

# Microbial reduction and storage quality of fresh-cut cilantro washed with acidic electrolyzed water and aqueous ozone

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## Abstract

Efficacy of decontamination treatments in reducing microbial populations on cilantro and in improving its storage quality was investigated. Fresh-cut cilantro samples were washed with one of the five treatments: tap water, acidic electrolyzed water (AEW), aqueous ozone, chlorinated water, and aqueous ozone followed by AEW (sequential wash). Treated cilantro was packaged in polyethylene bags prepared with films of selected oxygen transmission rate of 6200 mL/(dm<sup>2</sup>) and stored at 0 °C for 14 days. The total aerobic bacterial population, total enterobacteriaceae, electrolyte leakage and sensory qualities were examined every 4 days. Test results indicated that the sequential wash is effective in initial microbial count reduction. This treatment also maintained low microbial growth during storage. However, the higher electrolyte leakage may indicate cilantro tissue damage in this treatment. Using AEW alone also resulted in moderate control of aerobic bacterial growth during storage. Ozone treatment, on the other hand, achieved the highest overall quality of cilantro during storage and also maintained the typical cilantro aroma.

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**Keywords:** Acidic electrolyzed water; Aqueous ozone; Fresh-cut; Cilantro; Sequential wash

## 1. Introduction

Cilantro has been widely used in Mexican dishes, particularly salsa and ceviche, as well as in Asian and Indian specialties. However, the safety of cilantro has raised concerns. Surveys conducted by the Food and Drug Administration (FDA) reported that 1.6% cilantro samples were contaminated by both *Salmonella* and *Shigella* (FDA, 1999, 2001) and 5.0% by *Cryptosporidium* oocysts, a parasite (Monge & Chinchilla, 1996). In 1999 there was an outbreak caused by *S. Thompson* on cilantro in California (Anon., 2002). Fresh-cut cilantro is

more susceptible than whole cilantro to spoilage microbial and pathogen contaminations due to tissue damage.

Conventional fresh-cut cilantro production uses rinse water, usually chlorinated at 100 mg/L, to decontaminate cilantro leaves. However, the relatively low inactivation rate of chlorine at concentrations limited by regulation, as well as the adverse effect of chlorine by-products, has raised concerns in the food industry. Scientists have been searching for alternative methods to protect fresh-cut produce from decaying, to prolong shelf life, and to secure product safety.

Fan, Niemira, and Sokorai (2003) used ionizing radiation at different doses to treat cilantro that resulted in 2.2- to 3-log reductions in initial total aerobic plate count (TPC) and relatively good retention of sensorial quality and shelf life. Luo, Wachtel, McEvoy, Kim, and Hung (2004) developed a modified atmosphere

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packaging system for fresh-cut cilantro leaves with acceptable quality and a 14-day shelf life. Ozone as an aqueous disinfectant was declared to be generally recognized as safe (GRAS) for food contact applications in 1997 (Graham, 1997). Ozone's primary advantages include fast decomposition in water to oxygen, no residue, and improved microbial reduction efficacy against bacteria, viruses, and fungal spores than hypochlorite (Khadre, Yousef, & Kim, 2001). Aqueous ozone has been tested for its efficacy in the decontamination of lettuce (Kim, Yousef, & Chism, 1999; Singh, Singh, Bhunia, & Stroshine, 2002), and alfalfa seeds and sprouts (Sharma, Demirci, Beuchat, & Fett, 2002a, 2002b; Singh, Singh, & Bhunia, 2003; Wade et al., 2003). Microbial studies in laboratory testing typically show a 2-log reduction in total microbial counts and significant reduction of spoilage species commonly found in fruits and vegetables (Khadre et al., 2001). Large scale testing, however, usually yields only a 90% microbial reduction (Anon., 1999).

