Quality evaluation of packaged acidified vegetables subjected to continuous microwave pasteurization☆

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ARTICLE INFO

ABSTRACT

The study evaluated the use of 915 MHz continuous microwave processing with a rotation apparatus for pasteurization of acidified vegetable packages. Broccoli florets, and 1.2 cm cubes of broccoli stems, red bell pepper, and sweetpotato were pre-equilibrated to 1 g/100 g NaCl and 0.38 g/100 mL citric acid, and separately placed in 110 mL cups with a 0.5 g/100 mL citric acid solution. Unsealed packages were placed on a conveyor belt and run through a 915 MHz microwave cavity operating at 3.5 kW (residence time = 4 min). After processing, cups were sealed with a lidding film, and held in insulating molds for 30 min. Infrared thermocouples, fiber optic temperature sensors, and infrared imaging were used to monitor product temperatures. Microbial stability and changes in color and instrumental textural properties were measured over a 60-day storage period at 30 °C. Good retention of color and texture of acidified vegetable pieces was observed after microwave pasteurization. Over storage, textural properties significantly degraded for all vegetables, but the brilliant color of red bell pepper and sweetpotato was relatively retained. Chemical indicators of microbial spoilage were not detected at the end of storage. This study demonstrates a successful continuous microwave pasteurization process for producing shelf-stable acidified vegetable packages.

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1. Introduction

The common goals of the food industry and many other manufacturing operations include developing strategies and processes to reduce water and energy usage, utilize waste streams, and generate less waste (Dieu, 2009; Khan & Hanjra, 2009). Microwave processing technology provides opportunities to reduce water usage and improve efficiency of thermal processes due to its rapid, volumetric heating caused by the conversion of electromagnetic energy into heat, as opposed to heat transfer by convection and conduction. Utilization of microwave processing technology for thermal processing of low acid foods has increased in recent years due to technological advancements and proven improvements in product quality (Kumar et al., 2008).

For high acid foods such as fruit juices and acidified vegetables, however, pasteurization of the products through the use of microwave energy has received little attention. A study by Lau and Tang (2002) used 915 MHz microwaves to pasteurize 1.8 kg glass bottles of pickled asparagus in a batch process. The authors used a combination of hot-fill and water bath heating to bring the product temperature to 80 °C before applying microwave energy to reach their target of 88 °C for 10 s. Pasteurizing batches of pickled asparagus bottles by microwave heating was shown to reduce the heating time by half, and improve the textural properties compared to the traditional pasteurization method (Lau & Tang, 2002). Recently, Koskiniemi, Truong, Simunovic, & McFeeters (2011) reported the application of continuous microwave heating for pasteurization of acidified vegetable packs. Uniform heating within the packs was achieved by implementation of a two-stage rotation apparatus to rotate vegetable packs 180° during processing in the microwave tunnel for increasing exposure of the packs to incident microwaves, which allowed a temperature of 77 °C to be attained at the cold spot, as measured by fiber optic temperature probes during processing. This temperature was above the industrial standard of 74 °C for in-pack pasteurization of acidified vegetables (Etchells & Jones, 1942). A study was also conducted for better understanding on the influence of processing treatments including vegetable

blanching, addition and distribution of acid and salt on dielectric properties of acidified vegetable pieces using a 915 MHz continuous microwave system (Koskiniemi, Truong, McFeeters, & Simunovic, 2013). However, the quality and microbial stability of the pasteurized packs were not evaluated.

With regards to product quality, previous studies have examined the effects of blanching (Goncalves et al., 2009; Tijskens, Schijvens, & Biekman, 2001) and cooking methods (Lin & Chang, 2005) on the texture and color of broccoli, but the aspects on acidification and pasteurization of broccoli for producing shelf-stable products were not examined. Methods to control softening of acidified red bell pepper have been studied (McFeeters, Barrangou, Barish, & Morrison, 2004; Papageorge, McFeeters, & Fleming, 2003), and improved firmness of a sweetpotato French fry-type product through tissue acidification was shown by Walter, Fleming, and McFeeters (1992). However, no previous study has examined the effects of acidification and microwave pasteurization on the texture and color in packaged acidified vegetables such as broccoli, red bell pepper and sweetpotato.

Therefore, the current study illustrates the application of a process for producing shelf-stable acidified vegetable packs using a 915 MHz continuous microwave system and evaluates the microbial stability and changes in color and texture of the product as affected by microwave pasteurization.

2. Materials and methods

2.1. Vegetable preparation

Two lots of broccoli and red bell pepper (cultivars unknown) were purchased from two local supermarkets in Raleigh, NC, U.S.A. Sweetpotatoes (cv. Covington) were grown in Clinton, NC and samples were taken from two batches. Broccoli florets were prepared by cutting into pieces of 3 ± 1 cm in length, and 2 ± 1 cm in width. Broccoli stems, red bell peppers, and sweetpotatoes were diced into 1.2 cm cubes.

The vegetables were blanched prior to acidification to facilitate acid and salt penetration into the tissues (Koskiniemi et al., 2013). The blanching treatment involved submersion of the vegetables in 95 °C water for 30 s, followed by immediate cooling in an ice-water bath for 2 min. Each lot was then transferred to a 3.79 L glass jar, and a 2 g/100 mL sodium chloride (NaCl), 0.75 g/100 mL citric acid soaking solution was added to the vegetables at a 50 g:50 g ratio for red bell pepper and sweetpotato cubes, and 33 g:67 g ratio for broccoli florets. The percentages of NaCl and citric acid in the soaking solution were previously optimized by pH and dielectric property measurements (Koskiniemi et al., 2013), and heating profiles of varying vegetable and cover solution treatments (Koskiniemi et al., 2011). The ratio of broccoli to soaking solution was different than red bell pepper and sweetpotato due to the bulky, irregular shape of the florets. Therefore, more liquid was needed to fully submerge the broccoli. The blanched vegetables were allowed to equilibrate in the cover solution for 24 h at 20 ± 2 °C. After 24 h, the cover solution was drained from the vegetables. Samples of sweetpotato and red bell pepper (45 g), and samples of broccoli (30 g) were individually placed in 110 mL cups. Immediately prior to microwave processing, pre-measured volumes of 0.5 g/100 mL citric acid were added to the cups containing vegetables, which brought the net weight of each cup to 90 g. Cups were not sealed prior to microwave processing.

