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Microwave pasteurization of pre-packaged carrots

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ABSTRACT

This research investigated the application of 915 MHz microwaves in pasteurizing pre-packaged vegetables. A specially designed 915 MHz single-mode microwave-assisted pasteurization (MAP) system was used to process carrot cuboids in brine pre-packaged in 8-oz polymer pouches. Gellan gel was formulated and selected as the model food to simulate the real foods processed by the MAP system; heating patterns and cold spots of the pouched samples were detected by a chemical-marker based computer vision method. Two MAP processes ($F_{90^\circ C}$ = 3 min and $F_{90^\circ C}$ = 10 min) targeting *Clostridium botulinum* type E spores were developed and compared with conventional hot water (HW) processes resulting in equivalent microbial safety. Compared with an equivalent HW process, MAP process greatly reduced the total processing time, reduced the cook values and improved quality uniformity of the products. Quality evaluation showed the impacts of MAP processing on each quality attribute of carrot products depended on the specific quality parameter selected.

1. Introduction

The increased public awareness of healthy diet and the needs for ready-to-eat foods make pasteurization an effective method to provide safe convenient foods with high quality. Microwave processing is one of the emerging thermal technologies applied to foods for pasteurization. It takes relatively short heating times (usually several minutes) due to its volumetric heating generated within food materials. The rapid heating results from interaction between the alternating electromagnetic field and dielectric materials, and it overcomes the slow heating of conventional thermal processes depending on conductive and convective heat transfer. Therefore, microwave pasteurization has the potential to produce high quality food products (Tang, 2015).

However, there are very limited publications about systemically design of a microwave pasteurization process for vegetable products, especially using 915 MHz microwaves which can provide deeper penetration depth and, therefore, more uniform heating than 2450 MHz microwaves used by the common domestic ovens. The major considerations for developing a pasteurization process include determining the most resistant pathogen that is likely to survive the process for the food; assessing and validating the required level of inactivation of the target microorganism; and evaluating appropriate storage temperature and shelf life (Peng et al., 2017). For microwave processing, non-uniformity heating caused by the uneven electric field distribution results in the cold and hot spots (the lowest and highest thermal energy reception areas) in the processed foods; and the thermal treatment at the coldest location in food package will determine the safety of the process. Thus, it is critical to detect the heating pattern and identify the cold spots in pre-packaged foods processed by microwave heating systems in order to meet the regulation requirements for food safety. Tang (2015) provides a historical overview on the development of 915 MHz single-mode microwave-assisted thermal sterilization and pasteurization systems, including system design, chemical marker methods for heating pattern determination, temperature measurement for process development, food quality and shelf-life studies. However, no case study is included to illustrate the complete process design for vegetable pasteurization using the 915 MHz microwave system. Lau and Tang (2002) applied 915 MHz microwaves to pasteurize pickled asparagus in glass bottles in a batch process. The process reduced process time by half and resulted in improved textural quality of the processed products compared with conventional water heating. Koskiniemi et al.

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(2013) established a pasteurization process to produce shelf-stable acidified vegetable packs (broccoli, red bell pepper, and sweetpotato) using continuous 915 MHz microwaves with a rotation apparatus. Good retention of color and texture of the processed vegetable pieces was observed, while no microbial spoilage was detected after 60-day storage at 30 °C. Both works mentioned above used fiber optic temperature sensors to monitor the temperatures of samples during microwave heating. The fiber optic temperature sensors were reliable and accurate, but not applicable for a continuous industrial process.

Carrots are one of the most commonly consumed vegetables in the United States, one-fourth of which are consumed in processed form, largely canned or frozen (Lucier and Lin, 2007). The objectives of this study were to develop a pilot-scale microwave-assisted pasteurization (MAP) process for pre-packaged carrots in brine using a 915 MHz single-mode microwave system, and evaluate the quality attributes of the products processed by MAP system and by conventional hot water (HW) pasteurization process on an equivalent microbial safety basis. This study should provide useful information for future commercial microwave pasteurization applications in vegetable processing.

2. Materials and methods

2.1. Sample preparation

The same batch of fresh carrots (Bolthouse Farms, Inc., Bakersfield, CA) were purchased from a local supermarket and stored at 4 °C. Carrots were cut into cuboids (12 × 12 × (6–8) mm) using a Hallde Flexi RG-7 dicer (Hicksville, NY) the same day right before processing. A total of 136.5 ± 0.5 g carrot cuboids and 90.5 ± 0.5 g brine (0.2% NaCl with 0.1% or 1.4% $CaCl_2$ in distilled water, w/w, total samples in each pouch) were filled into each 8-oz laminate polymer pouch (18.5 × 13.2 × 1.6 cm, Printpack Inc., Atlanta, GA). The salt NaCl was added to improve taste, while $CaCl_2$ was a firming agent to retain texture. The ratio of carrots to brine and the percentage of NaCl came from commercial canned carrot products. The two levels of $CaCl_2$ concentration came from our previous work (Peng et al., 2014); one was based on the FDA regulation for canned carrot products (0.036% Ca in the final products), the other one fell into the range of $CaCl_2$ concentration (0.5–2.0%) typically added to vegetable products in published reports (Rastogi et al., 2008; Smout et al., 2005). All filled pouches were sealed using an UltraVac 250 vacuum pouch sealer (KOCH Packaging Supplies Inc., Kansas City, MO) with vacuum setting −0.85 bar and sealing time setting 2 s. Prepared carrot pouches were loaded to the MAP or conventional heating system for processing immediately. The color and texture of the processed samples were measured on the same day of processing; the sample pouches for enzyme and carotenoids assay were stored at −30 °C until the day of analyses.

