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The Effectiveness of Ozone and Acidulant Treatments in Extending the Refrigerated Shelf Life of Fresh-Cut Potatoes

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Abstract: The objective of the study was to determine the effectiveness of acidulant dip treatments (with or without aqueous ozone) to reduce enzymatic browning and to extend the shelf life of fresh-cut potato slices during refrigerated storage (4 °C) for 28 d. Potato slices subjected to aqueous ozone (2 ppm) had significantly ($P \leq 0.05$) higher *L*-values and lower *a*-values, but ozone did not appear to have any effect on aerobic plate counts (APCs) or polyphenol oxidase (PPO) activity. NatureSeal (NS) and sodium acid sulfate (SAS) were the most effective acidulant treatments in reducing browning (significantly [$P \leq 0.05$] higher *L*-values, lower *a*-values, and browning index values) regardless of ozone treatment. NS and SAS also had lower PPO activity compared to other treatments on days 0 and 28, and significantly ($P \leq 0.05$) lower APCs (≤2.00 log CFU/g) over refrigerated storage. Therefore, the SAS treatment was comparable to NS, a commercially available product, and showed promise as an effective antibrowning dip to reduce browning and spoilage in fresh-cut potato products.

Keywords: acidulants, browning, fresh cut, ozone, potatoes

Practical Application: A 1% SAS dip treatment which included 1% citric and 1% ascorbic acid was found to be an effective antibrowning dip for fresh-cut potatoes along with NatureSeal®'s PS-10, compared to other treatments. They were both effective in maintaining low microbial counts over refrigerated storage. Additionally, aqueous ozone washes (2 ppm) showed significant benefits to reduce browning; however, ozone did not affect microbial counts or PPO enzyme activity. Therefore, the SAS treatment could have potential use in the fruit and vegetable industry to reduce browning and spoilage in fresh-cut potato products.

Introduction

The consumption of fresh-cut produce is growing rapidly due to consumer demand for health and convenience. However, fresh-cut potatoes exhibit undesirable and immediate enzymatic browning (Gunes and Lee 1997) which reduces quality and consumer acceptability. Minimally processed potatoes are also susceptible to microbial growth (Beltrán and others 2005). The perishable nature of fresh-cut potato products remains a challenge for potato processors.

Sulfites are one of the most effective chemical preservatives to inhibit browning; however, the FDA has prohibited the use of sulfites in fruits and vegetables labeled as "fresh" or intended to be served in the raw form (FDA 2011) due to the risk of severe allergic reactions in individuals highly sensitive to sulfites (Timbo and others 2004).

Current methods and techniques to reduce browning or bacterial growth in fresh-cut products include modified-atmosphere packaging; chemical-based treatments such as organic acids (acidulants), chlorinated solutions, or calcium-based treatments; and blanching, all which have limited effectiveness (Rico and others 2007).

Ozone (aqueous and gaseous) application is another method that has been researched to preserve fresh-cut products because it is a potent oxidant and strong antimicrobial agent. Ozone was granted GRAS (generally recognized as safe) status by the FDA in 1982, and was also approved as a sanitizer for foods under good manufacturing practices in 1997 (Guzel-Seydim and others 2004). Restaino and others (1995) showed that ozone was an extremely effective antimicrobial agent against bacterial pathogens (gram negative and positive), spoilage microorganisms, and yeasts when deionized water was inoculated in a recirculating ozone system with an average ozone output of 0.188 mg/mL (Restaino and others 1995). Other advantages of ozone include its rapid decomposition to oxygen, leaving no toxic residue (Khadre and others 2001), and it is approved by the National Organic Program for processed foods that are intended to be labeled "organic" or "made with organic" (USDA 2002). Beltrán and others (2005) found aqueous ozone (20 mg/L min) in conjunction with peroxyacetic acid (Tsunami™, Henckel Ecolab Ibérica S.A., San Joan Despí, Barcelona, Spain) to inhibit browning of raw potato strips under vacuum packed conditions for 14 d at 4 °C and also maintained relatively low microbial counts. However, ozone by itself was not effective to inhibit microbial growth over refrigerated storage.

Other recently investigated antibrowning agents are sodium acid sulfate (SAS) and catechin, which can be potentially labeled as

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natural additives. SAS was shown to be successful in reducing microbial growth and enzymatic browning in apples (Fan and others 2009) and in fresh-cut French fries (Calder and others 2011). Catechin, a natural tea polyphenol, has recently been reported to reduce melanosis (browning) shrimp by inhibiting polyphenol oxidase (PPO) activity, while also suppressing microbial growth (Nirmal and Benjakul 2009).

Consumers are more conscientious about food preservatives and are requesting foods that are more natural, microbially safe, fresh, and of higher quality (Gould 2000); therefore, more research is warranted to find additional natural processing aids that are effective browning inhibitors for produce. However, SAS and catechin have not been evaluated along with ozone to reduce the browning of fresh-cut potato products at this time.

The objective of the study was to build upon previous work (Calder and others 2011) to determine the effectiveness of acidulant dip treatments (with or without aqueous ozone) to reduce enzymatic browning, maintain low microbial counts, and extend the shelf life of refrigerated fresh-cut potatoes.

