorted to remove damaged and defective fruit. Fruits that were less than three-quarters red or over mature were also eliminated. Strawberries with weights ranging from 25 to 30 g were used for this study. Forty-nine strawberries were prepared with seven strawberries for each of the seven treatment groups (unwashed controls, washed with tap water, washed with chlorinated water, washed with EO water, washed with tap water plus ultrasonication, washed with chlorinated water plus ultrasonication, washed with EO water plus ultrasonication).

For the broccoli study, broccoli with uniform head size and floret color and without any visible decay were selected. Broccoli florets were cut to include 1 cm of the stems and divided into segments with a floret diameter of 4 cm. Each broccoli floret had a final weight of between 15 and 20 g. Forty-nine broccoli florets were prepared with seven broccoli florets for each of the seven treatment groups (unwashed controls, washed with tap water, washed with chlorinated water, washed with EO water, washed with tap water plus ultrasonication, washed with chlorinated water plus ultrasonication, washed with EO water plus ultrasonication). The whole experiment was replicated twice.

Preparation of Treatment Solutions: EO and Chlorinated Water

EO water was generated using a Hoshizaki EO water generator (model ROX 20TA, Hoshizaki Electric Inc., Toyoake, Aichi, Japan). EO water generated at the current setting of 14 A (55 ± 2 mg/L of residual chlorine) and chlorinated water [$Ca(OCl)_2$, certified for biological work, Fisher Scientific Co., Fair Lawn, NJ] with chlorine concentrations similar to that EO water were used for the strawberry study. Another EO water treatment produced at a higher amperage (20 ± 0.5 A) and chlorinated water with chlorine concentrations similar to EO water (100 ± 2 mg/L of residual chlorine) were used for the broccoli study. When the amperage of the EO water generator was stabilized, an appropriate amount of acidic EO water was collected at 24 ± 2C from the anode outlet in a 2-L glass jar for the strawberry and broccoli treatments, respectively. The treatment solutions were covered and stored at 1C for 5 h to achieve a solution temperature of 4C.

Procedure for Treating Samples

Detailed descriptions of the sample treatment can be found in Hung *et al.* (2010). They indicated that the most effective conditions for inactivating *E. coli* O157:H7 on strawberries and broccoli were at 4C for 5 min in combination with ultrasonication. Hence, treatments were performed by immersing individual sample (strawberry or broccoli) into Nasco WHIRL-PAK® bags (18 oz) containing 125 or 150 mL of the appropriate solution at 4C for 5 min either with or without ultrasonication (model FS60, 44–48 kHz, Fisher Scientific Co.) for the strawberry and broccoli studies, respectively.

Strawberries and broccoli were then rinsed with 125 or 150 mL of deionized water for 1 min, respectively, to remove any possible chlorine residuals on the samples. After eliminating excess water on the surface of samples by shaking for 10 s, they were placed into a partitioned Rubbermaid® tray (Rubbermaid Home Products, OH), which was covered with perforated plastic Glad® clingwrap (The Glad Products Company, Oakland, CA) to prevent dehydration and physical contact among the samples during storage. Boxed strawberries and broccoli florets were stored in a refrigerator at 4C for the 13-day and 21-day experimental periods, respectively.

Determination of the Properties (pH, ORP and Residual Chlorine) of Treatment Solutions

Properties (pH, ORP, residual chlorine) of chlorinated water and EO water were measured immediately after storage at 1C. Readings of pH and ORP were taken before and after treatment using a dual scale pH meter (ACCUMET, model 50, Denver instrument Company, Denver, CO) with pH and ORP electrodes. The residual chlorine of the treatment solutions was determined before and after treatment by an iodometric method using a digital titrator (model 16900, Hach Company, Loveland, CO) with a 0.113 N sodium thiosulfate standard solution (Hach Company).

Nondestructive Measurements on Strawberry and Broccoli Quality

At each sampling time, samples were retrieved from the storage for the nondestructive measurements described below and returned back to the storage after the measurements. Weight loss of the same sample was measured during storage using an analytical balance (model AT400, Metter Toledo, Inc., Columbus, OH). Weight losses were expressed as percentage loss of original weight on the day of purchase.

Changes in the color of samples were determined during storage. For strawberry, three readings were taken from the top, middle and bottom section of each strawberry. Strawberries were arranged during storage to ensure color readings were taken from the same general location for each strawberry during the entire storage period. For broccoli, three readings were taken from the top of each broccoli floret on each sampling date. Instrumental measurements of the surface color were determined using a hand-held tristimulus reflectance colorimeter (model CR-200, Minolta Camera Co., Ltd, Osaka, Japan) equipped with a D_{65} illuminant, 0° viewing angle and a measuring area of 8 mm diameter. The instrument was calibrated with a white standard tile ($L^* = 97.47$, $a^* = -0.67$ and $b^* = 2.56$). A red tile ($L^* = 48.76$, $a^* = 36.79$ and $b^* = 14.46$) for strawberries and a green tile ($L^* = 64.64$, $a^* = -29.03$ and $b^* = 8.56$) for broccoli florets were used as references. Standard C.I.E. 1976 chromatic coordinates (L^*, a^* and b^*) were determined and these values were used to calculate chroma ($C^* = [a^{*2} + b^{*2}]^{0.5}$), hue angle ($h° = \tan^{-1}[b^*/a^*]$) and total color difference ($\Delta E = [(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2]^{0.5}$, where L_0^*, a_0^* and b_0^* represent initial chromatic parameters of the red or green tile).