2.2. Thermal processing

The microwave and conventional thermal treatment levels were selected based on equivalent microbial safety (with the same F-value, the cumulative thermal lethality). For severe pasteurization of low-acid foods which allows a shelf life up to 6 weeks at 5 °C, a 6D process (6-log reduction) of psychrotrophic *Clostridium botulinum* is suitable; and a process of a minimum cumulative lethality of $F_{90°C} = 10$ min is generally recommended for most foods to achieve this goal (ECFF, 2006; Vervoort et al., 2012). For carrots, the target pathogen under this pasteurization level is non-proteolytic (NP) *C. botulinum* type E spores (Vervoort et al., 2012). In the current study, 90 °C was chosen as the processing temperature for the carrots samples based on our previous kinetic study of carrot texture degradation (Peng et al., 2014). The literature reported by Gaze and Brown (1990) studied the thermal resistance of NP *C. botulinum* type E spores in carrots at 75–90 °C and reported their D value of 0.48 min at 90 °C, therefore a 6D process of NP *C. botulinum* type E spores in carrots was calculated to be a process of $F_{90°C} = 2.88$ min. Thus, two thermal treatment levels were used in this study for carrots processing: one was $F_{90°C} = 3$ min which allows a 6D reduction of the target pathogen in carrots, the other one was $F_{90°C} = 10$ min which is generally considered as an adequate thermal pasteurization process for low-acid foods with a shelf life up to 6 weeks at 5 °C (ECFF, 2006).

2.2.1. Microwave processing

The microwave processing of pre-packaged carrots was performed in a pilot scale MAP system developed at Washington State University (Fig. 1). The MAP system used single-mode 915 MHz cavities, and consisted of four sections (preheating, microwave heating, holding and cooling). More details about the specially designed single-mode cavities can be found in Tang (2015). The preheating and cooling sections also played the roles of loading and unloading, respectively. Each section had a separated water circulation system to control water flow at a constant speed and temperature. The MAP system had two microwave heating cavities in the microwave heating section, with a total microwave power of 14 kW. Food pouches were preloaded in carriers that were transported on a conveyor through the four sections at a constant speed, which was adjusted to achieve the target process (desired F-values). After processing, sample pouches for color and texture measurements were held at 4 °C, and sample pouches for enzyme

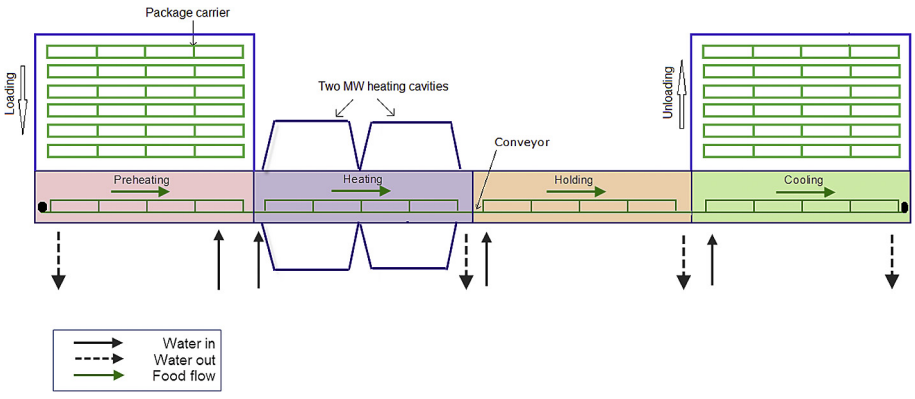

Fig. 1. Front view of the MAP system at Washington State University.

and carotenoids assay were stored at −30 °C.

2.2.2. Conventional hot water processing

Conventional HW heating was also conducted on the carrot pouches with the MAP system. During the HW processing, the settings of the system pressure and supply water temperatures were the same as for the MAP processing, only the microwave power was turned off. The holding time of food pouches in the holding section was adjusted to achieve the target process. After processing, sample pouches were stored at the same conditions as those for the MAP-processed samples.

2.3. Measurement of dielectric properties of carrot samples and selection of model foods

Detecting the heating pattern and cold spot inside the pre-packaged real foods processed by the MAP system is difficult. Therefore model foods with chemical marker precursors need to be developed to simulate the real foods for heating pattern determination. The dielectric properties of the model food should match those of the real food. Gellan gel has been demonstrated as a model food for microwave pasteurization processes in our previous work, and its dielectric properties can be adjusted to a wide range with different formulations to match with the real products (Zhang et al., 2015). Thus, gellan gel was used as the model food and formulated to match the carrot samples in their dielectric properties.

The dielectric properties of carrot samples were measured using an open-ended coaxial probe connected to an HP 8752C network analyzer (Hewlett Packard Corp., Santa Clara, CA, USA). Drained carrot cuboids were blended into puree before testing. The measurement of the dielectric properties of the carrot puree and the solution (0.2% NaCl with 0.1% or 1.4% $CaCl_2$ in distilled water) was carried out following the procedures explained in Peng et al. (2013). The dielectric properties (dielectric constant and loss factor) were measured over a frequency range of 300–3000 MHz at temperatures ranged between 22 and 100 °C. Each measurement was replicated three times.

2.4. Determination of the heating pattern and cold spot in sample pouches

The heating pattern and cold spots in carrot pouches during microwave processing were determined by a chemical–marker-based computer vision method (Pandit et al., 2007; Zhang et al., 2014). The model food gellan gel formulated to similar dielectric properties as carrot products was added with chemical marker precursors (D-ribose and lysine) and processed by the MAP system under the same processing conditions as those for carrot products. The chemical marker M2 (4-hydroxy-5-methyl-3(2H)-furanone) formed inside the model food through chemical marker precursors caused brown color changes. Positive correlations were established between the color intensity and the accumulative thermal lethality (F-value) as calculated from Eq. (1) (Pandit et al., 2007). The color changes in the gellan gel which reflect the distribution of M-2 and thermal lethality were detected using a computer vision method as described in Pandit et al. (2007). Based on our system design, the configuration of the microwave heating system for each cavity is symmetrical in the thickness direction (vertical line), as a result the electric field distribution is symmetrical, where the middle layer of homogenous samples receives the least energy (Resurreccion et al., 2013). This is confirmed by our previous work (Luan et al., 2016; Tang et al., 2008; Zhang et al., 2014). Therefore, the microwave pasteurized gellan gel model food was cut horizontally in the middle to get the middle layer images using the computer vision method mentioned above, and the heating pattern and cold spot of the gellan gel were determined. Since the selected model food (gellan gel) could simulate the pouched carrot samples in MW processing for heating pattern determination, the cold spot location of the samples was determined accordingly.