Materials and Methods

Three 50 lb. (23 kg) bags of Maine Russet Burbank potatoes were obtained from the Aroostook Farm (Maine Agricultural and Forest Experiment Station, Presque Isle, Maine, U.S.A.) and transported to the Department of Food Science and Human Nutrition, University of Maine. Potatoes were stored at 3 to 4 °C until the day of processing. The treatment solutions and treatment codes are listed in Table 1. These treatments were selected based on preliminary research conducted at the University of Maine which indicated the most promising browning inhibition of Russet Burbank potatoes.

The ascorbic and citric acids were produced from Spectrum Chemical MFG Corp. (Gardena, Calif., U.S.A.). The catechin was (+)-catechin hydrate ≥98% (Sigma-Aldrich, St. Louis, Mo., U.S.A.). The SAS and NatureSeal PS-10 commercial dip were provided from NatureSeal® (ReduSal, Mantrose-Haeuser Co., Inc., Westport, Conn., U.S.A.). The NatureSeal® PS-10 was prepared at 6.5% as per the manufacturer's recommendations. The solutions were prepared in 3 L batches. Six potatoes per batch were randomly selected, washed, peeled by hand, and sliced into oval, au gratin-style slices using a Robot Coupe (R2 Model, Ridgeland, Miss., U.S.A.). The approximate weight per raw, whole potato was 145 g. Potato slices were then rinsed for 30 s with tap water. Each batch of potato slices was placed into approximately 500 mL of dip treatment to ensure that all slices were covered in solution. The container with samples was then slowly agitated on an orbital shaker (Thermolyne Roto Mix—Type 50800, Barnstead/Thermolyne, Dubuque, Iowa, U.S.A.) for 5 min.

Half of the treatments were also subjected to a 2 ppm aqueous ozone pretreatment dip for 1 min prior to the dip treatment application. The ozone was produced by an ozone generator (Pacifica Ozone Technology, Model # ICS104, Benicia, Calif. U.S.A.) and bubbled into 10 °C tap water. The aqueous ozone was continuously piped into an 81.3 L polycarbonate dip tank (StorPlus™, Carlisle FoodService Products, Oklahoma City, Okla., U.S.A.) at an average flow rate of 40.7 L/min. The dip tank for aqueous ozone treatments was rinsed after each dip treatment. Aqueous ozone levels were monitored hourly with a Hach test kit (Hach Company, 0.0 to 2.3 mg/L, Model OZ-2 Color Disc, Loveland, Colo., U.S.A.). Treatment order was randomly assigned. After soaking, samples were drained in a plastic colander for 1 to 2 min and placed into 12″ × 14″, 3 mil poly nylon bags (Ultravac Solutions, LLC, Kansas City, Mo., U.S.A.), heat sealed, and stored at 3 to 4 °C for 28 d. The 10 treatments were processed in triplicate, and the 30 batches were subsampled in duplicate for analyses.

Table 1–Treatments and treatment codes.

Code	Treatment
W	Distilled water control
W-O	Distilled water control with ozone treatment
AACA	1% ascorbic acid & 1% citric acid
AACA-O	1% ascorbic acid & 1% citric acid with ozone treatment
CAT	0.25% catechin & 1% ascorbic acid & 1% citric acid
CAT-O	0.25% catechin & 1% ascorbic acid & 1% citric acid with ozone treatment
SAS	1% SAS & 1% ascorbic acid & 1% citric acid
SAS-O	1% SAS & 1% ascorbic acid & 1% citric acid with ozone treatment
NS	NatureSeal® PS-10 commercial dip (6.5%)
NS-O	NatureSeal® PS-10 commercial dip (6.5%) with ozone treatment

pH

The pH level of the solutions was measured prior to treating potato samples. The pH analysis was conducted with a Beckman flat surface pH electrode and model 32 Beckman pH meter (Beckman Coulter, Inc., Brea, Calif., U.S.A.).

Colorimetric analysis

Five potato slices per treatment were analyzed in triplicate using a Hunter LabScan XE (Hunter Associates Laboratory, Inc., Reston, Va., U.S.A.) with a port size of 30.5 mm, area view of 25.4 mm, the color display set to D65 illuminant, and observer of 10*. Each potato slice was measured 3 times, and *L*-, *a*-, *b*-values were based on an average of 3 measurements. The potato samples were rotated a 3rd of a turn between measurements. Colorimetric analysis was performed on days 0, 7, 14, 21, and 28 of refrigerated storage.