Acidic electrolyzed water (AEW) has a strong bactericidal effect against pathogens and spoilage microorganisms, more effective than chlorine, due to its low pH, high oxidation reduction potential (ORP) and the presence of residual chlorine (Bari, Sabina, Isobe, Uemura, & Isshiki, 2003; Izumi, 1999; Kiura et al., 2002; Park, Hung, Doyle, Ezeike, & Kim, 2001; Venkitanarayanan, Ezekike, Hung, & Doyle, 1999). Koseki, Yoshida, Isobe, and Itoh (2001) applied AEW (pH 2.6, ORP 1140 mV, 30 mg/L available chlorine) to surface treat lettuce and reported a 2-log reduction in viable aerobes that was higher than the 1.5-log reduction using ozonated water (5 mg/L). AEW was also tested for its efficacy in inactivating *Salmonella* on alfalfa seeds and sprouts by Kim, Hung, Brackett, and Lin (2003) and Stan and Daeschel (2003). Electrolyzed water at high pH (pH 6.8, 20 mg/L available chlorine) was tested as a disinfectant and the research found that it did not affect tissue pH, surface color, or general appearance of fresh-cut vegetables (Izumi, 1999). Inactivation of *Listeria monocytogenes* biofilm formers on stainless steel surfaces with AEW treatment reported a 9-log reduction in viable count (Kim, Hung, Brackett, & Frank, 2000). Inactivation of *Salmonella* and *Escherichia coli* O157:H7 on alfalfa seeds was generally enhanced by a simultaneous treatment of ultrasound, chemicals and heat (Scouten & Beuchat, 2002). However, Singh et al. (2003) found that no individual treatment among aqueous ClO<sub>2</sub>, ozonated water, and thyme oil was able to completely eliminate *E. coli* O157:H7 inoculated on alfalfa seeds. They employed a sequential wash strategy (thyme oil followed by ozonated water and aqueous chlorine dioxide) to inactivate *E. coli* O157:H7 and found only the sequential wash controlled the growth of microbial populations during sprouting (Singh et al., 2003). The use of combined or sequential treatment in produce decontamina-

tion is an approach worthy of further investigation. It is hoped that a combination of AEW and ozonated water will be an effective way to wash fresh-cut produce. The objective of this study was to examine the effect of AEW, ozonated water and sequential wash (ozonated water followed by AEW) on texture, color, electrolyte leakage, sensory, and microbial reduction of cilantro during 14-day storage at 0 °C.

## 2. Materials and methods

### 2.1. Preparation of treatment solutions

Acidic electrolyzed water (AEW) was generated using an AEW generator (TYH-91, TOYO Inc., Osaka, Japan). A 24% solution of sodium chloride and de-ionized water from a laboratory supply line were simultaneously pumped into the generator chamber and the final concentration of sodium chloride solution passing through electrodes in the AEW generator chamber was about 0.2%. When the strong acidic indicator was on, AEW was collected from the anode outlet with a sanitized bucket. The pH and oxidation reduction potential (ORP) of the AEW were measured with an AR15 pH and ORP meter (Accumet Research, Fisher Scientific Co., Pittsburgh, PA, USA), while the residual chlorine concentration was determined by a portable chlorine colorimeter (HI93711, HANNA Instruments, Fisher Scientific Co., Pittsburgh, PA, USA). AEW was used within one hour.

Aqueous ozone solution was prepared by continuously circulating the water through an ozone generator (Clean Air and Water Systems Inc., Poulosbo, WA, USA) and a stainless steel water tank. The ozone generator was equipped with a vortexer to facilitate dissolving of gaseous ozone in the water, and a de-gassing system to remove the undissolved ozone. The concentration of dissolved ozone was determined following a modified indigo method (Bader & Hoigne, 1981). The ozone solution was used immediately after the required ozone concentration was reached.

Chlorine solution was prepared with food grade bleach and the pH was adjusted to 6.5 with 1N HCl. The available chlorine was determined with a HI93711 portable chlorine colorimeter. The solution was used within 30 min.

### 2.2. Sample preparation

Fresh cilantro (*Coriandrum sativum* L.) was obtained from a produce wholesale market (Jessup, MD). Defective leaves and unusable stems were removed, and leaves were cut into approximately 3 cm segments using a sharp knife (Luo et al., 2004). Fresh-cut cilantro samples (1.5 kg each) were washed with gentle agitation in buck-

ets each containing 45 L solution from one of the following treatments: tap water, chlorinated water (NaClO, available chlorine 50 mg/L, pH 6.5), aqueous ozone, acidic electrolyzed water (pH 2.45, ORP 1130 mV, and available chlorine 16.8 mg/L), and aqueous ozone followed by AEW (sequential washing). The wash time was 5 min for all the treatments except the sequential wash in which a 5 min aqueous ozone wash was followed by a 5 min AEW wash. Washed samples were centrifuged at 300 rpm for 2 min with a T-304 salad centrifugal dryer (Garrouite Spin Dryer, Meyer Machine Co., San Antonio, TX, USA) to remove excess water. Dewatered samples of 85 g each were packaged in sealed polypropylene bags (19×22 cm) of film oxygen transmission rate (OTR) of 6200 mL/(dm<sup>2</sup>). The packages were flushed with 5 kPa O<sub>2</sub> to accelerate the gas equilibrium rate. Samples were stored at 0 °C for 14 days. Sampling for quality evaluation was at days 0, 4, 8, 11, and 14.