2.5. Heat penetration tests

Heat penetration tests were conducted to determine temperature profiles at the cold spot inside food packages during processing, the information was used to develop the desired process to achieve target microbial inactivation. For the processing of carrot samples, 90 °C was selected as the pasteurization temperature based on the kinetic results of carrot texture degradation (Peng et al., 2014). As explained in Section 2.2, two thermal treatment levels $F_{90°C} = 3$ min and $F_{90°C} = 10$ min were selected as the desired processes. The calculation of the F value was based on the following equation:

$$F = \int_{o}^{t} 10^{\frac{T-T_{ref}}{z}} dt \quad (1)$$

where T (°C) is the temperature measured at the cold spot at time t during process, T_{ref} is the reference temperature, and z is the z-value of the target bacteria in the products. In the current study, T_{ref} was 90 °C for carrots; z value was 9.84 °C for NP *C. botulinum* type E spores in carrots (Gaze and Brown, 1990).

Considering the moving pouches in the microwave system during processing, mobile metallic temperature sensors, TMI sensors (TMI-USA inc., Reston, VA, USA) were used to record the temperature profiles at the cold spot inside the sample pouches in the current study. More information about the mobile metallic temperature sensors and their use as reliable temperature measurement in continuous microwave processing can be found in a systematic study by Luan et al. (2013, 2015). Carrots and solution (0.2% NaCl with 0.1% or 1.4% $CaCl_2$, w/w) were added at a 1.5:1 ratio to bring the net weight of each pouch to 227.0 ± 1.0 g. The TMI sensor tip was inserted into a carrot cuboid, and a microwave transparent frame was used to fix the position of the TMI sensor tip at the cold spot of the sample pouch. Two prepared sample pouches with TMI sensors were loaded to the MAP system and processed along with other sample pouches in each test.

In the heat penetration tests for carrot samples, the system pressure for the MAP system was normal atmosphere; the total power for two microwave heating cavities was 14 kW; the circulating water temperatures were set to 61/93/93/20 °C for pre-heating, microwave heating, holding and cooling sections, respectively. The moving speed of the package carrier was adjusted to achieve the target processes. Tests were conducted in duplicates.

2.6. Quality evaluation

2.6.1. Color

The CIE L^* (lightness), a^* (redness), and b^* (yellowness) color attributes of the treated samples and raw control were determined using a computer vision system following the procedures explained in Kong et al. (2007). The color images were analyzed using Adobe PhotoShop. The “L”, “a” and “b” values under “Lab color model” from PhotoShop were recorded and then converted to standard CIE L^*, a^*, and b^* values using the following equations (Yam and Papadakis, 2004):

$$L^* = \frac{Ligtness}{255} \times 100 \quad (2)$$

$$a^* = \frac{240a}{255} - 120 \quad (3)$$

$$b^* = \frac{240b}{255} - 120 \quad (4)$$

The total color differences (ΔE) were calculated by the following equation:

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

where the raw samples were used as the control in the calculation of ΔE.

2.6.2. Texture

The firmness of treated carrots was determined using a TA.XT2 Texture analyzer (Stable Micro Systems Ltd., Godalming, UK) fitted with a 25 mm diameter aluminum cylinder probe following the methods described by Lemmens et al. (2009). The samples were compressed to 70% strain at a cross head speed of 1 mm/s. For each test, one piece of sample was placed under the probe. The maximum force (the peak value of the first compression of the sample) was recorded as the indicator of firmness. At least 6 replicates were measured for each treatment condition.

2.6.3. Pectin methylesterase (PME) activity

PME was extracted from carrots following the method by Vervoort et al. (2012) with some modification. Ten grams of homogenate was mixed with 0.2 M Tris-HCl buffer containing 1 M NaCl (pH 8.0, 1:1.3 w/v) and stirred at room temperature for 30 min.

The PME activity of the homogenate was quantified as the production of H^+ during pectin hydrolysis as a function of time at pH 7.0 and 30 °C, following the methods by Anthon and Barrett (2002) and Anthon et al. (2002). Briefly, 30 ml solution containing 0.25 M NaCl and 0.25% citrus pectin was equilibrated to 30 °C and adjusted to pH 7.0. One milliliter of homogenate was added to the solution and the pH was readjusted to 7.0 and maintained at this pH for 10 min by the addition of 0.01 M NaOH. The rate was calculated as μmol of NaOH consumed over a 10-min time period. The results were reported as percentages of the unheated control.

2.6.4. Carotene analysis

The extraction of carotene from the raw and processed carrots followed the methods described in Sadler et al. (1990) with modifications. Briefly, 5 g of carrot homogenate was mixed with 50 ml extraction solvent hexane-acetone-ethanol (2:1:1) containing 0.1% BHT and stirred for 20 min. After adding 15 ml milli-Q water to the mixture and stirred for another 10 min, the mixture was centrifuged at 600 × g for 8 min to separate the organic layer from the water layer. The organic layer was collected and filtered through a 0.45 μm syringe filter as the final extract for assay.