2.2. Microwave processing

Vegetable packs were processed using a 915 MHz, 5-kW continuous conveyor-type microwave system (Industrial Microwave Systems, Morrisville, NC, USA). The system was outfitted with a two-stage rotation apparatus to rotate the vegetable packs 180° during heating, as previously described (Koskiniemi et al., 2011). The microwave system was operated at 3.5 kW, the conveyor belt speed was 0.711 m/min, and residence time in the microwave cavity was 4.7 min. Vegetable packs were spaced 4 cm apart, and were placed along the left wall of the conveyor to ensure rotation of the cups during processing. To minimize the use of vegetable material, a food simulant comprised of 0.5 g/100 g NaCl and 0.5 g/100 g carboxymethylcellulose (NaCl–CMC) was placed in cups that preceded and followed the lot of vegetable packs. Prior to startup, the microwave applicator was filled with packs containing NaCl–CMC (referred as CMC cups from now on) to provide a load for energy absorption. Upon system startup, CMC cups were continuously fed onto the conveyor until conditions in the microwave applicator had equilibrated. At this point, one lot of 45 vegetable packs containing all three vegetables were processed. Individual vegetable packs were placed on the belt in the following repeating order: sweetpotato, red bell pepper, and broccoli (e.g. an individual red bell pepper pack was adjacent to a sweetpotato and a broccoli pack on either side).

As each vegetable pack exited the microwave cavity, it was immediately sealed with a lidding film comprised of polyethylene terephthalate (PET) and cast polypropylene (CPP) (Cello-Pack Corporation, Buffalo, NY, USA) using a table-top pre-cut lid sealing machine (Quality Cup Packaging Machinery, Corp., Menomenie, WI, USA). Upon sealing, each pack was placed in an insulating mold fabricated from polyurethane foam sealant (Dow Chemical Company, Wilmington, IL, USA), inverted, and held for 30 min to minimize heat loss and ensure proper pasteurization. All packs were then held at 20 °C for 2 d until placed in a controlled atmosphere chamber at 30 °C and 99% relative humidity for 60 d when final quality evaluation was conducted. It should be noted that sealing the packs prior to microwaving was tested, but could not be accomplished. Steam generated in the packs during heating caused the packs to bulge significantly, such that packs could not physically exit the microwave cavity.

2.3. Fiber optic temperature sensor measurements

Vegetable and brine temperatures were continuously monitored during and after microwave processing in different cup locations by inserting pre-calibrated fiber optic temperature sensors (FOT-L/10M, Fiso Technologies, Inc., Quebec, Canada) through the walls of the polypropylene cup. The fiber optic temperature sensors were connected to a 4-channel fiber optic signal conditioner (Model UMI 4, Fiso Technologies) controlled by FISO Commander software (FISO Technologies), and measured the temperature in 0.6 s intervals. This temperature measurement method was validated by Koskiniemi et al. (2011) to determine the cold spot and overall temperature distributions in acidified vegetable packs. Placement of temperature probes was based on prior works. Upon exit of the microwave cavity, the vegetable pack with the sensors was placed in an insulated polyurethane mold and held for 30 min to monitor the heat treatment delivered after processing. Reported data were the average of eight replicate measurements for each vegetable.

2.4. Infrared thermocouple temperature measurements

Surface temperatures of the product in the microwave applicator were measured by 16 infrared thermocouples (Model OS36-T, OMEGA Engineering, Inc., Stamford, CT, USA) spaced throughout the microwave. The data were collected from five infrared thermocouples located nearest the operator-side wall of the microwave tunnel at incremental distances from the start of the microwave cavity.

2.5. Infrared imaging

Infrared images of the cup surfaces were recorded at the end of the conveyor belt by a Thermovision Alert N infrared camera (FLIR Systems AB, Danderyd, Sweden) as a measure of cup-to-cup temperature uniformity. The infrared camera was controlled remotely by Thermovision Remote Software (FLIR Systems AB) installed on a laptop computer. Infrared images were analyzed using Thermovision Researcher 2000 software (FLIR Systems AB). Average surface temperatures of the cups were analyzed using the circle tool.

2.6. Microbial stability

The efficiency of thermal treatment applied through the continuous microwave pasteurization process was evaluated by monitoring the indicators of microbial spoilage over 60 d of storage at 30 °C. Each vegetable pack was evaluated weekly for visual signs of spoilage such as turbidity, mold growth, or gas production. In addition, metabolic products indicative of bacterial and yeast growth such as lactic acid and ethanol, respectively, were measured at 2 and 60 d after microwave processing using high-performance liquid chromatography (HPLC). Two days after microwave processing, 1.5 mL samples of the cover solution were drawn from six randomly selected vegetable packs in each lot (two of each vegetable type), and frozen at −20 °C in microcentrifuge tubes until further analysis. These materials were referred to as post-processed or 0 day stored samples. The same sampling procedure was used after 60 d of storage. Samples were prepared for HPLC analysis by thawing and centrifuging at $16,053 \times g$ for 10 min (Marathon 16 km, Fisher Scientific, Pittsburgh, PA, USA). For HPLC analysis, 1:2 and 1:10 dilutions were prepared by pipetting 500 μL and 100 μL of sample into 500 μL and 900 μL volumes of 0.03 mol equi/L sulfuric acid diluent, respectively. Samples were randomized and run on a 30 cm HPX-87H column (Bio-Rad Laboratories, Hercules, CA, USA), which was heated to 65 °C, and eluted with 0.03 N sulfuric acid at a flow rate of 0.9 mL/min (Olsen & Pérez-Díaz, 2009). A UV6000 LP detector (Thermo Separation Products, Inc., San Jose, CA, USA) was used to analyze malic acid, succinic acid, lactic acid, acetic acid, propionic acid, and butyric acid. Glucose, fructose, and ethanol were quantified by a Waters model 410 refractive index detector (Waters, Milford, MA, USA).