### 2.3. Electrolyte leakage analysis

The electrolyte leakage of fresh-cut cilantro was measured immediately after treatment and during storage to determine possible tissue deterioration (Kim et al., 2003). Samples of 30 g cilantro leaves were submerged in 400 mL of deionized water for 30 min at 7–8 °C. The conductivity (μs/cm) of the solution was determined with a conductivity meter (Accumet Basic AB30, Fisher Scientific Co., Pittsburgh, PA, USA) and was used to characterize the electrolyte leakage of plant tissues.

### 2.4. Color measurement

A Minolta Chroma Meter CR-300 (Minolta Corp., Osaka, Japan) was used to assess the color of cilantro leaves. Considering color variations among cilantro leaves within the same bag, 30 readings per bag were taken to ensure that the data obtained truly represented the color of the samples. The means of  $L^*$ ,  $a^*$  and  $b^*$  from 30 readings were reported and hue angle was calculated from averaged  $a^*$  and  $b^*$  values (McGuire, 1992).

### 2.5. Texture measurement

The firmness of the fresh-cut cilantro leaves was measured using a TA.XT2i Texture Analyzer (Texture Technology Corp., Scarsdale, NY, USA) and a Kramer shear press with 10 blades. A randomly selected 30-g sample was placed in the press holder, and then the 10-blade plunger was moved down at 2 mm/s to 1 cm below the bottom of the holder. Maximum force was recorded using the Texture Expert software (version 1.22, Texture Technology Corp., Scarsdale, NY, USA). Texture measurements were conducted with samples from each treatment in triplicate.

### 2.6. Microbiological analysis

Cilantro samples (20 g) were homogenized in 180 mL of 0.1% sterile peptone water (pH 7.4) in a model 400 Lab Stomacher (Seward Medical, London, UK) and agitated for 2 min at 260 rpm. Homogenates were filtered through sterile glass wool, serially diluted in peptone water, and logarithmically plated (50 μL in duplicate) on appropriate media with a Wassp II Sprial Plater (DW Scientific, West Yorkshire, England). The total aerobic plate count (TPC) was determined by plating the samples on tryptic soy agar (TSA, Difco Lab, Detroit, MI, USA) and incubating at 28 °C for 24 h. Total Enteric bacteria enumeration was performed by culturing with McConkey agar (TSA, Difco Lab, Detroit, MI, USA) and incubating at 37 °C for 24 h. Microbial colonies were counted using a Protos Colony Counter (Model 50000, Synoptics Ltd., Cambridge, UK) and reported as log CFU/g of tissue.

### 2.7. Sensory evaluation

Sensorial quality attributes of typical cilantro aroma, off-odor and overall quality were evaluated immediately after opening the bags by a three-member trained panel following a modified procedure from Loaiza and Cantwell (1997). Aroma was scored on a 4 to 0 scale, where 4=extremely strong, 3=strong, 2=moderate, 1=slight, and 0=none. Off-odor was scored on a 0 to 4 scale, where 0=no off-odor and 4=extremely strong off-odor. Overall quality was evaluated with a 9-point hedonic scale, where 9=like extremely, 5=neither like nor dislike and 1=dislike extremely.

### 2.8. Statistical analysis

Triplicate samples from each treatment were analyzed at each sampling time. Data were analyzed using the Statistical Analysis System (SAS Institute, Cary, NC, USA) by one way analysis of variance (ANOVA). The Fisher's LSD test was used to determine differences at  $\alpha=0.05$ .