The total carotenoid content of the extract was measured by a spectrophotometer (Pharmacia Biotech Ltd., Cambridge, England) at 450 nm, the maximum absorbance wavelength of β-carotene. Hexane with 0.1% BHT was used as a blank. The total carotenoid concentration of the extract was calculated by Beer's law, with the extinction coefficient of β-carotene in hexane $E^{1\%}_{1cm} = 2560$. The α- and β-carotene contents of the carrot samples were determined by the method described by Vervoort et al. (2012), using an Agilent RP-HPLC system with a UV-DAD detector. A YMC Carotenoid column (150 × 4.6 mm, 5 μm) was used to separate the carotenoids through linear gradient elution from 100% solution A (81% methanol, 15% methyl-*t*-butyl ether, 4% milli-Q water) to 100% solution B (41% methanol, 55% methyl-*t*-butyl ether, 4% milli-Q water) in 28 min, held for 5 min, then returned to 100% solution A and equilibrated for 8 min. The flow rate was 1 ml/min and the detection wavelength was 450 nm. The standards of α- and β-carotenes were dissolve in hexane and used for standard curves.

2.7. Statistical analysis

Statistical analysis was conducted using SAS 9.2 (SAS Institute Inc., 2008). One-way analysis of variance (ANOVA) was used for all data. Differences among treatments by means were determined by least significant difference (LSD) multiple comparison test with significant level at $P < 0.05$.

3. Results and discussion

3.1. Dielectric properties of carrot samples and selection of model food

The dielectric properties of food materials reflect the interaction between the foods and electromagnetic energy. They include the dielectric constant (a material's ability to store electromagnetic energy) and dielectric loss factor (a material's ability to convert electromagnetic energy into thermal energy) (Nelson and Kraszewski, 1990). Due to the difficulty to detect the heating pattern and cold spot inside the prepackaged real foods during microwave processing, different model food and chemical marker systems were developed to simulate the real foods for heating pattern determination (Lau et al., 2003; Tang et al., 2008; Wang et al., 2009; Zhang et al., 2014). In the current study, gellan gel was used as the model food for heating pattern determination in MAP processes considering its relative low gelation temperature (<70 °C). Our previous work by Zhang et al. (2015) reported a wide range of dielectric properties of 1% gellan gel (with 6 mM Ca^{2+}) adjusted by various amounts of salt (0–300 mM NaCl) (Fig. 2). Regression equations relating the dielectric properties with gel formulation and temperature were also developed in that paper to calculate the formulation of gellan gel for a targeting dielectric property value. The comparison of dielectric properties of carrot samples (puree and solution) and the model food (1% gellan gel, 6 mM Ca^{2+}) with different amount of NaCl are shown in Fig. 2. Overall, the dielectric loss factors of the carrot puree and the solution (0.2% NaCl with 0.1% $CaCl_2$ in distilled water) were very close to each other at each temperature, ranged from 14 to 34 when the temperature increased from 22 °C to 100 °C. The dielectric constant of the carrot puree decreased from 72 to 58 when the temperature increased from 22 °C to 100 °C, and the solution from 76 to 58. In this case, the pouched samples can be seen as a whole (with similar dielectric properties of the two components). The model food gellan gel could simulate the pouched samples in microwave processing for heating pattern determination. From Fig. 2 it is also seen that the dielectric loss factor of carrot samples at each temperature matched well with the dielectric loss factor of gellan gel added with 40 mM NaCl calculated by the regression equations developed by Zhang et al. (2015). The calculated dielectric constant values of gellan gel added with 40 mM NaCl fell within the range of ±10% deviation of the real food's dielectric constants, and wouldn't change the heating pattern and cold spot location based on the computer simulation results (Resurreccion et al., 2015). Therefore, gellan gel (1% gellan gum, 6 mM Ca^{2+} and 40 mM NaCl) has similar dielectric properties to the carrot products, and was used as the model food (with 1% D-ribose and 0.5% L-lysine added as chemical marker precursors) for heating pattern and cold spot determination.

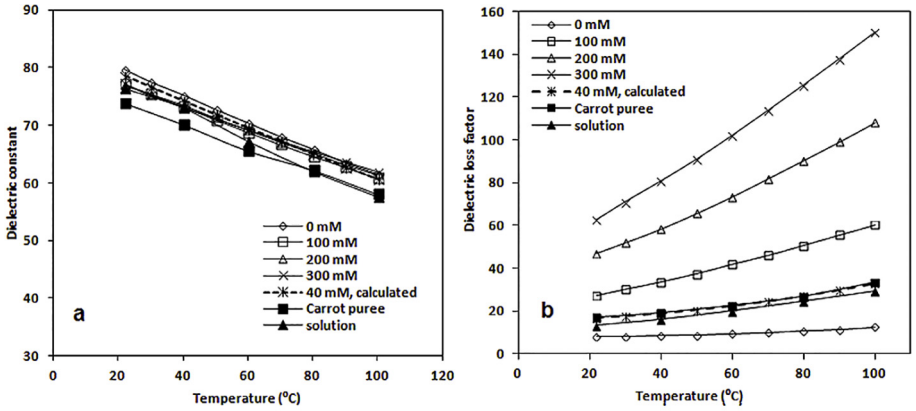

Fig. 2. Dielectric constant (a) and loss factor (b) at 915 MHz for carrot samples and gellan gel with NaCl (0–300 mM). Data related to gellan gel was adapted from Zhang et al. (2015).

3.2. Heating pattern and cold spot in sample pouches

Chemical marker method is an effective way for determining the cold spots in foods during a microwave process (Pandit et al., 2007). The heating pattern in carrot pouches obtained by the chemical-marker-based computer vision method using gellan gel as the model food is shown in Fig. 3. Based on our previous work by applying computer vision method to heating pattern determination, the gel model food is shown in colors ranging from blue for the coldest temperatures to red for the hottest (Zhang et al., 2014). It can be seen from Fig. 3 that the blue color region showed up around the origin (0, 0) mm. Therefore, the cold spot is located at the center of the middle layer in the carrot sample pouch.