2.7. Color measurements

The colors of broccoli florets and stems, sweetpotato and red bell pepper cubes were measured using a Minolta CR-300 Chroma Meter (Konica Minolta, Inc., Ramsey, NJ, USA) with D65 light source. The instrument was calibrated with a white plate, and measurements were taken using the CIE $L^*a^*b^*$ system. The color of the vegetables was measured after each processing step: dicing and cutting of the raw vegetable, blanching, 24 h equilibration, 2 d post-processing, and after 60 d of storage. Five samples from each lot were measured at each sampling point, meaning that each reported datum is the average of 10 measurements. Hue angle (H°) (Eqns. (1)–(3)), chroma (C^*) (Eqn. (4)), and total color difference (ΔE) (Eqn. (5)) were calculated using the following equations:

$$H° = \tan^{-1}(b^*/a^*) \quad \text{when } a^* > 0 \text{ and } b^* = 0 \tag{1}$$

$$H° = 180° + \tan^{-1}(b^*/a^*) \quad \text{when } a^* < 0 \tag{2}$$

$$H° = 360° + \tan^{-1}(b^*/a^*) \quad \text{when } a^* > 0 \text{ and } b^* < 0 \tag{3}$$

$$C* = \sqrt{(a^*)^2 + (b^*)^2} \tag{4}$$

$$\Delta E = \sqrt{(L^*)^2 + (a^*)^2 + (b^*)^2} \tag{5}$$

2.8. Instrumental texture measurements

Firmness of the vegetable cubes was measured using a TA-XT2 texture analyzer (Texture Technology Corp., Scarsdale, NY, USA) with a TA-42 knife probe with 45° chisel blade and slotted plate. A 50-kg load cell was used for all texture measurements. The pretest speed was 3.00 mm/s, the test speed was 2.50 mm/s, and the post-test speed was 10.00 mm/s. For each measurement, six cubes were placed over the slot of the guillotine holder, and the knife probe cut all the way through the vegetable material and advanced through the slotted plate. Red bell pepper pieces were placed skin side down. For each lot of vegetables, five replicate measurements were taken at each time point. Each datum is the mean of 10 measurements, and a bulk measurement 60 cubes. For post-processing evaluation, five samples were randomly selected from each lot.

2.9. Statistical analysis

Significant differences in color and texture over the course of processing and storage were determined at the $p < 0.05$ significance level using one way ANOVA and the Tukey–Kramer HSD method for mean comparisons using JMP 7 (SAS Institute Inc., Cary, NC, USA) for each vegetable type.