The browning index (BI) was calculated as described by Palou and others (1999). The BI calculation incorporates the *L*-, *a*-, and *b*-values of each sample to provide an overall indicator of browning associated with both nonenzymatic and enzymatic browning. The BI was calculated by using the following equation:

$$BI = [100(x^* - 0.31)]/0.172$$

$$x^* = (a + 1.75L)/(5.645L + a - 3.012b).$$

PPO analysis

PPO activity was assessed utilizing a spectrophotometric method as described by Rico and others (2006). Potato slices were homogenized in a food processor (Black and Decker® Handy Chopper Plus, Towson, Md., U.S.A.). Ten grams of potato homogenate was mixed with 20 mL of phosphate buffer (0.5 mol L^{-1}, adjusted to pH 6.5)/polyvinylpyrrolidone (50 g/L) solution. The potato and buffer were homogenized using a Polytron® (Model PT 10-35, Kinematica AG, Lucerne, Switzerland) on speed setting 4 for 1 min. The homogenates were centrifuged at 12720 × *g* for 30 min at 4 °C. The crude extracts were further filtered through cheesecloth and transferred to amber bottles and then used immediately. A 0.02 mol L^{-1} catechol solution was prepared in 0.5 mol L^{-1} buffer phosphate solution and adjusted to

pH 6.5. Catechol substrate solution (2.9 mL) was added to test tubes, along with 0.1 mL crude potato extract. Absorbance was monitored at 400 nm (DU 530, Beckman Coulter, Inc., Brea, Calif., U.S.A.) every 20 s for 1 min 40 s. The PPO activity was calculated as 0.1 units/min. PPO assays were conducted on days 0, 14, and 28 and each batch was analyzed in duplicate.

Microbiological analysis

Aerobic plate counts (APCs) were performed using the 3 M APC Petrifilm method (AOAC 2005). Potato slices were randomly selected and 50 g samples were weighed into Whirl-Pak® filter bags (Nasco, Fort Atkinson, Wis., U.S.A.) utilizing sterile techniques. Potato slices were diluted (1:10) with 0.1% Bactopeptone (Bacto™ Peptone, Becton, Dickinson and Co., Sparks, Md., U.S.A.) in filter bags and then immediately placed into a stomacher (BagMixer® Spiral Biotech, Advanced Instruments Inc., Norwood, Mass., U.S.A.) for 2 min. Petrifilms were incubated at 35 °C for 48 h. The detection limit was set at 100 CFU/plate and calculated as log CFU/g. APCs were performed in duplicate on days 0, 14, 21, and 28 of refrigerated storage.

Statistical analyses

Data were analyzed via one-way and multiway analysis of variance (ANOVA). One-way ANOVA was performed using Analyse-it® version 2.22 (Analyse-it Software Ltd., Leeds, U.K.). Multiway ANOVA was performed to determine any significant effects of time, treatment (W, SAS, AACA, CAT, NS), and ozone using Systat 12 (Systat Software, Inc., Chicago, Ill., U.S.A.). The Bonferroni test was utilized to determine significant differences among means. Significance was set at $P \leq 0.05$ for all statistical analyses.

Results and Discussion

pH of dip solutions

The pH levels of the dip solutions ranged from 1.72 to 5.28, and the individual pH values of the dip solutions were W = 5.28, AACA = 2.50, CAT = 2.48, NS = 2.21, and SAS = 1.72. Therefore, the SAS dip treatment was the most acidic over the other treatments. SAS is a stronger acidulant with a pKa of 2.0 compared to 3.1 for citric and 4.1 for ascorbic acid.

Color

***L*-values.** Potato slices began to brown immediately after slicing, and the distilled water control (W and W-O) treatments appeared to have the darkest color development among potato treatments on day 0. Our colorimetric results reflect our visual observations. *L*-values are a color scale measuring light to dark colors in food samples with the higher *L*-value ($L = 100$) signifying the lightest end of the range compared to $L = 0$, which indicates more black color. On day 0, treatments had quite similar *L*-values ranging from 60.85 to 64.07 (Table 2); however, W and W-O (distilled water) treatments had significantly ($P \leq 0.05$) lower *L*-values (darker in color) than all other treatments and this trend continued over storage time. By day 7, the NS and SAS treatments (with and without ozone) had the highest *L*-values among treatments, which remained fairly consistent throughout refrigerated storage.

Based on multiway ANOVA, *L*-values were significantly ($P \leq 0.05$) effected by ozone, time, and treatment. Potato slices treated with ozone prior to dip treatments had significantly higher *L*-values (exhibited less browning) overall than potato samples not receiving an ozone treatment. As expected, samples displayed increased browning over storage time. The *L*-values were significantly ($P \leq 0.05$) higher on day 0 than all other testing periods. With respect to individual treatments, W (with and without ozone)-treated potatoes had considerably lower *L*-values than those in all other treatments throughout the study. The NS and SAS (with and without ozone) treatments had higher *L*-values compared to AACA and CAT treatments (with and without ozone) from days 7 to 28, suggesting that NS and SAS were effective in minimizing browning.

***a*-values.** The *a*-value is a measure of green ($-a$) to red ($+a$) color in food samples. We expected higher *a*-values for the W and W-O (distilled water control) treatments which showed immediate signs of enzymatic browning (reddish-brown color development) on day 0. The CAT treatments produced a light orange tint on potato samples on day 0, but the *a*-values did not reflect this observation (Table 3).

NS- and SAS-treated potatoes had significantly ($P \leq 0.0001$) lower *a*-values than those in all other treatments starting on day 7 and lasting the duration of the study. The *a*-values for W- and W-O-treated slices increased throughout refrigerated storage and were considerably higher than those in all other treatments on day 0 and again on day 28. AACA- and CAT-O-treated potatoes had the highest *a*-values among treatments on day 7.