3.3. Heat penetration results

Processing conditions for both microwave and conventional pasteurization were selected to result in equivalent microbial safety. For the MAP processing, the loaded samples stayed at the preheating section and were preheated at 60 °C for 20 min, then consecutively passed through the microwave section, holding section (90 °C) and cooling section (20 °C). The moving speed of the package carrier was set at 42 and 39 inch/min to achieve a process of $F_{90°C}$ = 3 min and $F_{90°C}$ = 10 min, respectively. The total processing time was calculated starting from the sample getting into the microwave section and ending at the sample coming out of the holding section. It was 3.22 min for $F_{90°C}$ = 3 min MAP process and 4.96 min for $F_{90°C}$ = 10 min MAP process. Fig. 4A shows the typical temperature profile of the carrot samples recorded by the TIM sensor during microwave processing ($F_{90°C}$ = 10 min).

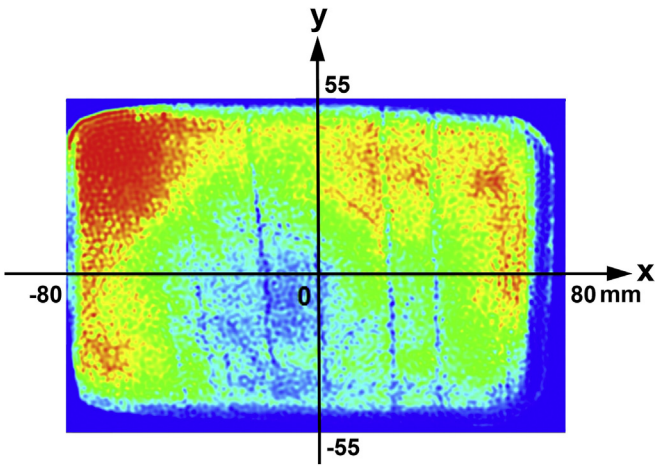

Fig. 3. Heating pattern in gellan gel model food (top view, middle layer) processed by a 915 MHz single mode microwave pasteurization system. Colors range from blue for the coldest temperatures to red for the hottest. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For conventional hot water processing with the MAP system, the holding time of the samples in the holding section was selected to be 7.80 and 13.96 min to achieve an equivalent process with F value at 90 °C for 3 min and 10 min, respectively. Fig. 4B shows the typical temperature-time profile at the cold spot in the sample pouch during the HW process for a target process of $F_{90°C}$ = 10 min. The processing parameters to achieve the target processes for carrots by microwave and hot water are summarized in Table 1. It can be seen that for an equivalent process of $F_{90°C}$ = 3 min, the total processing time by MAP (3.22 min) was reduced by half compared with the HW process (7.80 min), and by 2/3 compared with the HW process for an equivalent $F_{90°C}$ = 10 min process.

Cook value *C* is often used to evaluate the impact of a thermal process on food quality by volumetric integration of quality losses throughout the foods. It was calculated from Eq. (6) using time-temperature data obtained in heat penetration test (Tang et al., 2008):

$$C = \int_0^t 10^{\frac{T(t)-T_{ref}}{z}} dt \quad (6)$$

where T_{ref} is 100 °C, z is 33.1 °C based on the average of deterioration of chemical components in foods, and T(t) is the product temperature at time t. The calculation started from samples getting into the preheating section and ended at samples coming out of the cooling section. Since the pouch film was very thin, carrot pieces close to pouch films could be assumed fully exposed to the circulation water as the worst case of quality deterioration during heating processes. Therefore, *C* values of carrots on the surfaces were estimated using the circulation water temperatures. *C* values were also calculated for carrots at the geometric center of the packages using temperature data from the heat penetration tests. The *C* values for carrots after MAP and HW processing are summarized in Table 1. It can be seen that HW processes resulted in higher *C* values compared with an equivalent MAP processes. For example, the *C* value for carrots at the package center was 7.91 min for the HW process, and 4.96 min for the MAP process with the heating intensity of $F_{90°C}$ = 10 min. These results indicated that the overall quality attributes of carrot samples processed by MAP had