## 3. Results and discussion

### 3.1. Color and texture

The color changes of fresh-cut cilantro leaves expressed by  $L^*$ ,  $a^*$ ,  $b^*$ , and hue angle values are shown in Table 1. The changes in sample color among different treatments and over storage time were statistically insignificant. This indicates that the color of cilantro leaves was not affected by the strong oxidizing agents used in this study either in washing or during the entire storage period. The low storage temperature (0 °C) may have

Table 1  
Color measurements of cilantro leaves during storage at 0 °C

Color parameter	Treatment	Storage time (day)				
		0	4	8	11	14
$L^*$	Control	50.7±3.0	49.4±3.0	49.7±3.2	50.2±3.2	50.2±2.7
	Chlorine	50±1.8	49.7±3.2	49.5±3.3	49.3±2.7	49.7±3.2
	AEW	49.8±2.5	49.4±2.9	49.1±3.5	49.8±3.0	48.8±2.5
	Ozone	49.8±2.7	50.0±2.9	49.7±3.4	50.1±2.9	49.6±3.4
	Ozone-AEW	50.1±2.5	48.7±3.0	49.0±2.7	49.7±2.7	48.9±3.0
$a^*$	Control	-9.8±1.1	9.8±1.2	-9.7±1.1	-9.6±1.0	-9.3±1.2
	Chlorine	-9.6±1.1	-9.7±3.2	-9.4±1.1	-8.9±3.3	-9.1±1.1
	AEW	-9.5±1.1	-9.2±0.9	-9.3±1.1	-7.6±5.4	9.1±1.3
	Ozone	-9.7±0.8	-9.4±2.9	-9.5±1.1	-9.5±1.2	-9.4±1.1
	Ozone-AEW	-9.2±0.9	-9.0±1.1	-8.8±1.0	-9.2±1.1	-8.8±1.1
$b^*$	Control	12.8±1.6	12.3±1.9	12.8±1.9	12.6±1.7	12.8±1.9
	Chlorine	12±1.6	12.3±1.7	12.4±1.8	11.8±2.3	12.3±1.6
	AEW	12.4±1.7	11.9±1.5	12.2±1.7	7.7±5.2	11.6±1.9
	Ozone	12.6±1.3	12.1±1.4	12.4±1.6	12.5±1.8	12.6±1.6
	Ozone-AEW	12.1±1.5	11.7±1.6	11.6±1.5	12.3±1.8	12.2±1.7
Hue	Control	127.5±1.9	126.5±1.7	127.3±3.4	127.4±1.4	126.3±2.2
	Chlorine	131.3±1.9	128.4±2.2	127.3±2.3	130.6±1.4	126.6±2.1
	AEW	128.5±1.6	128.0±1.8	127.6±2.0	127.3±1.9	128.2±2.5
	Ozone	127.7±1.6	127.8±1.9	127.7±2.1	127.2±1.9	126.5±2.1
	Ozone-AEW	127.3±2.0	127.8±1.9	127.4±2.0	126.8±2.0	126.2±2.0

slowed down the degradation of chlorophyll, the major pigment of cilantro leaves. Loaiza and Cantwell (1997) also recorded similar color stability for bunched cilantro stored at 0 °C.

There was a slight decrease in firmness on treated samples compared to the un-treated control on day 0 (Fig. 1). However, there were no significant differences in firmness among chlorine, ozone, AEW and the se-

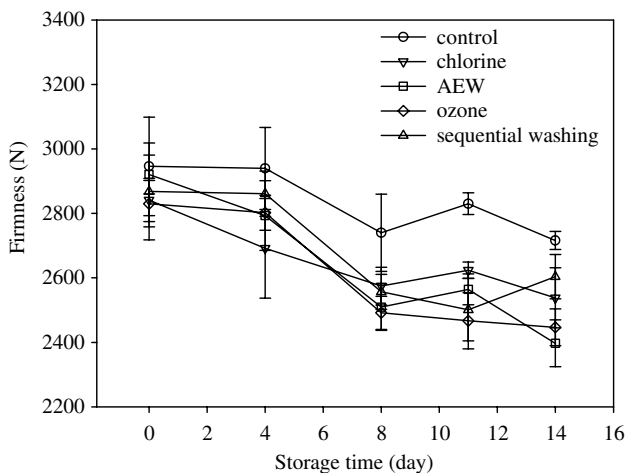


Fig. 1. Effect of produce wash treatments on firmness of fresh-cut cilantro during storage. Fresh-cut cilantro leaves were washed with for 5 min with tap water (control), chlorinated water, aqueous ozone, and AEW, or with sequential wash (aqueous ozone wash for 5 min followed by 5 min AEW wash), respectively and then stored at 0 °C. Data represent means of three replications ± SE.