Multiway ANOVA *a*-value results supported observations, as significant ($P \leq 0.01$) treatment, time, and ozone effects were detected. The potato samples on day 0 had significantly

Table 2–Mean *L*-values of fresh-cut, Russet Burbank slices over refrigerated storage time.

TRT	Day 0	Day 7	Day 14	Day 21	Day 28
W	60.85 ± 1.46c	40.73 ± 5.83d	37.64 ± 3.72e	38.72 ± 6.05d	36.29 ± 7.49c
W-O	60.86 ± 1.83c	44.66 ± 5.34d	45.15 ± 4.84d	43.20 ± 6.53d	40.59 ± 6.94c
CAT	64.07 ± 2.36a	57.73 ± 5.89abc	57.24 ± 6.25c	59.35 ± 2.86bc	57.35 ± 4.71ab
CAT-O	61.41 ± 2.58ab	53.63 ± 4.63c	57.48 ± 6.18c	59.36 ± 2.69bc	58.50 ± 2.22ab
AACA	63.69 ± 1.31a	56.35 ± 4.46bc	53.51 ± 5.10c	56.22 ± 5.32c	54.17 ± 7.94b
AACA-O	62.06 ± 2.40ab	58.51 ± 6.08abc	58.37 ± 3.00bc	56.77 ± 4.42c	54.00 ± 7.61b
NS	63.56 ± 3.16a	63.06 ± 3.43a	63.81 ± 2.76a	63.69 ± 2.23ab	62.59 ± 2.28a
NS-O	62.57 ± 2.71ab	63.31 ± 2.78a	62.78 ± 3.93ab	61.99 ± 2.61ab	64.33 ± 3.96a
SAS	62.55 ± 2.00ab	60.81 ± 5.45ab	63.25 ± 2.81ab	63.48 ± 2.91ab	59.80 ± 4.72ab
SAS-O	62.74 ± 1.36ab	63.21 ± 3.10a	64.30 ± 2.91a	64.70 ± 2.48a	60.49 ± 8.61ab

W = distilled water control, CAT = 0.25% catechin, 1% citric and ascorbic acid, AACA = 1% citric and ascorbic acid, NS = NatureSeal, SAS = 1% sodium acid sulfate, 1% citric and ascorbic acid. These treatments were dipped for 5 min. and not treated with ozone.
W-O = distilled water control with ozone, CAT-O = 0.25% catechin, 1% citric and ascorbic acid, AACA-O = 1% citric and ascorbic acid with ozone, NS-O = NatureSeal with ozone, SAS-O = 1% sodium acid sulfate, 1% citric and ascorbic acid with ozone. These treatments were subjected to an aqueous ozone pretreatment dip (2 ppm for 1 min) and then dipped in treatment solution for 5 min.
Values are means ± standard deviation ($n = 15$).
Significance ($P \leq 0.05$) is noted by different letters within columns for each time period (day).
Potato slices were stored at 4 °C.

($P \leq 0.000$) lower *a*-values (less red color) than on all other storage days, and day 21 *a*-values were lower than day 28. The treatments without ozone had significantly higher *a*-values than with ozone treatment, indicating that ozone appeared to help reduce red color development on potato slices compared to the treatments without ozone. NS and SAS treatments had the lowest *a*-values overall among treatments, while W (with and without ozone) treatments had considerably higher *a*-values than AACA-O, SAS, and NS (with and without ozone).

***b*-values.** The *b*-value is a measure of blue (–*b*) to yellow (+*b*) colors. Enzymatic browning, which was seen initially as reddish color development on W and W-O potato samples, developed into darker, blue-black colors over storage time; therefore, *b*-values were expected to increase over refrigerated storage.

Although no significant *b*-value differences were noted on day 0 among treatments, W and W-O had significantly ($p \leq 0.05$) lower *b*-values on day 7 and this trend was seen throughout storage time (Table 4). The CAT-treated potatoes had the highest *b*-values among all treatments on days 7, 14, and 28. On day 21, AACA-O had significantly ($P \leq 0.05$) higher *b*-values than NS-O, SAS-O, W, and W-O. Therefore, the *b*-value results indicate that the W- and W-O-treated samples had more substantial blue color development than the other treatments from days 7 to 28, which coincided with visual observations.

The multiway ANOVA results showed significant ($P \leq 0.01$) effects of ozone, treatment, and time on *b*-values. Overall, the nonozone-treated potatoes had notably higher *b*-values than the ozone-treated samples. The *b*-values on day 0 were significantly ($P \leq 0.05$) higher (more yellow) than those on all other testing days. As far as treatment and ozone effects combined, the AACA- and CAT-treated potatoes had higher *b*-values than the other treatments (with and without ozone).

Overall, *L*-values decreased and *a*-values increased over refrigerated storage. However, SAS and NS appeared to be the most effective treatment in maintaining higher *L*-values (lighter color) and lower *a*-values (less red color) than the other treatments. Based on colorimetric results, *L*-, *a*-, and *b*-values were all significantly affected by ozone regardless of dip treatment. Beltrán and others (2005) also found ozone to be effective in reducing browning of fresh-cut potato strips up to 14 d of refrigerated storage under vacuum-packed conditions.