Destructive Measurements on Strawberry Quality

All destructive measurements were determined on the last day of storage (13-day for strawberries and 21-day for broccoli). Firmness was measured by determining the maximum force required to shear each strawberry. The whole strawberry without calyx was sheared with an Instron Universal Testing Machine (model 5500R, Instron, Canton, MA) using a 50 kg load cell. Strawberry fruits were sheared through the side (Fig. 1) with the stem in a horizontal plane. A Kramer Shear Cell with blades running at a crosshead speed of

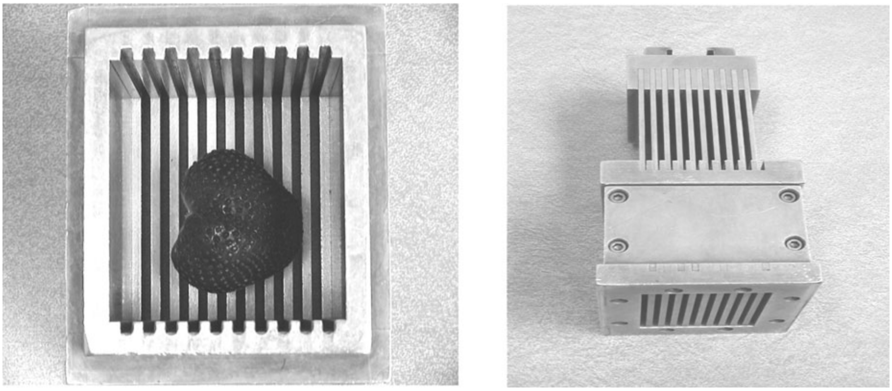

FIG. 1. TEXTURE DETERMINATION OF A WHOLE STRAWBERRY USING A KRAMER SHEAR CELL

50 mm/min was used. Seven samples were sheared for each of the two replicated experiments for each treatment. The shear force was expressed in Newtons (N).

All seven strawberries from the same treatment were homogenized together in a laboratory blender (BlendMaster™, Hamilton Beach, Canada) at high speed for 2 min. The homogenate was centrifuged (Model J2-21M, Beckman, Fullerton, CA) at 800× g for 30 min, filtered through cheesecloth (Nunes *et al.* 1995), and the soluble solids content (SSC) of the resulting clear juice samples was determined three times with a digital refractometer (ATAGO Pr101, NSG Precision Cells, INC., Farmingdale, NY). Brix (%) was used as a measurement of SSC. The pH of the juice was determined using an ACCUMET model 50 pH meter.

Three juice samples (6.00 g each) were diluted with 100 mL distilled water and the titratable acidity was determined by titrating with a 0.1N NaOH solution to an end point pH of 8.1. The results were converted to percent citric acid [(mL NaOH × 0.1N × 0.064/6.00 g of juice) × 100] (El-kazzaz *et al.* 1983; Nunes *et al.* 1995).

Destructive Measurement on Broccoli Quality

The shear force was evaluated as an indicator of firmness with an Instron Universal Testing Machine using a 500 kg-load cell. A Kramer Shear Cell with blades running at a crosshead speed of 50-mm/min was used (Latimer *et al.* 1988; Berrang *et al.* 1990). The broccoli stem was placed perpendicular to the Kramer shear blade axis. Seven broccoli floret samples including 1 cm of the stems were sheared for each of two replicated experiments for each treatment. The force to cut the broccoli was expressed in Newtons.

Decay Evaluation

A seven-member panel was used to conduct a descriptive analysis (Rosenfeld and Nes 2000). Panelists were recruited from the employee pool of the Department of Food Science and Technology, University of Georgia, Griffin, GA. The panelists were not informed about the purpose of the experiment. Sensory attributes of strawberries and broccoli were selected from those previously reported in the literature (Paradis *et al.* 1995; Cliff *et al.* 1996; Rosenfeld and Nes 2000; Wszelaki and Mitcham 2000). The panelists were trained with sets of reference photos and descriptive words to establish subjective scales for decay. Prior to wash treatments on day 0 as well as on day 3, 6, 9 and 13 for the strawberry study and on day 0, 5, 10, 14 and 21 for the broccoli, three samples from each treatment were presented at the same time to panelists. All samples were assigned three-digit numbers and were pre-

TABLE 1.
DESCRIPTIVE RATING SCALE FOR DECAY EVALUATIONS OF STRAWBERRIES AND BROCCOLI FLORETS

Rating scale	Strawberry decay	Broccoli decay
1 = none	No decay	No decay
2 = slight	Only minor surface indentation	One to three brown or black spots
3 = moderate	One to three black spots	Three or four brown or black spots
4 = severe	Visible mold growth or more than three black spots	More than four brown or black spots
5 = extremely severe	At least one-quarter decayed	More than 10 brown or black spots

sented in random order on white plates. All tests were performed in a sensory laboratory in partitioned booths. Strawberry and broccoli decay was evaluated using the scores shown in Table 1.

Statistical Analysis

Analysis of variance (ANOVA) was carried out on all the data using the Statistical Analysis System (SAS Institute Inc. 1982). Means were compared by ANOVA using Duncan's multiple range tests to determine if significant differences ($P \leq 0.05$) existed among mean values of treatments (Harker and Hallett 1992).