quential treatments at day 0. Firmness decreased gradually during storage as expected, but the difference in firmness among treatments was insignificant over storage time. The loss in firmness in the treated samples may be attributed to the tissue injury caused by the treatments. Hong and Gross (1998) postulated that oxidizing agents could cause oxidation of feruloylated cross-linkages or phenolic cross-linkages among cell wall pectin, structural proteins or other polymers, and thereby change the firmness of the product.

### 3.2. Sensory evaluation

There was no noticeable off-odor development in packaged cilantro during storage in all treatments. Since off-odor is often associated with the onset of anaerobic respiration under a low O<sub>2</sub> and high CO<sub>2</sub> condition, this may indicate that no anaerobic respiration occurred, probably due to the high oxygen transmission rate of the film used in this study. Luo et al. (2004) tested packaging films with different OTR and demonstrated that film with OTR of 6200 mL/(dm<sup>2</sup>) was able to develop a beneficial package atmosphere that will prevent rapid depletion of O<sub>2</sub> and accumulation of CO<sub>2</sub> so as to maintain acceptable quality of fresh-cut cilantro. There was a gradual loss of typical cilantro aroma during the first 8 days in all treatments (Fig. 2(a)), yet the treatment difference remained insignificant. During the period of day 8 to day 14, sequential wash and AEW treatment had the greatest loss of aroma, which

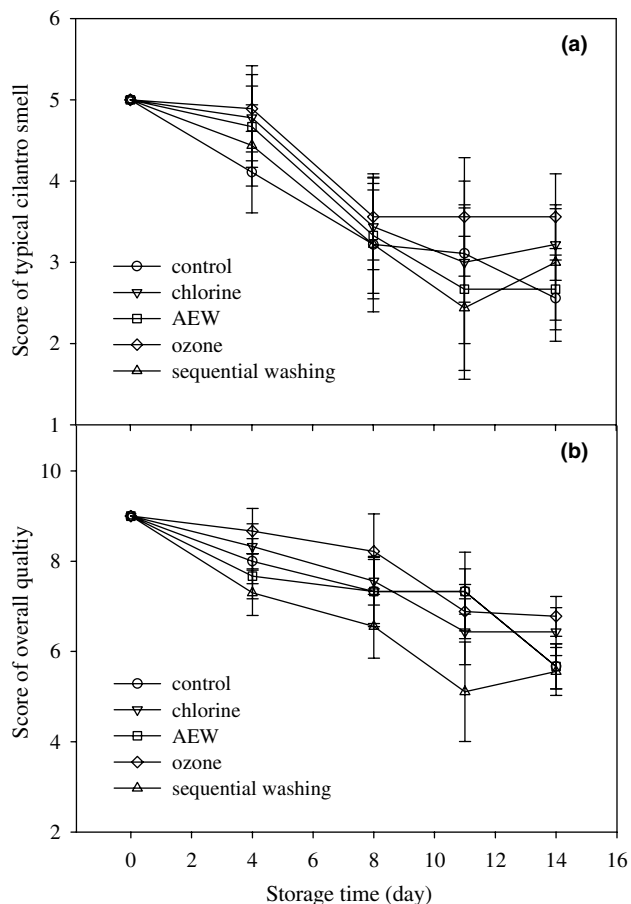


Fig. 2. Effects of produce wash treatments on typical cilantro smell and overall quality during storage. Cilantro smell was evaluated using a 5.0 scale, where 1 = none, 2 = slight, 3 = moderate, 4 = strong, 5 = extremely strong. Overall quality was evaluated using a 9-score scale where 0 = dislike extremely, 2 = dislike very much, 3 = dislike moderately, 4 = dislike slightly, 5 = neither like nor dislike, 6 = like slightly, 7 = like moderately, 8 = like very much, and 9 = like extremely.