3. Results and discussion

3.1. Process validation and evaluation systems

Two independent trials were conducted to test the effectiveness of continuous microwave pasteurization of acidified vegetables. Processing temperatures were measured through multiple approaches. Infrared thermocouples placed in the microwave applicator recorded surface temperatures, fiber optic temperature sensors inserted into vegetable pieces recorded time-temperature heating profiles, and an infrared camera recorded thermal images at the exit of the microwave. Fig. 1 shows the surface temperatures recorded along the length of the microwave applicator in real time. The surface temperatures of the packs were substantially lower than the measured temperatures of the vegetable pieces (Fig. 2). This may be due to the emissivity of the product surface, as well as any condensate that may have formed on the infrared thermocouple lens during processing. The condensate hypothesis is supported by the sharp initial peak in temperature at all distances, followed by a decrease in temperature measurements. The same phenomenon was found by Boldor, Sanders, Swartzel, and Farkas (2005), who used the same microwave system for drying peanuts. The surface temperatures of the peanut beds were found to be substantially lower than the measured internal temperature of the peanuts. Boldor et al. (2005) attributed the temperature difference between surface and internal temperatures to the difference in dielectric properties between the shell and peanut and evaporative cooling of the peanut shell. However, the trends in temperature throughout the microwave applicator were consistent with time-temperature heating profiles obtained through fiber optic temperature sensor measurements.
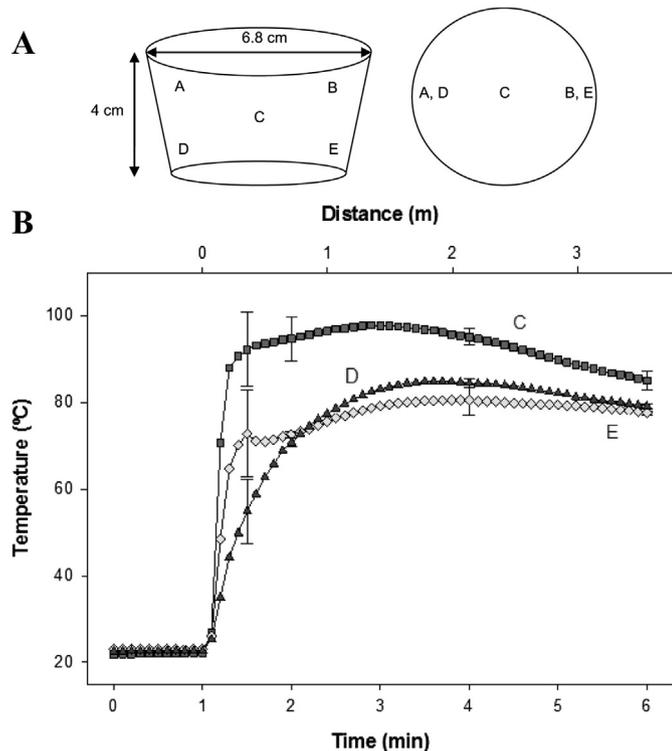
Continuous time-temperature heating profiles showed that pasteurization temperatures (>74 °C) were reached due to a 180° cup rotation apparatus (Fig. 2). Fig. 2 shows the heating of the hottest (C) and coldest (D and E) locations measured during the processing of sweetpotato. Previous work showed that temperatures reached at locations A and B fell between the hottest and coldest temperatures
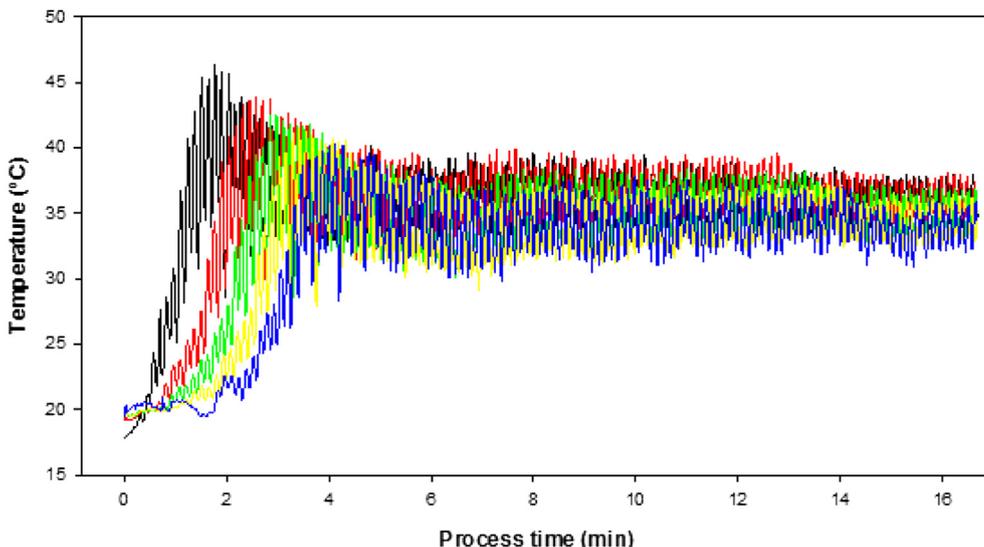
Fig. 1. Infrared thermocouple temperature measurements at fixed points along the length of the microwave tunnel during continuous microwave processing of acidified vegetable packs at 3.5 kW. —— 0.984 m, —— 1.670 m, —— 2.127 m, —— 2.508 m, —— 2.889 m.
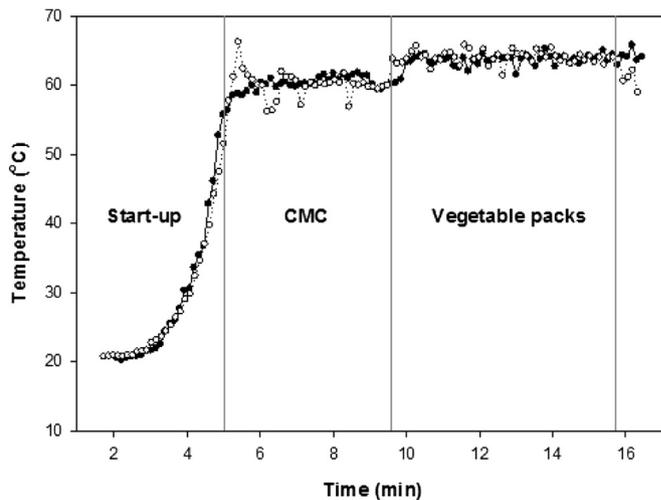
(Koskiniemi et al., 2011). However, most of the microwave energy was absorbed by the product in the first meter of the 3-m long microwave tunnel (Fig. 2). After this point, no additional microwave energy was available to further heat the product. Decreases in temperature were noted after the first meter in the upper half of the vegetable packs due to evaporative cooling since the packs were not yet sealed, and open to the atmosphere. While sealed packs would

dramatically improve heat distribution and eliminate evaporative cooling, this was not possible given the physical limitations of the microwave cavity, as bulging packs could not exit the microwave tunnel. Boldor et al. (2005) found similar results for peanuts. Heating was shown to be very rapid during the first meter in the microwave applicator, but was then followed by a decrease in both internal and surface temperatures. This finding was especially pronounced for peanuts with higher moisture content (21–33 g moisture/100 g). As it relates to the current issue of pasteurization, this cooling effect presents a process inefficiency, and a need for temperature verification at the exit of the microwave cavity.

Upon exit of packs from the microwave tunnel, thermal images of the cups were captured using an infrared camera. Thermal images were analyzed, and the average surface temperatures of each cup during processing, starting with cups of CMC at the start of processing, are shown in Fig. 3. Cups during the start up phase did not receive the full residence time in the microwave applicator, explaining the rise in surface temperatures leading to a plateau. The

Fig. 2. (A) Fiber optic temperature sensor locations: Side view (left) and top view (right). (B) Time–temperature heating profile of pre-equilibrated sweetpotato to 1 g/ 100 g NaCl in 0 g/100 mL NaCl cover solution. Product enters the microwave field at 0 m and exits at 3.3 m. Rotation occurs between 0.2 and 0.4 m (1.2 and 1.5 min), reversing the initial locations of D and E. Error bars represent 1 standard deviation of at least 2 replicates.