RESULTS AND DISCUSSION

Changes in Properties (pH, ORP and Residual Chlorine Concentration) of Treatment Solutions

The mean pH, ORP and residual chlorine concentration of EO water and chlorinated water before and after treatment are presented in Tables 2 and 3. The mean pH and ORP of tap water were 6.82 ± 0.2 and 308.8 ± 1.3 mV. Less than 1 mg/L of chlorine was detected in tap water.

For the strawberry study, EO water with and without ultrasonication was generated at the same pH (2.6), ORP (1050.5 mV) and residual chlorine concentration (55.3 mg/L). Chlorinated water was prepared at a higher pH (8.69) and at a lower ORP (679.5 mV) although the residual chlorine concentration (55.1 mg/L) was equivalent to the EO water. The pH of chlorinated water reduced significantly (from 8.69 to 7.83–7.95) after treatment, whereas the pH of EO water remained about the same (from 2.60 to 2.62–2.66). The ORP of chlorinated water was reduced about 4.4% after treatment, whereas the ORP of EO water reduced about 0.5 and 1.5% for without and with ultrasoni-

TABLE 2.
CHANGES IN PROPERTIES OF TREATMENT SOLUTIONS USED FOR STRAWBERRY IMMERSION*

Treatment	pH		ORP (mV)		Chlorine concentration of the solution (mg/L)	
	Before treatment	After treatment	Before treatment	After treatment	Before treatment	After treatment
Tap water	6.80	–	307.3	–	<1	–
Without ultrasonication						
EO water	2.60A	2.62A	1,050.5	1,045.7	55.3A	39.5B
Chlorinated water	8.69A	7.95B	679.5	649.5	55.1A	43.9B
With ultrasonication						
EO water	2.60A	2.66A	1,050.5	1,034.6	55.3A	30.4B
Chlorinated water	8.69A	7.83B	679.5	649.4	55.1A	35.0B

* Values in the same row within each property sharing a common letter are not significantly different ($P > 0.05$); properties of deionized water were a pH of 4.9, an ORP of 299.4 mV and a chlorine concentration of 0 mg/L.
ORP, oxidation-reduction potential; EO, electrolyzed oxidizing.

TABLE 3.
CHANGES IN PROPERTIES OF TREATMENT SOLUTIONS USED FOR BROCCOLI IMMERSION*

Treatment	pH		ORP (mV)		Chlorine concentration of the solution (mg/L)	
	Before treatment	After treatment	Before treatment	After treatment	Before treatment	After treatment
Tap water	6.84	–	309.9	–	<1	–
Without ultrasonication						
EO water	2.43	2.41	1,058.9	1,047.3	99.4A	63.6B
Chlorinated water	8.34	8.32	634.8	647.5	99.2A	84.3B
With ultrasonication						
EO water	2.43	2.46	1,058.9	1,049.4	99.4A	60.3B
Chlorinated water	8.34	8.43	634.8	644.3	99.2A	83.2B

* Values in the same row within each property sharing a common letter are not significantly different ($P > 0.05$); properties of deionized water were a pH of 4.8, an ORP of 297.9 mV and a chlorine concentration of 0 mg/L.
ORP, oxidation-reduction potential; EO, electrolyzed oxidizing.

cation, respectively. There was a significant reduction in the residual chlorine concentration (ranging from 11.2 to 24.9 mg/L) among all treatments ($P \leq 0.05$). The highest reduction was obtained for EO water treatments with ultrasonication.

For the broccoli study, properties of EO water prior to treatment were a pH of 2.43, an ORP of 1,058.9 mV and a chlorine concentration of 99.4 mg/L, whereas chlorinated water had a higher pH of 8.34, a lower ORP of 634.8 mV and similar chlorine concentration (Table 3). After treatments, the pH, and ORP of EO and chlorinated waters did not change significantly. Chlorine concentrations were significantly reduced after treatment and the highest reduction was observed for EO water (35.8 mg/L without ultrasonication, and 39.1 mg/L with ultrasonication). The chlorinated water treatment only had about 15 to 16 mg/L reduction of residual chlorine. Although ultrasonication increased the reduction of chlorine concentration, the difference was not significant.

Ultrasonication may damage the tissue and remove organic materials from produce during treatment, which can then react with free chlorine to form combined chlorine. Beuchat *et al*. (1998) reported that chlorine is highly reactive with any plant or vegetable matter and these chemical reactions reduce the amount of active chlorine in the solution. Unlike strawberries, the surface of broccoli is more rigid and consequently ultrasonication did not damage the broccoli as much as it did on strawberries. Thus, the reduction of the residual chlorine concentration during strawberry treatment with ultrasonication is markedly greater for both EO water and chlorinated water (45 and 36.5%, respectively) than for the same treatment on broccoli (39.3 and 16.1%, respectively).

Weight Loss

Regardless of treatment, strawberry weight loss increased with increasing storage time (Fig. 2). At each storage time, there were no significant differences on the percentage of weight loss among control, tap water wash and EO water wash without ultrasonication. At days 9 and 13, both EO water and chlorinated water with ultrasonication had a significantly higher weight loss than the other treatments (Fig. 2). At the end of storage, strawberries treated with chlorinated water and EO water had a weight loss ranging from 27.10 to 30.26%, while tap water treatments had a weight loss ranging from 26.23 to 26.51% (Table 4). Regardless of treatment, there was no significant effect on weight loss due to ultrasonication. Similar to what was observed in Fig. 2, nontreated strawberries had a significantly lower weight loss at the end of 13 days of storage than both chlorinated water and EO water treatments with ultrasonication (Table 4).