Browning index. The BI is a useful indicator of overall browning in potato samples because it takes into account *L*-, *a*-, and *b*-values. The BI was calculated to determine any significant differences of browning among treatments. On day 0, the W-O treatment had a significantly ($P \leq 0.05$) higher BI values than SAS-O, CAT-O, and AACA-O treatments (Figure 1A). On day 14, W-O and CAT-O BI values increased considerably compared to NS-O and SAS-O, which showed that both SAS and NS were effective to reduce overall browning. Even at day 28, the NS-O- and SAS-O-treated potatoes maintained low BI values (≤20), while W-O BI values increased over storage time from 18.66 on day 0 to 34.43 on day 28, and were notably higher than CAT-O-, NS-O-, and SAS-O-treated potato slices.

Table 3–Mean *a*-values of fresh-cut, Russet Burbank slices over refrigerated storage time.

TRT	Day 0	Day 7	Day 14	Day 21	Day 28
W	−0.53 ± 0.63b	2.28 ± 0.67abcd	2.66 ± 0.43b	3.07 ± 0.73abc	4.43 ± 1.76a
W-O	0.14 ± 0.52a	2.00 ± 0.56bcd	2.18 ± 0.44bc	2.56 ± 0.85abc	3.85 ± 1.88ab
CAT	−1.17 ± 0.12c	2.98 ± 2.61abc	3.63 ± 2.17ab	1.07 ± 1.00cd	3.79 ± 2.24ab
CAT-O	−1.08 ± 0.18c	3.85 ± 2.34ab	2.62 ± 2.14bc	1.25 ± 1.63bcd	1.14 ± 1.78cde
AACA	−1.17 ± 0.17c	4.35 ± 3.22a	4.61 ± 2.79a	3.17 ± 3.94ab	3.14 ± 2.61abc
AACA-O	−1.06 ± 0.23c	1.23 ± 2.68cde	0.90 ± 1.36cd	3.51 ± 2.91a	1.97 ± 1.64bcd
NS	−1.39 ± 0.10c	−0.92 ± 0.66ef	−0.95 ± 0.41e	−0.77 ± 0.39de	−0.61 ± 0.74e
NS-O	−1.17 ± 0.18c	−1.31 ± 0.21f	−1.28 ± 0.17e	−1.27 ± 0.28e	−0.57 ± 1.52e
SAS	−1.26 ± 0.19c	0.38 ± 2.09def	−0.56 ± 0.96de	−0.68 ± 0.62de	0.72 ± 1.62de
SAS-O	−1.27 ± 0.14c	−0.37 ± 0.99ef	−0.95 ± 0.35e	−1.04 ± 0.52e	0.53 ± 1.91de

W = distilled water control, CAT = 0.25% catechin, 1% citric and ascorbic acid, AACA = 1% citric and ascorbic acid, NS = NatureSeal, SAS = 1% sodium acid sulfate, 1% citric and ascorbic acid. These treatments were dipped for 5 min and not treated with ozone.
W-O = distilled water control with ozone, CAT-O = 0.25% catechin, 1% citric and ascorbic acid, AACA-O = 1% citric and ascorbic acid with ozone, NS-O = NatureSeal with ozone, SAS-O = 1% sodium acid sulfate, 1% citric and ascorbic acid with ozone. These treatments were subjected to an aqueous ozone pretreatment dip (2 ppm for 1 min.) and then dipped in treatment solution for 5 min.
Values are means ± standard deviation ($n = 15$).
Significance ($P \leq 0.05$) is noted by different letters within columns for each time period (day).
Potato slices were stored at 4 °C.

Table 4–Mean *b*-values of fresh-cut, Russet Burbank slices over refrigerated storage time.

TRT	Day 0	Day 7	Day 14	Day 21	Day 28
W	10.00 ± 1.06a	8.28 ± 1.14e	7.90 ± 0.80e	8.93 ± 1.78d	9.07 ± 1.73d
W-O	10.61 ± 0.98a	8.53 ± 0.91de	9.25 ± 1.25de	9.21 ± 1.10d	9.71 ± 1.36cd
CAT	10.45 ± 1.69a	14.14 ± 2.21a	14.48 ± 3.27a	11.69 ± 1.52abc	14.25 ± 2.46a
CAT-O	9.72 ± 1.70a	13.21 ± 2.63ab	12.80 ± 2.29abc	12.18 ± 1.39ab	12.14 ± 1.89ab
AACa	10.68 ± 1.30a	13.12 ± 2.13ab	13.72 ± 3.00ab	12.02 ± 1.88ab	11.99 ± 1.29abc
AACA-O	9.73 ± 1.62a	12.15 ± 2.48abc	11.12 ± 1.78bcd	12.48 ± 1.22a	12.58 ± 1.48ab
NS	10.64 ± 1.97a	11.86 ± 2.39abc	11.32 ± 2.24abcd	10.86 ± 2.20abcd	10.81 ± 0.96bcd
NS-O	10.45 ± 1.99a	10.27 ± 1.97cde	9.63 ± 3.00de	9.87 ± 1.93cd	10.41 ± 1.92bcd
SAS	9.37 ± 1.24a	11.49 ± 2.91bc	10.18 ± 2.35cde	10.82 ± 2.04abcd	12.22 ± 2.98ab
SAS-O	9.66 ± 1.22a	10.91 ± 2.03bcd	10.99 ± 1.99bcd	10.33 ± 1.67bcd	10.48 ± 2.53bcd