might be correlated to their high tissue electrolyte leakage. However, the cilantro aroma was maintained with a higher score by the ozone treatment at day 14 (Fig. 3(a)). The overall quality changes during storage and at day 14 followed a similar pattern to the typical cilantro aroma changes, as shown in Figs. 2(b) and 3(b). The ozone treatment exhibited a better overall quality retention compared to other treatments during storage. The ozone-treated sample scored 7.1 at day 14 on the 9-point hedonic scale, representing a “like strongly” to “like moderately” rating, which was significantly different from the others. The ozone-washed cilantro leaves appeared to be near the fresh or initial conditions of the cilantro, with a green and fresh appearance, no yellowing or dehydration, and no trace of off-odor. The sequential wash sample exhibited a high decline in overall quality during storage and was scored at 5.7–5.6 at day 14, representing “neither like or dislike” to “like slightly”. The cilantro still looked fresh but had a few

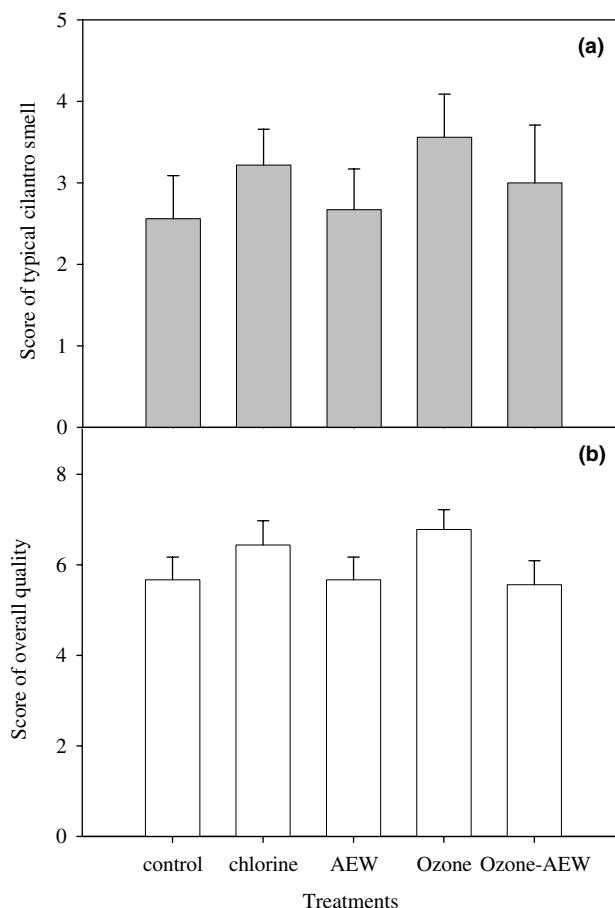


Fig. 3. Effects of produce wash treatments on typical cilantro smell and overall quality at last day (day 14) of the storage.

minor wilted leaves, which may have been due to relatively high electrolyte leakage, as well as to greater tissue damage and loss of moisture.

### 3.3. Electrolyte leakage

Fig. 4 shows the changes in electrolyte leakage of cilantro as a function of storage time. At day 0, the sequential wash and the AEW treatment recorded the highest (42.16  $\mu\text{s}/\text{cm}$ ) and the second highest (28.33  $\mu\text{s}/\text{cm}$ ) electrolyte leakage, respectively, while the electrolyte leakage of samples treated with chlorine and ozone (16.48 and 14.13  $\mu\text{s}/\text{cm}$ , respectively) was comparable to 15.78  $\mu\text{s}/\text{cm}$  of the control. The electrolyte leakage readings exhibited a decrease at day 4, reaching a minimum for all the treatments except the control. AEW and sequential wash treated samples experienced a sharp decrease in electrolyte leakage so that there was no significant difference between the two treatments ( $P < 0.05$ ) at day 4. After day 4, the electrolyte leakage of all samples started to increase gradually, although for the control and the chlorine treated samples the increase did not start until day 8. It can be noted that at

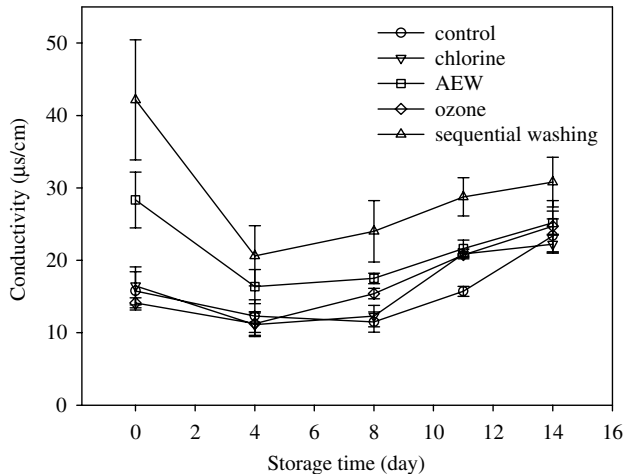


Fig. 4. Effect of produce wash treatments on electrolyte leakage of fresh-cut cilantro during storage at 0 °C.