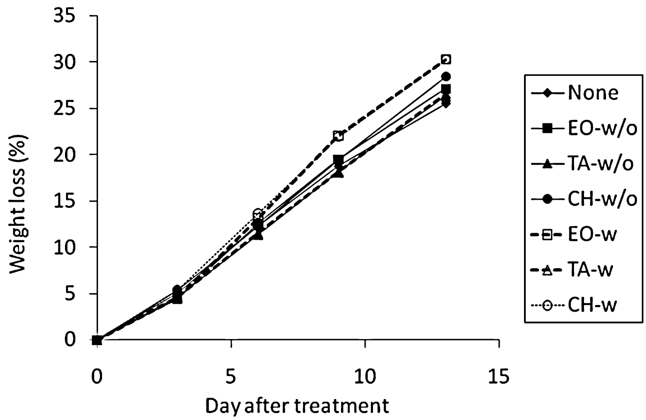

FIG. 2. EVALUATION OF STRAWBERRY WEIGHT LOSS (%) DURING THE 13-DAY EXPERIMENTAL PERIOD AT 4C

EO, electrolyzed oxidizing water; CH, chlorinated water; TA, tap water; none, nontreatment standard; w, with ultrasonication; w/o, without ultrasonication.

TABLE 4.
EFFECTS OF TREATMENT ON WEIGHT LOSS, SHEAR FORCE AND COLOR OF STRAWBERRIES AFTER STORAGE AT 4C FOR 13 DAYS†

Treatment	Weight loss‡ (%)	Shear force§ (N)	Color‡				
			*L**	*a**	Hue angle	Chroma	Δ*E*
None	25.51A	199.2A	29.63A	25.68A	26.94A	27.65A	73.37A
Without ultrasonication							
Tap water	26.23AB	189.3A	29.57A	27.13A	26.21A	30.30A	74.91A
EO water	27.10AB	188.2A	28.46A	24.95A	26.28A	28.00A	74.58A
Chlorinated water	28.36 B	184.9A	28.92A	26.30A	27.28A	29.42A	74.02A
With ultrasonication							
Tap water	26.51AB	189.5A	28.54A	25.94A	25.22A	28.64A	75.06A
EO water	30.23B	187.9A	27.51A	23.74A	25.63A	26.49A	74.80A
Chlorinated water	30.26B	184.6A	27.98A	24.49A	25.96A	27.12A	74.17A

† Values in the same column sharing a common letter are not significantly different ($P > 0.05$) by Duncan's multiple range test.

‡ Data are means of 14 individual strawberries.

§ Data are means of eight individual strawberries.

EO, electrolyzed oxidizing.

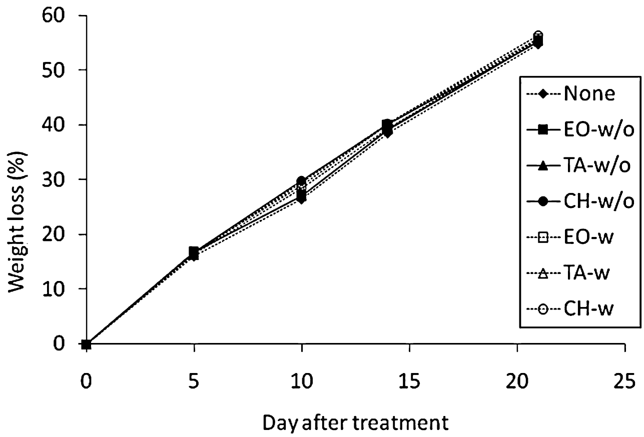

FIG. 3. EVALUATION OF BROCCOLI WEIGHT LOSS (%) DURING THE 21-DAY EXPERIMENTAL PERIOD AT 4C
EO = EO water, CH = chlorinated water, TA = tap water, none = nontreatment standard, w = with ultrasonication, w/o = without ultrasonication.

The rates of water loss for broccoli florets during storage were similar regardless of treatment as indicated by similar slopes of weight loss (Fig. 3). Weight loss rates of control broccoli and broccoli treated with sanitizers averaged 2.6 and 2.7% per day, respectively. After 21 days of storage, the weight loss for nontreated broccoli (54.75%) was not significantly different than other treated broccoli (55.05 to 56.38%) (Table 5). Ultrasonication slightly increased weight loss of broccoli over the same treatment without ultrasonication; however, no significant differences were found ($P > 0.05$).

The water content of broccoli and strawberries were 91 and 90%, respectively. At the same storage time, the water loss of broccoli was between 5 and 7% higher than for strawberries (Figs 2 and 3). In a study, Nunes *et al.* (1995) reported that water loss causes a negative effect on strawberry and broccoli appearance, leading to shriveling and a dull appearance of the epidermis. Chlorine-based sanitizers may damage cell walls and tissues and hence cause less internal turgor. Carbohydrate degradation may also occur with chlorine-based sanitizers and lead to loss of epidermis cohesiveness due to a decrease in cellulose viscosity, and a decrease in intermolecular bonding between cell wall polymers (Pekarovicova 1999; Suutarinen *et al.* 2000). Ultrasonication may also slightly increase cell wall fragility. However, results presented in Tables 4 and 5 indicated that there was no significant difference on weight loss for both strawberries and broccoli among EO water, tap water and control (no washing treatment). This demonstrated that EO water and ultrasonication treatments may not cause any cell or tissue damage during treatment.