W = distilled water control, CAT = 0.25% catechin, 1% citric and ascorbic acid, AACA = 1% citric and ascorbic acid, NS = NatureSeal, SAS = 1% sodium acid sulfate, 1% citric and ascorbic acid. These treatments were dipped for 5 min and not treated with ozone.
W-O = distilled water control with ozone, CAT-O = 0.25% catechin, 1% citric and ascorbic acid, AACA-O = 1% citric and ascorbic acid with ozone, NS-O = NatureSeal with ozone, SAS-O = 1% sodium acid sulfate, 1% citric and ascorbic acid with ozone. These treatments were subjected to an aqueous ozone pretreatment dip (2 ppm for 1 min) and then dipped in treatment solution for 5 min.
Values are means ± standard deviation ($n = 15$).
Significance ($P \leq 0.05$) is noted by different letters within columns for each time period (day).
Potato slices were stored at 4 °C.

For the nonozone treatments, no significant differences in BI values were noted on day 0 (Figure 1B). NS and SAS had significantly ($P \leq 0.05$) lower BI values than those in the other treatments on day 14, and NS BI values remained the lowest of all treatments by day 28. The W treatment BI values increased over storage time from 16.67 to 38.03. NS appeared to be the most effective treatment to maintain low BI values (<20) throughout storage time compared to the other treatments.

Multiway ANOVA results showed significant ($P \leq 0.05$) effects of ozone, treatment, and time on BI values. Treatments that received ozone had considerably lower BI values than treatments that did not receive an ozone treatment. Overall, the BI values significantly ($P \leq 0.05$) increased over time and NS and SAS had appreciably lower BI values than all other treatments.

BI results coincide well with *L*-value results and reinforce that NS and SAS were the most effective treatments to reduce browning over refrigerated storage, regardless of ozone treatment.

Polyphenol oxidase

Ozone had no significant effect on PPO activity according to multiway ANOVA; therefore, ozone and nonozone PPO data were compiled (Figure 2). However, significant ($P \leq 0.000$) effects of treatment and time were detected. For treatment effects, SAS-treated samples had considerably lower PPO activity. For the effects of time, overall PPO activity was lower on day 0, increased on day 14, and then slightly decreased on day 28.

NS-treated potato samples had significantly ($P \leq 0.05$) lower PPO activity than all other treatments on day 0 (Figure 2), but by day 14, SAS-treated slices had the lowest PPO levels than all the other treatments for days 14 and 28.

In this study, NS and SAS were the most effective treatments to reduce PPO activity possibly from being the most acidic dips which may have lowered the pH of the potato tissues to a less optimal level for PPO activity. Duangmal and Apenten (1998) determined potato PPO to be inactivated at pH levels below 4.0, with a maximum activity around pH 6.8. Whitaker and Lee (1995) mentioned that PPO can be inhibited at a pH level 2 units below the optimal pH level. NS had the highest dip concentration (6.5%); however, the SAS treatment was the most acidic with a pH of 1.72 (5 times more acidic than NS) and appeared to be more effective in suppressing PPO activity over storage time compared to other treatments. Previous research has shown that SAS and CA can penetrate potato tissues at 3% concentrations to significantly reduce the pH levels of inner (4.6) and outer (5.2) surfaces of fresh-cut potatoes (Calder and others 2011). SAS functions as an acidulant, similar to citric acid. However, citric acid does have a dual effect in reducing enzymatic browning, as it acts as both an acidulant and a metal chelator and will bind to the copper in PPO, as mentioned by Altunkaya and Gökmen (2008). The NS treatment may have chelated copper more effectively due to its higher concentration and lowered PPO activity on day 0 and once oxidized, possibly lost its effectiveness over time and may explain the increase in PPO activity on day 14.

Garcia and Barrett (2002) discussed that acidulants are often used in combination with other browning inhibitors because they are not as effective to control enzymatic browning by just controlling pH alone. Ascorbic acid works as an oxygen scavenger which