day 14, the electrolyte leakage values for AEW (25.2 µs/cm) and sequential wash (35.8 µs/cm) were still lower than the day 0 values, while those of the other treatments were higher than the day 0 values.

Cutting caused the release of tissue fluid by rupture of cell membranes, which resulted in fresh-cut cilantro leaves having a higher electrolyte leakage than intact cilantro leaves (Luo et al., 2004). Our results showed that washing of fresh-cut samples with AEW and sequential wash caused additional electrolyte leakage. Especially in the sequential wash (aqueous ozone followed by AEW) there was a significant increase in the electrolyte leakage of fresh-cut cilantro ( $P < 0.05$ ). At day 0, the value (42.16 µs/cm) of electrolyte leakage caused by the sequential wash almost equaled the sum of the leakage caused by AEW and ozone (28.33 and 14.13 µs/cm, respectively). This indicates that there may be an additive effect between the tissue damages induced by the two strong oxidizing agents, ozone and AEW.

It is known that electrolyte leakage is related to cell membrane integrity (Marangoni, Palma, & Stanley, 1996), while phospholipids and their unsaturated fatty acids are important components of membranes. Oxidation of unsaturated fatty acids in cell membranes has been reported to be one of factors which caused ion leakage in apples, potatoes, papayas, and tomatoes by increasing membrane viscosity and decreasing the degree of fatty acid unsaturation (Chan, 1991; Cote, Thompson, & Willemot, 1993; Knowles & Knowles, 1989; Lurie, Sonogo, & Ben-Arie, 1987). In studies on surface sterilization of tomatoes, Hong and Gross (1998) also noticed that sodium hypochlorite treatment significantly increased electrolyte leakage. AEW and ozone, as oxidizing agents stronger than sodium hypochlorite, must have promoted unsaturated fatty acid oxidation and decreased membrane fluidity, resulting

in increased electrolyte leakage. AEW caused more electrolyte leakage than other agents, probably due to its low pH, which impaired microsomal membrane  $K^+$ -stimulated  $H^+$ -ATPase activity that has been correlated to leakage of ions (Palma, Marangoni, & Stanley, 1995). The decrease in tissue electrolyte leakage during the first 4 days may suggest a membrane damage recovery process during the early stage of cold storage. This repair process has been reported in the studies on the effects of controlled atmospheric packaging on postharvest biology and quality of fresh-cut cilantro leaves (Luo et al., 2004). In the latter stage during storage, electrolyte leakage rose again, probably due to irreversible membrane damages and accumulation of  $CO_2$  from respiration.

### 3.4. Microbiological analysis

The initial total aerobic plate count (TPC) on the unwashed cilantro leaves was 6.7-log CFU/g. There was a significant decrease in TPC between washed samples and the control ( $P < 0.05$ ) at day 0 (Fig. 5). AEW and sequential wash treatments at day 0 reduced TPC on cilantro by 0.66-log CFU/g and 0.62-log CFU/g, respectively. AEW and sequential wash successfully suppressed bacterial growth in the first 4 days of storage. During the period of day 5 to day 11, TPC rebounded by 1–1.5 logs CFU/g in all treatments. Nevertheless, the AEW and sequential wash maintained a low level of microbial count compared to other treatments. The initial total enterobacteriaceae was 6.0 CFU/g. The sequential wash and AEW effectively curtailed total enterobacteriaceae growth during the first four days (Fig. 6). After four days, total enterobacteriaceae counts for all the treatments increased. At the end of the storage test, AEW