TABLE 5.
EFFECTS OF TREATMENT ON WEIGHT LOSS, SHEAR FORCE AND COLOR OF BROCCOLI AFTER STORAGE AT 4C FOR 21 DAYS†

Treatment	Weight loss‡ (%)	Shear force§ (N)	Color‡			
			L^*	Hue angle	Chroma	ΔE
None	54.75A	1,192.7A	43.02A	121.43A	21.24A	58.12A
Without ultrasonication						
Tap water	55.04A	1,095.7A	43.76A	121.54A	22.63A	57.98A
EO water	55.39A	1,046.7A	42.70A	120.81A	20.94A	58.11A
Chlorinated water	55.17A	1,004.8A	42.87A	122.06A	21.28A	58.28A
With ultrasonication						
Tap water	55.64A	1,084.3A	42.70A	121.18A	21.06A	58.71A
EO water	55.84A	1,083.2A	43.74A	120.70A	21.71A	57.77A
Chlorinated water	56.38A	1,017.1A	43.64A	121.31A	22.13A	57.49A

† Values in the same column sharing a common letter are not significantly different ($P > 0.05$) by Duncan's multiple range test.
‡ Data are means of eight individual broccolis.
§ Data are means of 14 individual broccolis.
EO, electrolyzed oxidizing.

Shear Force

Shear force is a destructive measurement of firmness. Although strawberries treated with tap water had a higher shear force value (199.2 N) than other treated strawberries (184.6 to 189.5 N), the differences were not significant. Overall results indicate that washing treatment and ultrasonication did not lead to a decrease in the firmness of strawberries.

The control (nontreated) broccoli was about 10% firmer (1,192.7 N) than other treated broccoli (1,004.8 to 1,095.7 N). However, differences were not statistically significant ($P > 0.05$) (Table 5). No significant differences were observed among different treatments and ultrasonication.

In general, treated strawberries and broccoli experienced more apparent shrinkage of the cytoplasm than the untreated controls due to osmotic water loss. However, these differences were not reflected in firmness measurements.

Color

Significant effects on strawberry color were observed during storage (data not shown). Moreover, Holcroft and Kader *et al.* (1999) stated that anthocyanins and the factors that affect their synthesis, expression and stability are responsible for the color of strawberry fruit. Color deterioration during

TABLE 6.
EFFECTS OF SANITIZER TREATMENT ON PROPERTIES OF STRAWBERRIES AFTER STORAGE FOR 13 DAYS AT 4C*

Treatment	pH	SSC (%)	Titratable acidity (% citric acid)
None	3.48A	10.25A	0.87A
Without ultrasonication			
Tap water	3.51A	10.25A	0.87A
EO water	3.51A	10.35A	0.87A
Chlorinated water	3.50A	10.35A	0.89A
With ultrasonication			
Tap water	3.48A	10.20A	0.84A
EO water	3.54A	10.55A	0.87A
Chlorinated water	3.52A	10.50A	0.88A

* Values in the same column sharing a common letter are not significantly different ($P > 0.05$) by Duncan's multiple range tests. Data are means of duplicated experiments of seven strawberries.
EO, electrolyzed oxidizing; SSC, soluble solids content.

storage is due to at least two factors: loss of red anthocyanin pigment and formation of brown pigment (Dervisi *et al.* 2001). There was no significant difference ($P > 0.05$) in the color parameters among all treatments at the end of storage (Table 4). In general, strawberries treated with ultrasonication were darker (lower L^* value), less red (lower a^* value) and less bright (lower chroma) than fruits from other treatment groups (Table 4). However, the differences were not significant. The reduction of a^* values (less redness) can be explained from the occurrence of browning reactions in the berries. Although pH may have a profound effect on anthocyanin stability and color expression (Montero *et al.* 1996), there were no significant differences in strawberry pH values (Table 6).

Color changes in broccoli were also not significantly affected by any of the treatments with or without ultrasonication (Table 5). These results were confirmed by the visual observation that all broccoli maintained a similar color when stored at 4C throughout the study. Although the L^* value, chroma and total color difference did not differ significantly ($P > 0.05$) among any treatments, storage time appeared to have a significant effect on colors particularly the reduction in hue angle, which corresponds to a color change from green to yellow (data not shown). However, more than 21 days may be required for the entire yellowing process of broccoli to occur at 4C. Results indicated that EO water treatments on both strawberries and broccoli did not significantly affect the color when compared with a tap water only treatment or a nontreated control.

Chemical Properties of Strawberries

Results of the chemical composition of strawberries: pH, titratable acidity and SSC are presented in Table 6. There were no significant differences among any treatments in the three chemical parameters at the end of storage (day 13, $P > 0.05$).

Strawberry pH was largely unaffected by the treatment, and the pH ranged from 3.48 to 3.54. Titratable acidity (expressed as citric acid equivalents) ranged from 0.84 to 0.89. Sugars are one of the main soluble components in soft fruits and Brix evaluations showed slight variations in SSC with no significant differences. In general, sanitizer treatments of strawberries had no significant effect on measured chemical properties.