Fig. 3. Average surface temperatures of vegetable packs after 915 MHz continuous microwave processing at 3.5 kW and 180° cup rotation as measured by infrared imaging. ——■—— Trial 1, ···◻··· Trial 2.

next phase, labeled CMC in Fig. 3, represents the stage at which all cups from that point forward received the full thermal treatment. Interestingly, surface temperatures of the vegetable packs were 5 °C higher than CMC cups. Average cup-to-cup surface temperatures for runs 1 and 2 were within 5 °C, indicating a reproducible process. While infrared images cannot be used as a temperature validation tool, it does provide a qualitative measure of cup-to-cup heating uniformity.

3.2. Post-process thermocouple measurements

A 30 min holding period was implemented after microwave processing in order to deliver a defined thermal treatment to the sealed vegetable packs. Fig. 4 shows the average of eight vegetable pack temperatures for sweetpotato, red bell pepper, and broccoli during the first 15 min of the hold period. Upon exit of the microwave cavity, temperatures were at least 75 °C, but did not retain this temperature. Even in an insulating mold, the temperatures of the vegetable packs decreased to 60 °C for sweetpotato and broccoli, and to 55 °C for red bell pepper within 15 min (Fig. 4). Since vegetable packs were not sealed during microwave processing, the remaining heat in the pack is responsible for killing any pathogens or spoilage microorganisms on the lidding film, similar to a hot-fill process. While the hold time conditions employed in this study were less stringent than industrial practices, the product was still stored for 60 d and evaluated for microbial stability.

3.3. Microbial stability

Vegetable packs were examined for signs of microbial spoilage over a 60 d storage period at 30 °C. Each pack was visually inspected on a weekly basis for turbidity, gas production, and mold growth. Visual inspections did not reveal any signs of spoilage, so the chemical analysis sought to confirm the absence of spoilage. If spoilage were to occur, lactic acid and/or ethanol would be present due to the growth of lactic acid bacteria and/or yeasts, respectively. To confirm the absence of spoilage, samples of cover solution were collected at the beginning and end of the storage period. These samples were tested for the presence of metabolites of microbial growth, particularly organic acids and ethanol. The chemical detection method was chosen over a microbiological enumeration method due to its simplicity. Detecting microbial growth during
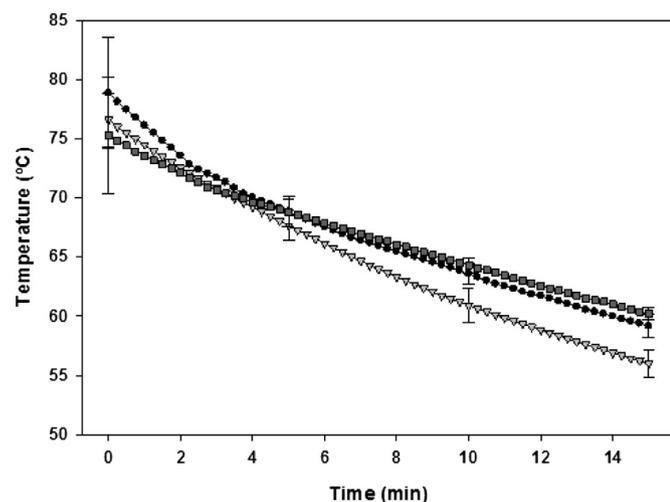
storage would have required frequent enumeration due to the unpredictable cell growth behavior. The chemical method is advantageous in that it does not require live cells at the time of sampling, and so can be used at the end of storage to measure metabolic products as evidence of spoilage (Loureiro & Malfeito-Ferreira, 2004).

As Table 1 shows, lactic acid and ethanol were not detected in any vegetable pack at 0 or 60 d of storage. Interestingly, small amounts (∼1 mM) of acetic acid were detected in all vegetables after storage. It is hypothesized that acetic acid may have arisen from pectin deacetylation caused by hydrolysis at low pH. The results in Table 1 suggested that malic acid was naturally present in broccoli and sweetpotato, but not red bell pepper. The apparent absence of malic acid in red bell pepper may have been due to the maturity stage of the peppers. The amount of malic acid has been shown to significantly decrease during ripening of bell peppers from green to red (Luning et al., 1994). Furthermore, since the samples of cover solution were diluted by a factor of 10, any malic acid present may have been below the detection limit. The presence of, and increase in succinic acid in red bell pepper could not be explained. The increases in glucose and fructose concentrations over the storage period could have been due to leaching of sugars from the vegetables into the cover solution, as well as starch and sucrose hydrolysis. These findings, coupled with no visual evidence of spoilage, proved that the microwave pasteurization process was effective in eliminating spoilage of acidified vegetable packs.

3.4. Color of vegetable pieces

Vegetable color was evaluated after each unit operation and 60 d storage period. The color of broccoli florets was found to change the most. After blanching, the color of broccoli was visually observed to be a bright green color. This change was noted by the decrease in a^* denoting an increased green color component, as well as the significant increase in hue angle (Table 2). The brightening of the green color after blanching is due to the elimination of intracellular air and ingress of blanch water and cellular fluids as a result of cell disruption (Tijskens, Barringer, & Biekman, 2001). Lightness decreased after blanching, and then remained unchanged throughout the study. The addition of acid during the equilibration process had a profound effect on green color. The green component (a^*) and hue angle significantly decreased, and produced an olive-green color. The addition of citric acid sufficiently lowered pH to induce and accelerate pheophytinization (Tijskens, Schijvens, et al., 2001). Pheophytinization is a process wherein two H^+ ions displace Mg^{++} from the porphyrin ring of chlorophyll, and convert

Fig. 4. Mean temperature and standard deviation of sweetpotato (●), red bell pepper (▼), and broccoli (■) packs during a 15 min hold period in an insulating mold after microwave processing ($n = 8$ for each vegetable).