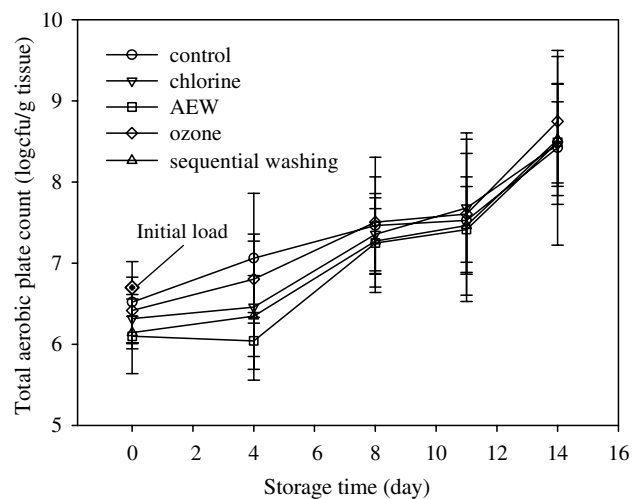


Fig. 5. Effect of produce wash treatments on total aerobic plate count (TPC) of fresh-cut cilantro leaves during storage at 0 °C.

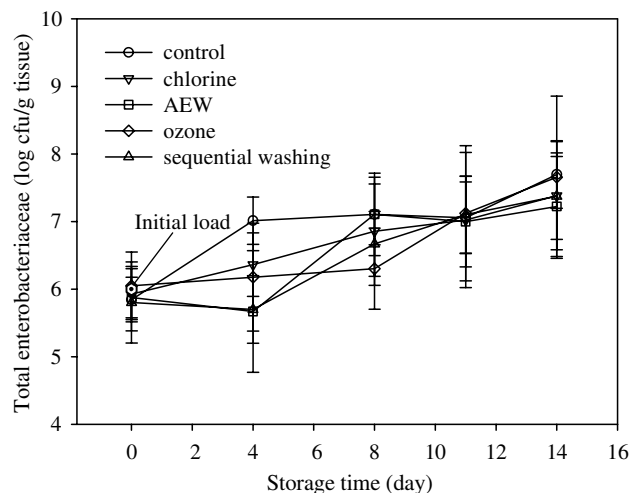


Fig. 6. Effect of produce wash treatments on coliform count of fresh-cut cilantro leaves during storage at 0 °C.

and sequential wash treated samples had a slightly low total enterobacteriaceae counts compared to the control.

Cilantro, like spinach, has a relatively high initial microbial count because it is a low-growing crop (Babic & Watada, 1996). Our results showed that AEW reduced TPC more effectively than aqueous ozone ( $P < 0.05$ ), which agreed with the results of lettuce decontamination using AEW conducted by Koseki and Itoh (2001). However, sequential wash failed to yield a higher TPC reduction than the AEW treatment. We had hypothesized that the sequential wash (ozone followed by AEW) would have a higher microbial inactivation rate because of the combined action of the two bactericidal agents. The unexpected outcome may be caused by factors such as the internalization of microbes on cilantro surfaces or the development of resistance following exposure to the ozone treatment. In the sequential wash study of Singh et al. (2003), treatment using thyme oil followed by ozonated water and aqueous  $\text{ClO}_2$  had a greater lethality than other treatments in which only one sanitizing agent was used on *E. coli* O157:H7 inoculated on alfalfa seeds. The relatively short residence time of the inoculated bacteria on cilantro surfaces may contribute to the higher microbial reduction in their study. In contrast, cilantro acquired from a farm had a long contact time with or close to soil so that microbial internalization or even biofilm formation may have taken place. The study of Fan et al. (2003) with cilantro reported an over 2-log reduction in TPC and a bacterial growth inhibition during a 14-day storage when the samples were irradiated at 2–3 kGy. The  $\gamma$ -irradiation can penetrate the cilantro tissue and kill the internalized microorganisms, and thereby resulted in a higher killing rate. Measures that will promote penetration of sanitizer into produce tissue may help to increase the inactivation rate.

#### 4. Conclusions

Sequential wash (aqueous ozone followed by AEW) is effective in reducing initial total aerobic plate count and maintaining a relatively low microbial count on fresh-cut cilantro during storage compared to aqueous ozone wash and chlorine wash. However, the combination of ozone and AEW led to more tissue injury, which influences the overall quality of cilantro. AEW wash can also effectively reduce total aerobic plate count at day 0 and during storage at the expense of produce quality. Ozone treatment effectively maintained the typical aroma and overall quality of fresh-cut cilantro leaves.

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