Decay Evaluation

For the strawberry study, there were significant effects in degree of decay based on storage time as well as treatment solutions (Table 7). In general, strawberries treated with chlorinated water had the greatest decay than other samples. After 13 days of storage at 4C, the chlorinated water treatment had the highest decay (without ultrasonication: 3.62, with ultrasonication: 3.79) followed by tap water (without ultrasonication: 2.98, with ultrasonication: 2.95), and EO water (without ultrasonication: 3.17, with ultrasonication: 3.07) treatments. Nontreated control had the lowest degree of decay after the 13-day storage period (2.43). Ultrasonication also had no significant effect on degree

TABLE 7.
EVALUATION OF STRAWBERRY DECAY DURING THE 13-DAY EXPERIMENTAL PERIOD AT 4C*

Treatment	Day 0	Day 3	Day 6	Day 9	Day 13
None	1.02A a	1.48A b	1.76AB b	2.24A c	2.43A c
Without ultraonication					
Tap water	1.02A a	1.52AB b	1.67A b	2.33AB c	2.98B d
EO water	1.02A a	1.52AB b	1.71A b	2.33AB c	3.17B d
Chlorinated water	1.02A a	1.79B b	1.98B b	2.64B c	3.62C d
With ultrasonication					
Tap water	1.04A a	1.55AB b	1.60A b	2.29A c	2.95B d
EO water	1.00A a	1.62AB b	1.76AB b	2.24A c	3.07B d
Chlorinated water	1.02A a	1.71AB b	1.76AB b	2.45AB c	3.79C d

* Same capital letter after each mean value in the same column and the same lower-case letter after each mean value in the same row indicate not significantly different ($P > 0.05$) by Duncan's multiple range tests. Data are means of 42 measurements per treatment (seven panel evaluations on duplicated experiments of three samples).

EO, electrolyzed oxidizing.

TABLE 8.
EVALUATION OF BROCCOLI DECAY DURING THE 21-DAY EXPERIMENTAL PERIOD AT 4C*

Treatment	Day 0	Day 5	Day 10	Day 14	Day 21
None	1.00A a	1.05A a	1.21A a	1.48A b	1.69A b
Without ultrasonication					
Tap water	1.00A a	1.07A ab	1.29A bc	1.52A cd	1.76A d
EO water	1.00A a	1.17A a	1.29A a	1.62A b	1.79A c
Chlorinated water	1.00A a	1.14A ab	1.31A b	1.67A c	1.93AB c
With ultrasonication					
Tap water	1.00A a	1.17A ab	1.31A bc	1.55A c	1.86AB d
EO water	1.00A a	1.17A ab	1.31A bc	1.55A c	1.90AB d
Chlorinated water	1.00A a	1.19A a	1.36A ab	1.62A b	2.19B c

* Same capital letter after each mean value in the same column and the same lower-case letter after each mean value in the same row indicate not significantly different ($P > 0.05$) by Duncan's multiple range tests. Data are means of 42 measurements per treatment (seven panel evaluations on duplicated experiments of three samples).

EO, electrolyzed oxidizing.

of decay. Fruit is usually not washed during the entire production, harvest and packing or marketing process due to its high susceptibility to fungal (gray mold) deterioration, which is promoted by an increase in moisture content on the surface. De Roever (1998) reported that fresh soft fruits (e.g., raspberries and strawberries) cannot tolerate exposure to water and concluded that for these products, disinfection rinses are not realistic options at the processing level. However, after 9 days of storage in our study, there were no significant differences in fruit decay between the control (2.24) and EO water (2.24–2.33) treatments.

Decay that developed on the broccoli floret (flower buds) was a combination of fungal spotting and bacterial rots. In general, rates of decay were lowest in the nontreated controls and the highest in the chlorinated water treated samples (Table 8). However, the only significant difference among all treatments was observed at the end of the 21-day storage period, whereas the control, tap and EO water treatments without ultrasonication (1.69 to 1.79) had significantly lower decay scores than chlorinated water treatments with ultrasonication (2.19). Due to an increase in water loss (>50% after 21 days of storage) observed in Table 2, panelists may be influenced by the dry appearance of some samples leading to downgrading in decay scores.

In general, broccoli was less affected by decay than strawberries during storage. This may be due to the fact that the strawberry tissue is softer and has a higher content of simple sugars leading to a more rapid increase in bacteria and fungi than in broccoli. In both cases, EO water treatments produced no significant differences in produce quality compared with tap water, which is commonly used to wash fresh produce in homes.

CONCLUSIONS

The results of this study revealed that washing strawberries and broccoli in EO water could be used as an effective produce wash without creating a negative impact on quality when stored up to 13 and 21 days, respectively. When strawberries and broccoli were washed in EO water, quality degradation was similar to tap water wash or nontreated controls. After the 13-day and 21-day experimental periods for strawberry and broccoli, respectively, strawberries and broccoli treated with EO water had no significant differences in color, shear force, weight loss, decay and chemical properties compared with a tap water treatment (commonly used to rinse treatment at home). Chlorinated water treatments had greater negative effects on quality characteristics of strawberries and broccoli than EO water treatment, in particular on weight loss, shear force and decay. In conclusion, EO water appears to be a feasible option at the processing level as well as for consumers in the home to wash strawberries and broccoli without affecting the quality.