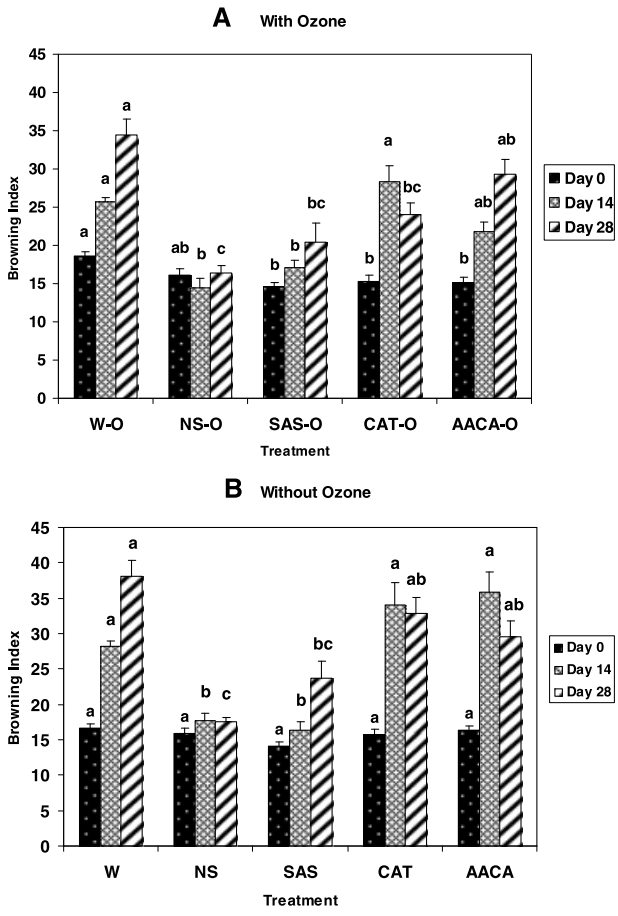

Figure 1–Browning index means of fresh-cut, Russet Burbank slices over refrigerated storage time. (A) Browning index means of treated potato slices with ozone. These treatments were subjected to an aqueous ozone pretreatment dip (2 ppm for 1 min) and then dipped in treatment solution for 5 min. Values are means ± standard error ($n = 15$). Significance ($P \leq 0.05$) is noted by different letters within time periods (day). (B) Browning index means of treated potato slices without ozone. These treatments were dipped for 5 min and not treated with ozone. Values are means ± standard error ($n = 15$). Significance ($P \leq 0.05$) is noted by different letters within time periods (day). Potato slices were stored at 4 °C.

removes the oxygen necessary for PPO reactions (Rico and others 2007) and is a complementary addition in antibrowning treatments to control PPO. Therefore, the SAS treatment may have had a slight advantage over other treatments to control PPO activity because of the combined effects of a strong acidulant (SAS), chelating (CA), and oxygen scavenging properties (AA) in one treatment.

Enzymatic browning studies are inconclusive at this time whether ozone is effective to reduce PPO activity. This study did not show ozone was effective to reduce PPO; however, Zhang and others (2005) determined that ozone was effective in reducing the PPO activity of fresh-cut celery. Rico and others (2006) also found that ozone was effective in reducing the PPO activity of fresh-cut lettuce. Therefore, more research is warranted to determine the mechanism of how ozone may affect PPO and slow its activity to be more effective in applications for the fresh-cut industry.

Although Nirmal and Benjakul (2009) reported that catechin was effective in inhibiting PPO activity in shrimp; according to PPO results, catechin (0.25%) appeared not to have an advantage in reducing enzymatic activity in fresh cut potato slices. AACA had no appreciable effects on PPO activity, as well.

Cantos and others (2002) found a poor correlation between browning and PPO activity in fresh-cut potatoes. In our findings, we had a similar experience with the PPO activity for NS-treated potatoes which increased on day 14, but this change was not reflected in a decrease in *L*-values which was unexpected.

However, some PPO and color results appeared to correspond well and show expected trends. The W-treated potato slices had significantly lower *L*-values and had the highest PPO activity on days 0 and 14. SAS-treated samples showed consistent *L*-values, as well as PPO activity, over time. On day 14, *L*-values decreased for most treatments (except for NS and SAS) and PPO activity increased which was expected. BI values also increased for most treatments (W, CAT, AACA) on day 14 and PPO activity also increased for these same treatments.

Aerobic plate counts

Ozone is well known to be an effective sanitizer against many microorganisms at low concentrations (Khadre and others 2001). In this study, ozone had no effect on APCs; therefore, the ozone and nonozone data were compiled (Figure 3). However, multiway ANOVA detected significant ($P \leq 0.000$) time and treatment effects. Overall, the control (W) had significantly ($P \leq 0.000$) higher log values than all other treatments on days 21 and 28.

After compiling treatment data, W- and AACA-treated potatoes had significantly ($P \leq 0.05$) higher APCs than the SAS-treated potato samples on day 0. APCs ranged from log values of 1.34

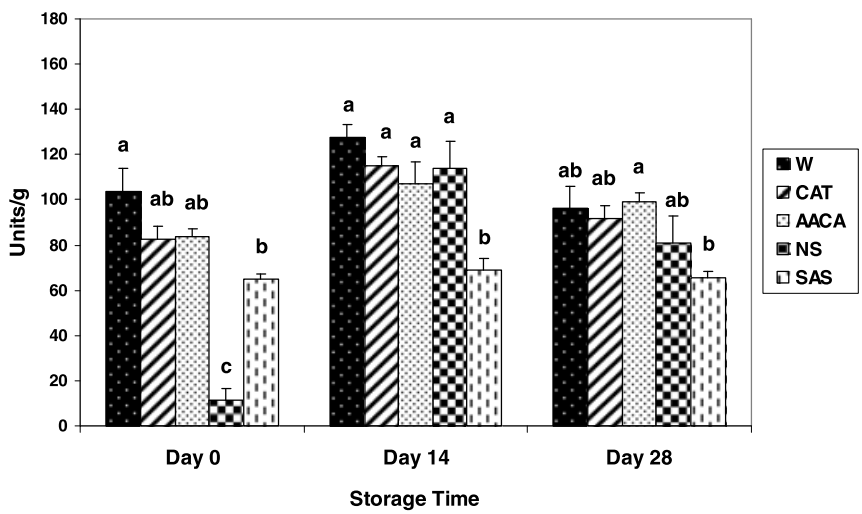

Figure 2–Mean polyphenol oxidase activity (units/g) of fresh-cut, Russet Burbank slices over refrigerated storage time (compiled ozone and nonozone data). Values are means ± standard error ($n = 6$). Significance ($P \leq 0.05$) is noted by different letters within time periods (day). Potato slices were stored at 4 °C.