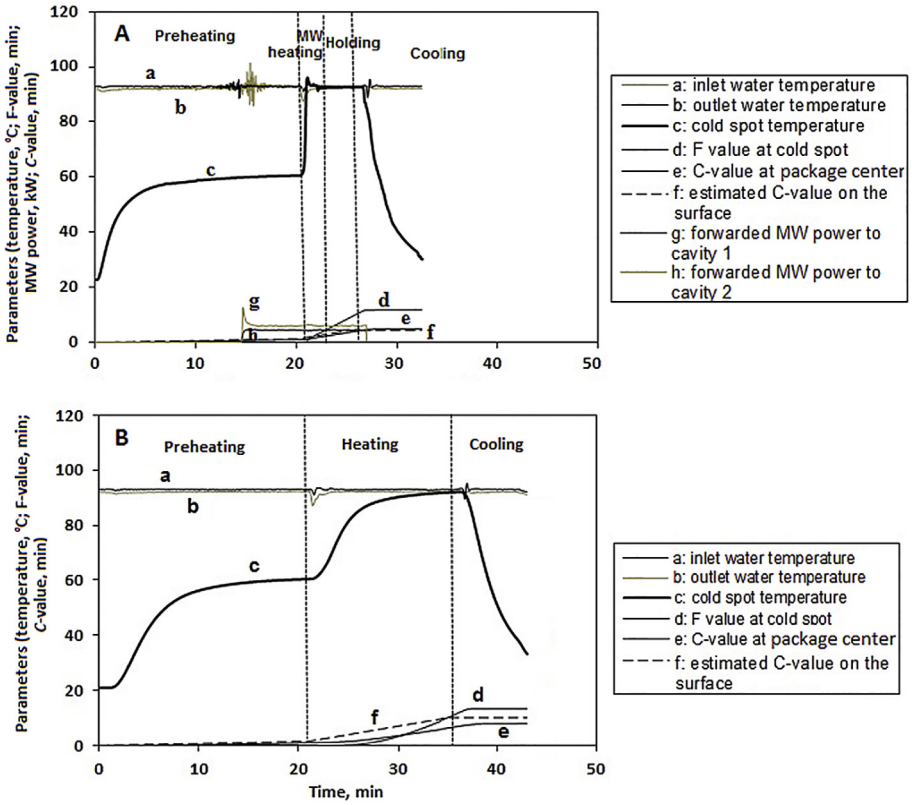

Fig. 4. Example of temperature-time profiles of the cold spot in the carrot pouch under MAP (A, $F_{90°C} = 10$ min) and HW (B, $F_{90°C} = 10$ min) processing with preheating at 60 °C for 20 min.

Table 1
Processing conditions for equivalent MAP and conventional HW processes with regard to microbial safety.

	Processing levels	$F_{90°C} = 3$ min	$F_{90°C} = 10$ min
MAP processing	Water temperature setting (preheating/MW heating/holding/cooling)	61/93/93/20 °C	
	Preheating time (min)	20	20
	MW heating time (min)	1.36	1.46
	Holding time (min)	1.86	3.50
	Total processing time (min)	3.22	4.96
	C_{center} (min)	3.28	4.96
	$C_{surface}$ (min)	3.36	4.44
HW processing	Preheating time (min)	20	20
	Total processing time (min)	7.80	13.96
	C_{center} (min)	4.43	7.91
	$C_{surface}$ (min)	6.14	10.08

C_{center} denotes the cook value for carrots at the geometric center of the package, and $C_{surface}$ denotes the estimated cook value for carrots close to the surface of pouch film.

less thermal deterioration compared with those of the samples treated by traditional HW process at the same heating intensity. Differences of *C* values between carrots at package center and the surface of pouch film were much smaller for a MAP process compared with a HW process, indicating better quality uniformity in products processed by MAP. Slightly higher *C* value at package center than on the surface of pouch film was observed in the $F_{90°C} = 10$ min MAP process. This resulted from the accumulative thermal effect during a slower cooling at the package center, suggesting samples locating at the other parts of the pouch might be heated more than those on the surface in a short MAP process.

3.4. Quality evaluation

3.4.1. Color

The CIE LAB color values of raw and processed carrot cuboids are given in Table 2. Both MAP and HW processes significantly reduced a^* values in the carrot samples, from 48.32 of raw carrots to 38.40–42.90 of processed ones, 11–20% reduction compared with the initial value. All carrots processed by MAP had slightly higher a^* values than those by HW heating under the same conditions (process intensity and calcium concentration), and significant difference was found in samples with 1.4% $CaCl_2$ at F = 10 min processing level. For b^* values, no significant difference was found between the raw and MAP-processed carrots. However, the difference in b^* values was significant between the raw and HW-processed carrots either in 0.1% $CaCl_2$ at F = 3 min processing level or in 1.4% $CaCl_2$ at F = 10 min processing level. The overall L^* values of processed carrots remained relatively stable compared to those of raw samples (with values around 61–63), though two MAP-processed and one HW-processed carrots showed significant higher values. The changes in the a^* and b^* values indicate a

Table 2
CIE L*, a*, b* values, and total color differences (ΔE) of diced carrots under different treatments. The color attributes of raw carrots were used as the control. For each parameter (values in the same column), significant differences ($p < 0.05$) are indicated with different letters, and values marked with a same letter are not significantly different.

Treatments		L*	a*	b*	Total color difference (ΔE)
Untreated		61.68 ± 0.60^{c}	48.32 ± 0.57^{a}	59.51 ± 0.60^{bc}	
0.1% $CaCl_2$	$F_{3min,\ MAP}$	61.15 ± 1.38^{c}	42.90 ± 2.14^{b}	58.55 ± 1.36^{c}	5.54
	$F_{3min,\ HW}$	61.17 ± 0.95^{c}	42.84 ± 3.09^{b}	61.14 ± 0.70^{a}	5.74
	$F_{10min,\ MAP}$	62.92 ± 2.06^{ab}	42.62 ± 3.23^{b}	59.13 ± 1.64^{c}	5.84
	$F_{10min,\ HW}$	61.19 ± 1.44^{c}	40.16 ± 2.85^{bc}	59.17 ± 1.54^{c}	8.18
1.4% $CaCl_2$	$F_{3min,\ MAP}$	63.07 ± 0.93^{ab}	41.84 ± 2.51^{bc}	58.64 ± 1.45^{c}	6.69
	$F_{3min,\ HW}$	62.24 ± 1.75^{abc}	39.79 ± 3.97^{bc}	60.83 ± 1.04^{ab}	8.65
	$F_{10min,\ MAP}$	62.16 ± 0.93^{abc}	42.26 ± 3.99^{b}	58.88 ± 1.44^{c}	6.30
	$F_{10min,\ HW}$	63.57 ± 2.07^{a}	38.40 ± 3.66^{c}	61.62 ± 1.60^{a}	10.32

deterioration of initial intense orange color of the carrots, which were mainly related to the carotenoids that might undergo degradation and isomerization during thermal processing.