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REFERENCES

ABBOTT, J.A. 1999. Quality measurement of fruits and vegetables. Postharvest Biol. Technol. *15*, 207–225.

BERRANG, M.E., BRACKETT, R.E. and BEUCHAT, L.R. 1990. Microbial, color and textural qualities of fresh asparagus, broccoli, and cauliflower stored under controlled atmosphere. J. Food Prot. *53*, 391–395.

BEUCHAT, L.R., NAIL, B.V., ADLER, B.B. and CLAVERO, M.R.S. 1998. Efficacy of spray application of chlorinated water in killing pathogenic bacteria on raw apples, tomatoes and lettuce. J. Food Prot. *61*, 1305–1311.

BRACKETT, R.E. 1999. Incidence, contributing factors, a control of bacterial pathogens in produce. Postharvest Biol. Technol. *15*, 305–311.

CLIFF, M.A., THOIVONEN, P.M.A. and KING, M.C. 1996. Effect of atmosphere on broccoli sensory attributes in commercial map and microperforated packages. J. Food Qual. *20*, 105–115.

DE ROEVER, C. 1998. Microbiological safety evaluations and recommendations on fresh produce. Food Control *9*, 321–347.

DELAQUIS, P.J., FUKUMOTO, L.R., TOIVONEN, P.M.A. and CLIFF, M.A. 2004. Implications of wash water chlorination and temperature for the microbiological and sensory properties of fresh-cut iceberg lettuce. Postharvest Biol. Technol. *31*, 81–91.

DERVISI, P., LAMB, J. and ZABETAKIS, I. 2001. High pressure processing in jam manufacture: Effects on textural and colour properties. Food Chem. *73*, 85–91.

EAVES, C.A. and LEEFE, J.S. 1962. Note on the influence of foliar sprays of calcium on the firmness of strawberries. Can. J. Plant Sci. *42*, 746–747.

EL-KAZZAZ, M.K., SOMMER, N.F. and FORTLAGE, R.J. 1983. Effect of different atmospheres on postharvest decay and quality of fresh strawberries. Phytopathology *73*, 282–285.

EZEIKE, G.O.I. and HUNG, Y.-C. 2004. Acidic electrolyzed water properties as affected by processing parameters and their response surface models. J. Food Process. Preserv. *28*, 11–27.

HARKER, F.R. and HALLETT, I.C. 1992. Physiological changes associated with development of mealiness of apple fruit during cool storage. HortScience *27*, 1291–1294.

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

HUA, I. and THOMPSON, J.E. 2000. Inactivation of *Escherichia coli* by sonication at discrete ultrasonic frequencies. Water Res. *34*, 3888–3893.

HUANG, Y.-R., HSIEH, H.-S., LIN, S.-Y., LIN, S.-J., HUNG, Y.-C. and HWANG, D.-F. 2005. Application of electrolyzed oxidizing water on the reduction of bacterial contamination for seafood. Food Control *17*, 987–993.

HUANG, Y.-R., SHIAU, C.-Y., HUNG, Y.-C. and HWANG, D.-F. 2006. Change of hygienic quality and freshness in tuna treated with electrolyzed oxidized water and carbon monoxide gas during refrigerated and frozen storage. J. Food Sci. *71*, M127–M133.

HUNG, Y.-C., TILLY, P. and KIM, C. 2010. Efficacy of electrolyzed oxidizing (EO) water and chlorinated water for inactivation of *Escherichia coli* O157:H7 on strawberries and broccoli. J. Food Qual. *33*, 559–577.

KIM, C., HUNG, Y.C. and BRACKETT, R.E. 2000. Roles of oxidation-reduction potential in electrolyzed oxidizing and chemically modified water for the inactivation of food-related pathogens. J. Food Prot. *63*, 19–24.

KIM, C., HUNG, Y.-C., BRACKETT, R.E. and LIN, C.-Y. 2003. Efficacy of electrolyzed water in inactivating Salmonella on alfalfa seeds and sprouts. J. Food Prot. *66*, 208–214.

KIM, C., HUNG, Y.-C. and RUSSELL, S.M. 2005. Efficacy of electrolyzed (EO) water in the prevention and removal of fecal material attachment and its microbicidal effectiveness during simulated industrial poultry processing. Poultry Sci. *84*, 1778–1784.

KOSEKI, S. and ITOH, K. 2001. The effect of acidic electrolyzed water on the quality of cut vegetables. J. Jpn. Soc. Food Sci. Technol. *48*, 365–369.

LATIMER, J.G., BEVERLY, R.B. and BLUM, B. 1988. Analysis of shear force data in broccoli transplant studies. Hortscience *23*, 627.

LILLARD, H.S. 1993. Bactericidal effect of chlorine on attached salmonellae with and without sonification. J. Food Prot. *56*, 716–717.

MAAS, J.L. 1971. Timing of benomyl application in relation to control of Botrytis strawberry rot. Plant Dis. Rptr. *55*, 883–885.

MONTERO, T.M., MOLLA, E.M., ESTEBAN, R.M. and LOPEZ-ANDREU, F.J. 1996. Quality attributes of strawberry during ripening. Scientae Hortic. *65*, 239–250.