Table 1
Changes in acid, sugar, and ethanol concentrations in the cover solutions of pasteurized vegetable packs over a 60-day storage period at 30 °C.

Analyte[a]	Broccoli		Red bell pepper		Sweetpotato	
	0 day	60 day	0 day	60 day	0 day	60 day
Malic acid	0.61	0.54	–	–	4.67	4.99
Succinic acid	–	–	5.30	7.01*	–	–
Lactic acid	–	–	–	–	–	–
Acetic acid	–	1.2**	–	0.90**	–	1.12**
Propionic acid	–	–	–	–	–	–
Butyric acid	–	–	–	–	–	–
Glucose	3.98	4.81	23.83	30.41**	21.15	44.30**
Fructose	3.88	4.74	25.84	32.95**	12.80	37.39**
Ethanol	–	–	–	–	–	–

* Denotes a significant difference ($p < 0.05$) from initial time ($n = 4$).
** Denotes a significant difference ($p < 0.01$) from initial time ($n = 4$).
[a] All analyte concentrations are in mM; '–' denotes analyte was below detection level.

Table 2
Color values of raw and acidified vegetables after each unit operation and 60-day storage at 30 °C.[a]

Vegetable	Treatment	L^*	a^*	b^*	Hue (°)	Chroma	ΔE	ΔE
Broccoli floret	Raw	52.87a	−10.18a	17.20ab	120.08b	20.02ab	Ref[b]	
	Blanched	40.99b	−16.13b	19.40a	130.42a	25.28a	13.46	
	Equilibrated	43.63b	0.04c	17.88ab	89.62d	17.89bc	13.79	Ref
	Post-process	39.28b	−0.48c	17.45ab	91.48cd	17.46bc	16.70	4.41
	Storage	40.38b	−1.13c	13.38b	94.78c	13.44c	15.89	5.68
Broccoli stem	Raw	68.43a	−9.38a	21.92a	113.14a	23.84a	Ref	
	Blanched	53.62b	−10.23a	20.98a	115.94a	23.52a	14.87	
	Equilibrated	56.89b	−3.06b	10.86b	106.04ab	11.30b	17.19	Ref
	Post-process	57.81b	−2.70b	8.45b	110.16bc	8.93b	18.41	2.60
	Storage	54.10b	−2.16b	9.75b	102.73c	10.00b	20.14	3.14
Red bell pepper	Raw	37.64a	16.61ab	15.71bc	43.10a	23.13ab	Ref	
	Blanched	41.44b	16.28ab	17.42abc	46.84a	23.88ab	4.17	
	Equilibrated	39.04ab	18.48a	20.17a	47.26a	27.42a	5.03	Ref
	Post-process	36.08a	16.62ab	18.31ab	47.77a	24.77a	3.03	3.96
	Storage	35.87a	13.25b	14.22c	47.25a	19.56b	4.09	8.54
Sweet-potato	Raw	63.99a	22.30a	33.52a	56.77ab	40.42a	Ref	
	Blanched	51.22c	20.30a	31.74a	57.37ab	37.68a	13.05	
	Equilibrated	53.05b	22.02a	33.36a	56.54b	39.97a	10.94	Ref
	Post-process	52.99b	19.37a	31.51a	58.46ab	36.99a	11.56	3.24
	Storage	50.50c	16.41b	28.08b	59.70a	33.53b	15.70	8.12

[a] For each vegetable, different letters within a column denote significant differences ($p < 0.05$) between treatments ($n = 10$).
[b] 'Ref' denotes the reference value for ΔE calculations.

chlorophyll (green) into pheophytin (olive green). This acid effect was most detrimental to broccoli color, as microwave processing and extended storage did not produce further changes in any measured color component (Table 2).

The processing of red bell pepper also resulted in color changes, although not as drastic as was seen for broccoli. Compared to the raw material, blanching and equilibration significantly increased L^* and b^* values (Table 2). The increases in lightness (L^*) and yellowness (b^*) were likely due to a combination of leaching of carotenoids into the blanch water and soaking brine thereby changing the pigment composition in the tissue, and carotene isomerization by acid and heat treatments (Chandler & Schwartz, 1988; Melendez-Martinez, Britton, Vicario, & Heredia, 2007). Hue angle did not change significantly ($p < 0.05$) throughout processing and storage; however, chroma decreased over the 60-day storage period. It is important to note that microwave processing did not produce any significant color change when the color values were compared before (equilibrated) and after processing (post-process) (Table 2). A comparison of the equilibrated and 60-day storage samples showed a significant decrease of a^*, indicating a slight loss of the red color component. Despite these measured changes in color, informal visual observations found the final color to be acceptable after the 60-day storage period.

Sweetpotato color was stable over the course of processing, and only slightly degraded over the 60-day storage period. Blanching was found to only decrease L^*, which resulted in a deeper orange color. This decrease in lightness is thought to be a result of the release of inter- and intracellular air, as well as the decompartmentalization of pigments in the cell (Purcell, Walter, & Thompkins, 1969) and carotene isomerization (Chandler & Schwartz, 1988). Equilibration and microwave processing did not significantly affect any of the color parameters (Table 2). It was only after the 60-day storage period that color degraded. This was observed by significant decreases in L^*, a^*, b^*, and chroma. Decreases in a^* and b^* were indicative of losses of red and yellow color components. Hue was more or less unchanged throughout the course of this study. However, chroma was significantly lower after processing. This loss of color intensity may have been caused by the oxidation of carotenes since the packaging material used was not impervious to oxygen (Minguez-Mosquera & Hornero-Mendez, 1994). However, despite the instrumentally measured degradation

of sweetpotato color during storage, sweetpotato packs still maintained a vibrant orange color after storage.