Total color differences (ΔE) between the processed samples and their control (raw carrots) are also summarized in Table 2. Theoretically speaking, a ΔE of 1 represents a just-noticeable color difference to the human eyes under ideal viewing conditions; while ΔE values between 2 and 3 could be considered equivalent by some viewers in less than ideal lighting (Vervoort et al., 2012). From Table 2 it is clear that all the ΔE values were higher than 3, suggesting that the color differences between all the processed carrots and the untreated ones are perceptible by human eyes under normal lighting conditions. Carrot cuboids in the 1.4% $CaCl_2$ solution processed by HW with $F_{90°C} = 10$ min had the largest ΔE value, denoting the least color retention of the carrots. The ΔE values of processed carrots varied from 5.54 to 10.32, and all carrot samples processed by microwave heating have lower ΔE values than those by hot water under same conditions, denoting a better color retention. This might be due to the shorter heating time of MAP processing compared with HW processing.

3.4.2. Texture

Texture changes of carrots under different processing conditions are shown in Fig. 5. Apparent texture loss was observed in all processed carrot samples compared with the raw samples, and the texture decreased with increased heating intensity. The texture loss of carrot cuboids with $F_{90°C} = 3$ min processing was 27–30% in 0.1% $CaCl_2$ and 16–21% in 1.4% $CaCl_2$ respectively, while the values were 45–50% in 0.1% $CaCl_2$ and 21–25% in 1.4% $CaCl_2$ with $F_{90°C} = 10$ min processing. The firming efforts of calcium on texture were obvious from the results, higher concentration of calcium led to a better texture retention. This can be explained by interaction of calcium with the pectins in the cell wall and middle lamella, which improved structural integrity and resulted in a firmer texture. Our results show that increasing calcium concentration from 0.1% to 1.4% at $F_{90°C} = 3$ min treatment reduced the texture loss by 1/3, while the value improved to 1/2 at $F_{90°C} = 10$ min treatment. The firming effects of calcium were more apparent at increased thermal processing. Texture loss of processed vegetables mainly attributes to the breakdown of cellular membranes and the cell wall degradation resulting from enzymatic and non-enzymatic transformations of pectic polymers (Anthon et al., 2005; Sila et al., 2008). The breakdown of cellular membranes resulting from turgor loss occurs at a fast phase under high temperature treatment while the changes in cell wall structure, particularly from β-elimination cleavage of pectins occur at a slower phase (Anthon et al., 2005). For low-acid carrots, β-elimination of pectins is the major contributor to texture loss during high-temperature processing. Calcium addition to carrots during the low-temperature preheating period may reduce the extent of β-elimination which occurs at a slow phase and in pectins with methyl ester group only. This explains that calcium treatment for a longer time and at increased heat intensity is more effective. It can be seen from Fig. 5 that under the same heating intensity, the texture of carrot samples processed by MAP heating and HW processing was not significantly different. .

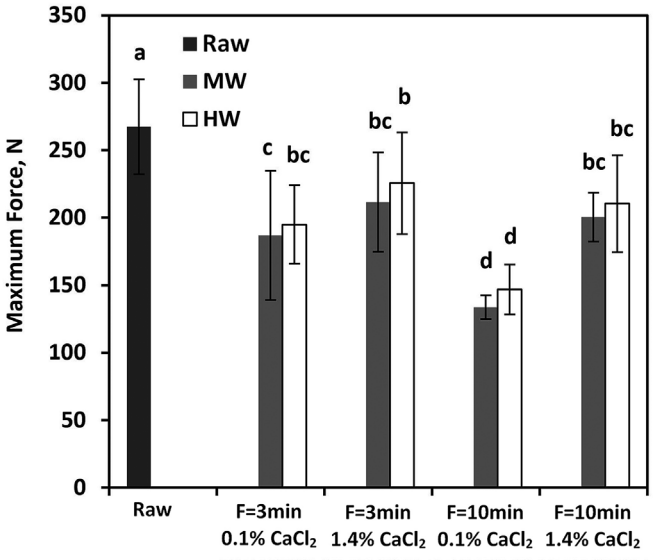

Fig. 5. Texture of carrot cuboids under different treatments. Columns labeled with the same letters are not significant different ($p < 0.05$).

3.4.3. PME (pectin methylesterase) activity

PME is one endogenous enzyme that plays an important role in stabilizing the cell wall structure of carrots. PME can catalyze the de-esterification of pectins, creating binding sites for divalent cations (primarily Ca^{2+}, naturally present in the tissue or added during processing) on the polygalacturonic acid backbone of the pectin to form cross-links between pectin chains, which improves the texture. In the current study, no PME activity was detected in the processed products under the two processing intensities. The results indicate that after a preheating treatment of 60 °C for 20 min, heating at 90 °C for even 3.22 min could cause a complete loss of PME activity in the pasteurization processes of carrots. This is in agreement with the published papers that most PMEs are heat sensitive. Anthon and Barrett (2002) studied the kinetics of thermal inactivation of PMEs in carrot juice, and reported $D_{65.7°C} = 5$ min for the labile form and $D_{70.5°C} = 5$ min for the resistant form. Lemmens et al. (2009) studied the thermal pretreatments of carrot pieces using different heating techniques, and reported no PME activity detected in the samples blanched at 90 °C for 4 min.