NAGAWARA, S., GOTO, T., NARA, M., OZAWA, Y., HOTTA, K. and ARATA, Y. 1998. Spectroscopic characterization and the pH dependence of bactericidal activity of the aqueous chlorine solution. Anal. Sci. *14*, 691–698.

NGUYEN-THE, C. and CARLIN, F. 1994. The microbiology of minimally processed fresh fruits and vegetables. Crit. Rev. Food Sci. Nutr. *34*, 371–401.

NUNES, M.C.N., BRECHT, J.K., MORAIS, A.M.M.B. and SARGENT, S.A. 1995. Physical and chemical quality characteristics of strawberries after storage are reduced by a short delay to cooling. Postharvest Biol. Technol. *6*, 17–28.

NUNES, M.C.N. and EDMOND, J.P. 1999. Chlorinated water treatments affects post harvest quality of green bell peppers. J. Food Qual. *22*, 353–361.

PANGLOLI, P., HUNG, Y.-C., BEUCHAT, L.R., KING, C.H. and ZHAO, Z.-H. 2009. Reduction of *Escherichia coli* O157:H7 on produce by use of electrolyzed water under simulated food service condition. J. Food Prot. *72*, 1854–1861.

PARADIS, C., CASTAIGNE, F., DESROSIERS, T., FORTIN, J., RODRIGUE, N. and WILLEMOT, C. 1995. Sensory, nutrient and chlorophyll changes in broccoli florets during controlled atmosphere storage. J. Food Qual. *19*, 303–316.

PARK, H., HUNG, Y.-C. and BRACKETT, R.E. 2002. Antimicrobial effect of electrolyzed water for inactivating *Campylobacter jejuni* during poultry washing. Int. J. Food Microbiol. *72*, 77–83.

PARK, C.M., HUNG, Y.C., DOYLE, M.P., EZEIKE, G.O.I. and KIM, C. 2001. Pathogen reduction and quality of lettuce treated with electrolyzed oxidizing and acidified chlorinated water. J. Food Sci. *69*, 1368–1372.

PARK, C.-M., HUNG, Y.-C., LIN, C.-S. and BRACKETT, R.E. 2005. Efficacy of electrolyzed water in inactivating *Salmonella Enteritidis* and *Listeria monocytogenes* on shell eggs. J. Food Prot. *68*, 986–990.

PEKAROVICOVA, A. 1999. Pulp bleaching. http://www.wmich.edu/ppse/pekarovicova/160999b.html (accessed January 10, 2009).

PETERSON, R.V. and PITT, W.G. 1999. The effect of frequency and power density on the ultrasonically enhanced killing of biofilm-sequestred *Escherichia coli*. Colloids Surf. B Biointerfaces *17*, 219–227.

RANGEL, J.M., SPARLING, P.H., CROWE, C., GRIFFIN, P.M. and SWERDLOW, D.L. 2005. Epidemiology of *Escherichia coli* O157:H7 outbreaks, United States, 1982–2002. Emerging. Infect. Dis. *11*, 603–609.

RICO, D., MARTIN-DIANA, A.B., BARRY-RYAN, C., FRIAS, J.M., HENEHAN, G.T.M. and BARAT, J.M. 2008. Use of neutral electrolyzed water (EW) for quality maintenance and shelf-life extension of minimally processed lettuce. Innovative Food Sci. Emerg. Technol. *9*, 37–48.

ROSENFELD, H.J. and NES, A. 2000. Prediction of sensory quality of strawberry jam by means of sensory quality attributes of fresh fruits. J. Sci. Food Agric. *80*, 1895–1902.

SAPERS, G.M. and SIMMONS, G.F. 1998. Hydrogen peroxide disinfections of minimally processed fruits and vegetables. Food Technol. *52*, 48–52.

SAS INSTITUTE, INC. 1982. *SAS User's Guide*, Statistics, Cary, NC.

SIMMONS, J.L., RYU, J.-H. and BEUCHAT, L.R. 2006. Comparison of treatment of fresh-cut lettuce and diced tomatoes with sodium hypochlorite and calcium hypochlorite for effects on microbiological and sensory qualities. Food Prot. Trends *26*, 662–667.

SUUTARINEN, J., HEISKA, K., MOSS, P. and AUTIO, K. 2000. The effects of calcium chloride and sucrose prefreezing treatments on the structure of strawberry tissues. Lebensm. Wiss. Technol. *33*, 89–102.

UDOMPIJITKUL, P., DAESCHEL, M.A. and ZHAO, Y. 2007. Antimicrobial effect of electrolyzed oxidizing water against *Escherichia coli* O157:H7 and *Listeria monocytogenes* on fresh strawberries (*Fragaria x ananassa*). J. Food Sci. *72*, M397–M406.

VENKITANARAYANAN, K.S., EZEIKE, G.O., HUNG, Y.C. and DOYLE, M.P. 1999. Efficacy of electrolyzed oxidizing water for inactivating

Escherichia coli O157:H7, *Salmonella enteridis*, and *Listeria monocytogenes*. Appl. Environ. Microbiol. *65*, 4276–4279.

WSZELAKI, A.L. and MITCHAM, E.J. 2000. Effects of superatmospheric oxygen on strawberry fruit quality and decay. Postharvest Biol. Technol. *20*, 125–133.

XU, L. 1999. Use of ozone to improve the safety of fresh fruits and vegetables. Food Technol. *53*, 58–62.