3.5. Firmness of vegetable pieces

Textural properties of the vegetable cubes were measured by a cut test. This type of test was used in order to quantify the force and the amount of work required to shear through the entire sample. Additionally, this method enabled the measurement of representative samples in a timely manner, since six cubes could be measured at one time, and cleanup time between samples was reduced compared to a Kramer Shear test. Fig. 5 shows typical texture profiles for sweetpotato, red bell pepper, and broccoli. The first peak is representative of the force required to fracture the vegetable cubes, and can be considered as the hardness of the vegetable. The second peak indicates the force required to cut through the vegetable cubes, as the knife probe passes through the guillotine holder. The total area under the curve represents the total
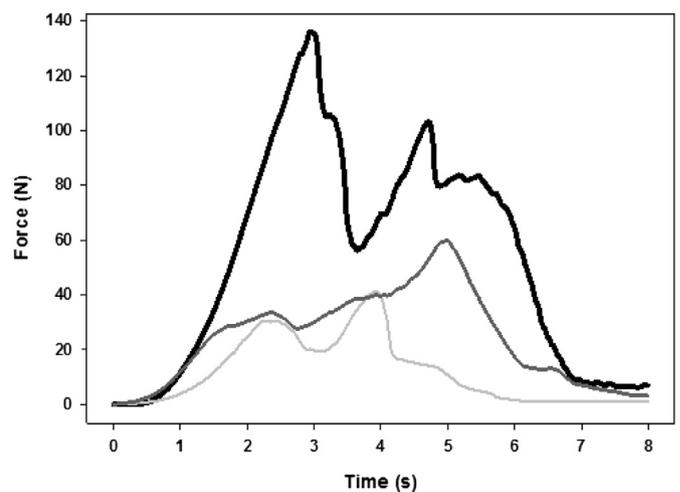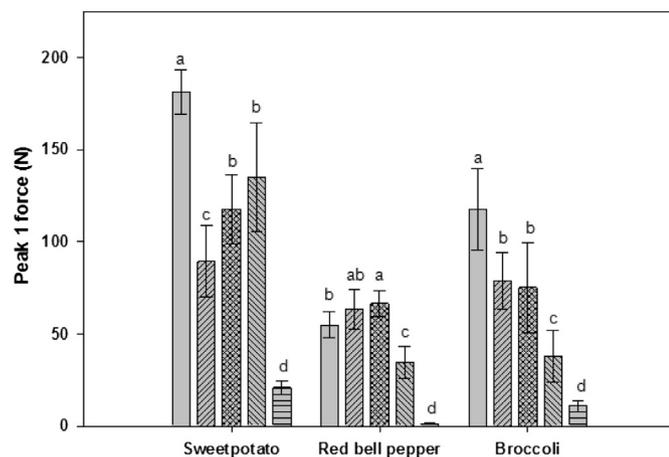
Fig. 5. Typical texture profiles of sweetpotato (▬▬▬), red bell pepper (▬▬▬), and broccoli (▬▬▬) obtained from the cut test (above profiles are of vegetables 2 d after microwave processing).

amount of work contributed by compression, puncture, shear, and extrusion forces.

Instrumental texture measurements were taken after each unit operation and 60-day storage at 30 °C. Fig. 6 shows the peak fracture forces of each vegetable over the course of processing. Blanching significantly reduced the fracture force (Fig. 6) and total work (Fig. 7) required to cut through the sweetpotato cubes. The dramatic decrease in peak force was likely related to the change in tissue structure near the surface of the cubes caused by blanching. Changes in cellular adhesion and loss of turgor pressure due to cell rupture may have been responsible for the decreased fracture force after blanching.

Interestingly, an increase in the fracture force was noted for sweetpotato after a 24-h equilibration period in the soaking solution comprised of 0.75 g/100 mL citric acid and 2 g/100 mL NaCl (0.34 mol/L) (Fig. 6). Examination of the total work (Fig. 7) showed the same trend, although to a lesser extent. These results were consistent with the findings of other investigators. Walter et al. (1992) found that sweetpotato tissue firmness increased as hydrogen ion concentration increased when sweetpotato strips were vacuum- infiltrated with various acidulants, including citric acid. These authors were able to demonstrate that tissue acidification decreased starch hydrolysis through inactivation of α- and β-amylase systems and reduced the amount of water-soluble pectin. However, the exact mechanism responsible for increased firmness was not determined. Since starch can play a role in cell structure, and pectin present in the middle lamella is important in cellular adhesion, maintenance of these components may contribute to firmness retention. Furthermore, increasing the ionic strength by addition of 0.3 mol/L NaCl was found to decrease firmness of the acidified tissue, but the mechanism could not be explained (Walter et al., 1992). Despite the observed increase in firmness after tissue acidification, firmness was not retained when subjected to further heat treatment.