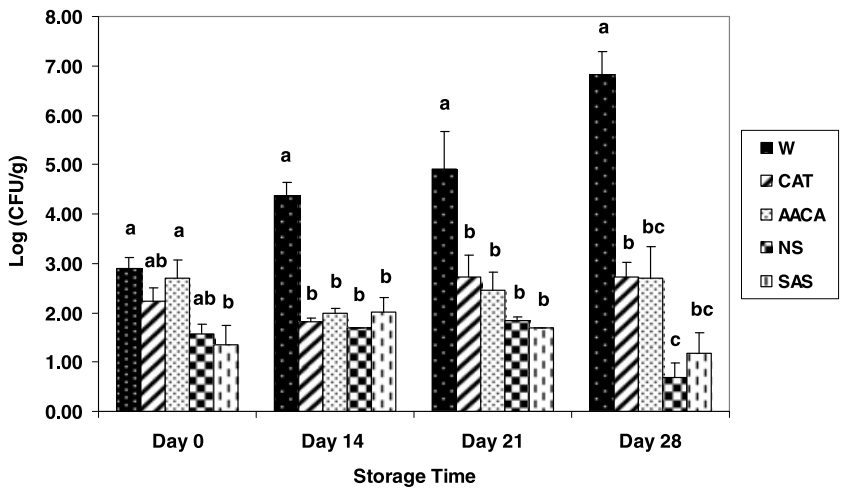

Figure 3–Mean aerobic plate counts (Log CFU/g) of fresh-cut, Russet Burbank slices over refrigerated storage time(compiled ozone and nonozone data). Values are means ± standard error ($n = 6$). Significance ($P \leq 0.05$) is noted by different letters within time periods (day). Potato slices were stored at 4 °C.

(SAS) to 2.91 (W). By day 14, W-treated potato slices had significantly ($P \leq 0.05$) higher APCs than all other treatments and the log values increased substantially over storage time. By day 28, W rose to 6.82 log CFU/g, while NS-treated potatoes had the lowest APCs.

Overall, all treatments were more effective than W to suppress microbial counts and this antimicrobial effect was maintained over time. By day 14, microbial counts were reduced by 2.4 to 2.7 log CFU/g for all treatments compared to W. By day 21, CAT and AACA treatments had reduced APC counts of 2.2 and 2.5 log CFU/g, respectively. By day 28, NS and SAS had more dramatically reduced microbial counts of 6.1 (NS) and 5.7 (SAS) log CFU/g.

According to APC results, NS and SAS treatments appeared to be the most effective in maintaining low APCs over storage time (≤2.00 log CFU/g). Organic acids are known to have antimicrobial action due to their low pH which can also decrease the internal pH of microbial cells, and the acids can also alter cell wall permeability which can inhibit cell transport (Beuchat 2000).

This study did not find any additional benefits of aqueous ozone to reduce APCs on potato slices, which is similar to Beltrán and others' (2005) findings. They determined that ozone was not effective to lower microbial populations on vacuum-packed, fresh-cut potato strips. However, Koseki and Isobe (2006) found aqueous ozone washes on iceberg lettuce significantly decreased bacterial load as ozone concentration increased. The ozone concentration in this study may have been too low to have an antimicrobial effect on potato slices. However, Ölmez and Akbas (2009) found that a 2 ppm aqueous ozone wash for 2 min was adequate to reduce the microbial load of fresh-cut lettuce. They also discussed why research findings differ on ozone's effectiveness to reduce bacteria. They mentioned that many variables can influence ozone efficacy, such as the method of ozone application, amount, and type of microorganism, and variety of produce.

Conclusions

Aqueous ozone (2 ppm) decreased enzymatic browning in fresh-cut potatoes as indicated by higher *L*-values and lower *a*-values compared to treatments not receiving an ozone dip treatment. However, ozone did not appear to have any effect on APCs or PPO activity in this study.

SAS and NS treatments were the most effective treatments to reduce enzymatic browning and APCs over 28 d of refrigerated storage, as indicated by the higher *L*-values, lower *a*-values, and consistently low APCs (≤2.00 log CFU/g) over storage time compared to the other treatments. SAS also appeared to retain low PPO activity over storage time, which may be attributed to its low pH and combined effects of citric and ascorbic acid.

More research should investigate whether aqueous ozone at higher concentrations may be effective in lowering APCs and PPO activity and to better understand the mechanism of how ozone and these acidulants affect PPO activity. Further research needs to be conducted to determine the consumer acceptability of SAS and NS on fresh-cut potatoes. Results from this study indicate that SAS is comparable to NS, a commercially available antibrowning product for fruits and vegetables, in maintaining the shelf life of value-added potato products.

Acknowledgments

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