3.4.4. Carotenoids

Carotenoids are responsible for the bright orange color of carrots, and α- and β-carotene are the two major carotenoids in carrots. The total carotenoids, α- and β-carotene contents in raw and processed carrot products are shown in Fig. 6. In raw carrots, the dry weight of the total carotenoids, α- and β-carotene contents are 130.13 ± 3.35, 34.15 ± 1.04 and 93.64 ± 3.12 mg/100 g, respectively. Both MAP and HW processing significantly reduced the contents of the total carotenoids, α- and β-carotene in the final carrot products. Thermal processes for $F_{90°C} = 3$ min caused a loss of 15–23% in total carotenoids compared with the initial value; for $F_{90°C} = 10$ min, the loss was 19–35%. For β-carotene, the loss was 11–20% for the processes achieving $F_{90°C} = 3$ min and 17–37% for the processing of $F_{90°C} = 10$ min. The α-carotene seems to be more heat sensitive than β-carotene at the low heat intensity, with 22–30% loss for a process of $F_{90°C} = 3$ min. In most cases, no significant differences were found in the carotenoids for samples processed by MAP and HW heating. However, for carrots in 1.4% $CaCl_2$ solution by processing with $F_{90°C} = 10$ min, the total carotenoids and β-carotene losses by MAP heating were larger than HW processing. One possible reason might be the longer time heating of HW processing causing more cell disruption of carrot tissue, which resulted in an improved extractability of the carotenoids. Vervoort et al. (2012) also observed a decrease of α- and β-carotene contents in carrot products going from mild pasteurization at 70 °C to sterilization. However, Knockaert et al. (2011) reported an increased β-carotene content in sterilized carrots after a process of $F_0 = 3$min.

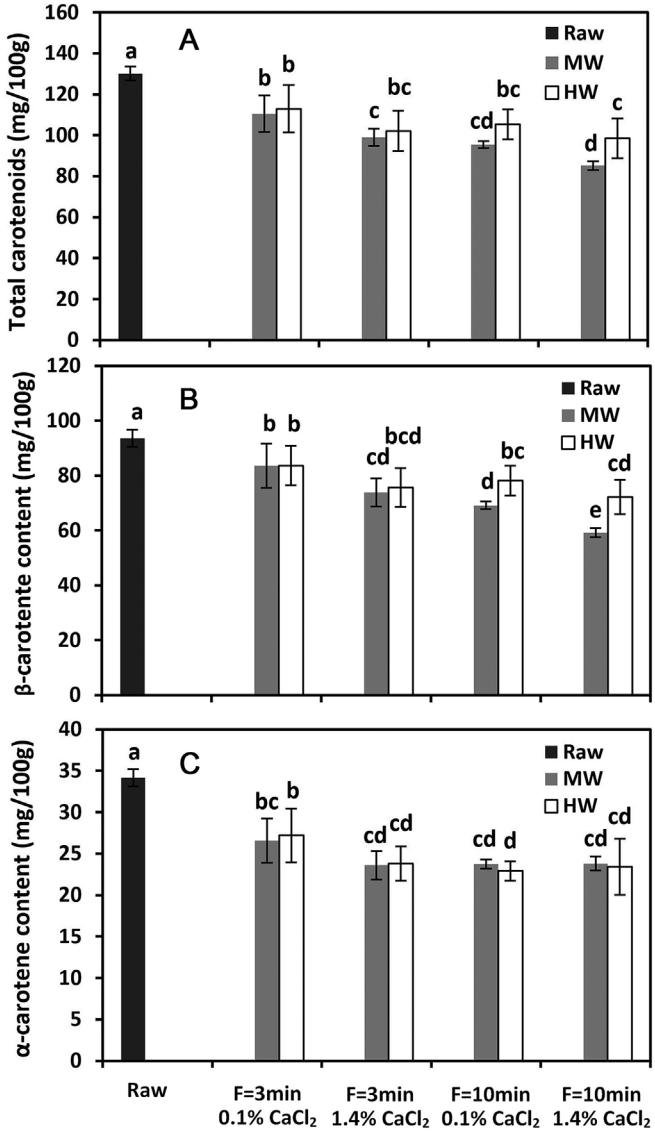

Fig. 6. Total carotenoids content, α- and β-carotene contents in carrot products under different treatments. Columns labeled with the same letters are not significant different ($p < 0.05$).

4. Conclusions

This study demonstrated the applicability of using a 915 MHz single-mode microwave-assisted pasteurization (MAP) system in pasteurizing pre-packaged carrots in brine. Gellan gel (1% gellan gum, 6 mM Ca^{2+}, 40 mM NaCl, 1% D-ribose and 0.5% L-lysine) was formulated and chosen as the model food to simulate the carrot samples for heating pattern and cold spot determination. The cold spot location detected by a chemical-marker based computer vision method was at the center of the middle layer in the carrot sample pouch. Two MAP processes ($F_{90°C} = 3$ min and $F_{90°C} = 10$ min) were established for carrot cuboids in brine (with NaCl & $CaCl_2$ added in distilled water) pre-packaged in 8-oz polymer pouches, along with conventional HW processes resulting in equivalent microbial safety. The total processing time of a MAP process was greatly reduced compared with an equivalent HW process (reduced by 1/2 for a process of $F_{90°C} = 3$ min and 2/3 for a process of $F_{90°C} = 10$ min). MAP process also reduced the cook values and improved the quality uniformity of carrots compared with an equivalent HW process, indicating less thermal deterioration of the overall quality in MAP-processed samples.

Our results showed that the impacts of MW processing on each quality attribute of carrot products depended on the specific quality parameter selected. For color, all carrot samples processed by MAP had lower ΔE values and slightly higher a^* values than those by HW under same conditions, denoting a better color retention in MAP-processed samples. No significant differences of texture and PME activities were found in carrots processed by MAP and HW under all treatments. In most cases, no significant differences were found in the carotenoids for samples processed by MAP and HW heating. Only for carrots in 1.4% $CaCl_2$ solution with severe process of $F_{90°C} = 10$ min, the β-carotene loss (also the total carotenoids loss) by MAP heating was larger than HW heating, which was probably caused by improved extractability of the carotenoids due to the longer and more intense HW heating. Since all the quality attributes of pasteurized carrots were tested and compared immediately after processing only, further work should be carried out to investigate the quality changes during the shelf life of products. Further systematic research is also needed to optimize MAP system and process designs for improvement in the product quality. Our team has developed new carrier designs to improve heating uniformity since this study. Future optimized MAP processes should take advantage of short heating time while considering different sensitivities of food quality attributes to thermal degradation.

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