The largest texture degradation in sweetpotato occurred over the 60-day storage period. Both the fracture peak force and total work significantly decreased by 85% from post-process to 60-day storage sampling times. The addition of NaCl and citric acid may have contributed to tissue softening. While no calcium was added to any of the products to increase firmness, the ability of endogenous Ca^{++} to crosslink pectin polymers may have been impeded by the high concentration of Na^+ competing for carboxylic acids. Vu,
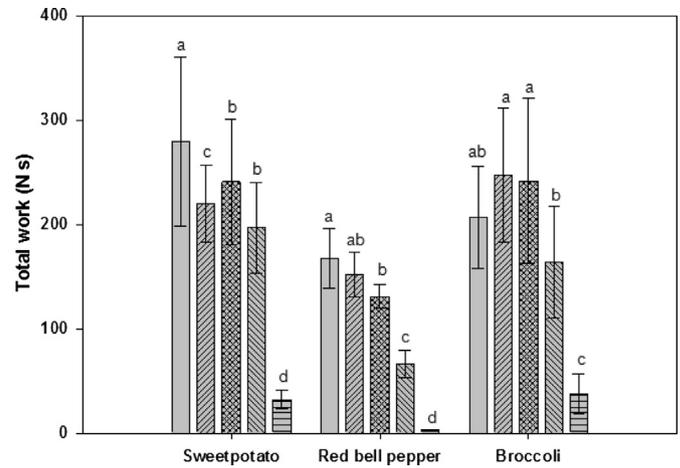
Fig. 7. Total work required cut through sweetpotato, red bell pepper, and broccoli cubes after each unit operation and 60-day storage at 30 °C. ▢ Raw, ▨ Blanched, ▨ Equilibrated, ▨ Post-process, ▤ 60 day storage. Different letters within each vegetable denote significant differences ($p < 0.05$); error bars represent one standard deviation ($n = 10$).

Smout, Sila, Van Loey, and Hendrickx (2006) showed that the addition of known chelating agents such as EDTA, ascorbic acid, and citric acid to the brine increased the degree of tissue softening in carrots by binding Ca^{++} and weakening the pectin network. Nevertheless, despite the observed reduction in firmness, sweetpotato cubes still maintained their shape and were not easily deformed, and required a force of 20.9 N to fracture six cubes or 3.5 N per cube which was within the fracture forces of 1.1–5.0 N per cube of canned sweetpotatoes pretreated by low temperature blanching for firmness improvement reported by Truong, Walter, and Bett (1998).

Textural properties of red bell pepper also changed significantly over the course of processing and storage. Compared to the raw tissue, the fracture force of red bell pepper tissue increased after 24-h equilibration in the cover solution, but significantly decreased after microwave processing and 60-day storage (Fig. 6). Total work decreased after each processing step for red bell pepper (Fig. 7); a trend contrary to the measured fracture forces. The increase in fracture force after blanching and equilibration indicated that the tissue became more deformable, whereas the simultaneous decrease in total work indicated tissue softening. Two days after microwave processing (post-process) the fracture force and total work decreased by 48 and 51%, respectively, until the peppers were extremely soft (total work = 2.9 N s) after the 60-day storage period.

Softening of acidified red bell peppers is a well-known problem. The work of Papageorge et al. (2003) and McFeeters et al. (2004) sought to identify factors and methods to improve texture retention of acidified red bell peppers. The authors identified many factors such as genetic variability, growing conditions, blanching conditions, pH, oxygen, and calcium ion concentration which may significantly influence texture. In the current study, the final pH of red bell pepper was 3.12. Papageorge et al. (2003) suggested that at a pH < 3.4, softening is the result of nonenzymatic degradation of cell wall components, but other studies on cucumbers suggested that tissue softening is not based on hydrolysis of pectic substances at low pH (Krall & McFeeters, 1998; McFeeters & Fleming, 1990). In addition, peppers in the current study were packaged in the presence of oxygen. While the mechanism is unknown, oxygen has been shown to accelerate the softening of acidified red bell peppers (McFeeters et al., 2004), and likely contributed to the softening observed in this study.

Fig. 6. Peak forces obtained from the knife-cut test of sweetpotato, red bell pepper, and broccoli cubes after each unit operation and 60-day storage at 30 °C. ▢ Raw, ▨ Blanched, ▨ Equilibrated, ▨ Post-process, ▤ 60 day storage. Different letters within each vegetable denote significant differences ($p < 0.05$); error bars represent one standard deviation ($n = 10$).

Broccoli was the third vegetable examined in this study. Firmness of broccoli decreased as the degree of processing increased. Blanching reduced the fracture force (Fig. 6), but no significant change was observed in the total work (Fig. 7). The 24-h equilibration period did not change the textural properties of broccoli, although the fracture force significantly decreased by 50% 2 d after microwave processing compared to force measured at the equilibrated stage. Over the course of storage, the fracture force and total work decreased by 71 and 77%, respectively. These results were similar to those of sweetpotato and red bell pepper.

With the exception of sweetpotato, significant decreases in fracture force and total work were observed for red bell pepper and broccoli 2 d after microwave processing. It has been known that vegetable firmness decreased by thermal processing and various processing techniques have been developed for improvement firmness retention in processed vegetables. In this study, any potential quality improvement conferred by microwave technology could not be quantified since pasteurization of the tested vegetables were not performed using the traditional water bath technique (15 min hold time at 74 °C). However, previous studies that have looked at the effects of blanching and pasteurization on firmness retention of acidified peppers also observed similar reductions in firmness (Fleming, Thompson, & McFeeters, 1993; Papageorge et al., 2003). These studies suggested that the addition of calcium ions has been most effective in maintaining firmness. Further studies must be done to improve the textural properties of acidified broccoli, red bell pepper, sweetpotato and other vegetables.

4. Conclusion

This study demonstrated the applicability of 915 MHz continuous microwave processing as a pasteurization method for packaged, acidified vegetables. However, due to equipment and material limitations, vegetable packs were sealed after microwave processing, and then held to deliver a defined thermal treatment. Nevertheless, there was no sign of microbial spoilage during a 60-day storage, indicating an adequate thermal treatment. However, texture degradation over storage needs to be overcome for broccoli and red bell pepper. Broccoli color degraded due to pheophytinization, but red bell pepper and sweetpotato retained much of the brilliant red and orange color during thermal processing and after storage. Further work must be done to enable cup sealing prior to microwave processing, and pretreatments evaluated to improve the textural properties of acidified vegetables.

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