Green Pea and Garlic Puree Model Food Development for Thermal Pasteurization Process Quality Evaluation

Ellen R. Bornhorst, Juming Tang, Shyam S. Sablani, Gustavo V. Barbosa-Cánovas, and Fang Liu

Abstract: Development and selection of model foods is a critical part of microwave thermal process development, simulation validation, and optimization. Previously developed model foods for pasteurization process evaluation utilized Maillard reaction products as the time–temperature integrators, which resulted in similar temperature sensitivity among the models. The aim of this research was to develop additional model foods based on different time–temperature integrators, determine their dielectric properties and color change kinetics, and validate the optimal model food in hot water and microwave-assisted pasteurization processes. Color, quantified using a^* value, was selected as the time–temperature indicator for green pea and garlic puree model foods. Results showed 915 MHz microwaves had a greater penetration depth into the green pea model food than the garlic. a^* value reaction rates for the green pea model were approximately 4 times slower than in the garlic model food; slower reaction rates were preferred for the application of model food in this study, that is quality evaluation for a target process of 90 °C for 10 min at the cold spot. Pasteurization validation used the green pea model food and results showed that there were quantifiable differences between the color of the unheated control, hot water pasteurization, and microwave-assisted thermal pasteurization system. Both model foods developed in this research could be utilized for quality assessment and optimization of various thermal pasteurization processes.

Keywords: color, dielectric properties, food quality, kinetics, pasteurization

Practical Application: Green pea and garlic model foods could be used by the food industry to optimize thermal pasteurization processes and evaluate the potential food quality of various processes. The green pea model food would be most applicable for quality evaluation of a target process of 90 °C for 10 min, whereas the garlic model would be better for a milder heat treatment, such as a target process of 70 °C for 2 min.

Introduction

Pasteurization is a common food preservation method that aims to destroy microorganisms that are pathogenic to humans and extend the shelf life of food products by reducing the microbial load. In order to achieve a minimum 6 log reduction of a target pathogen in pre-packaged food, an equivalent heat treatment of 90 °C for 10 min has been recommended for the control of nonproteolytic *Clostridium botulinum* spores and 70 °C for 2 min for *Listeria monocytogenes* (ECFF 2006; FDA 2011). Nonproteolytic *C. botulinum* spores were the pathogen of interest in this research.

Thermal pasteurization could be optimized to improve product quality while maintaining safety. Previous work has shown that high temperature, short time processes are ideal for producing high-quality, safe food (Holdsworth 1997). This concept has been leveraged in the development of a microwave-assisted pasteurization system (MAPS) with 915 MHz at Washington State Univ. (Tang 2015). A key advantage of the MAPS is that it heats food rapidly and shortens the come-up time for the product to reach the target temperature; this yields a safely pasteurized product with an improved quality (Tang 2015). However, there are still challenges in using microwaves for thermal processing, especially with nonuniform heating (Ohlsson and Bengtsson 2001). During the design and optimization of the MAPS, it is critical to have tools to visualize the heating pattern of food products. Obtaining multipoint temperature measurements throughout the product to visualize the temperature distribution and heating pattern is not practical in a pilot-scale system, such as the MAPS. Thus, single-point temperature measurements are combined with computer simulation and model foods to predict, visualize, and validate the temperature distribution in microwaved processed foods (Tang 2015).

Selection of appropriate model foods is a critical part of microwave process development. Ideal model foods should be easy to cut, have a low-temperature exposure of the prepared model, short preparation time, dielectric properties similar to food products, measurable amount of a time–temperature indicator (TTI), and large range of reaction rates of the TTI (Bornhorst and others 2017a). Model foods with large ranges of reaction rates and differing temperature sensitivities are benefical because this provides the researcher with more options in matching the model system to pathogen or food quality degradation reaction rates (Bornhorst and others 2017a).

In order to successfully employ model food systems in determining the heating pattern of real foods heated in microwave processes, it is critical to match the dielectric properties of model foods to real

JFDS-2016-1670 Submitted 10/10/2016, Accepted 4/13/2017. *Dept. of Biological Systems Engineering, Washington State Univ., L.J. Smith 204, P.O. Box 64120, Pullman, WA 99164-6120, U.S.A. Direct inquiries to author Tang (E-mail: jtang@wsu.edu).*

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foods or food categories of interest. Model foods can be designed or modified according to the desired dielectric properties. Documenting baseline dielectric properties of the model food systems is paramount before additional formula adjustments can be made (Zhang and others 2015). Dielectric properties are also inputs in computer simulations for predictive modeling of microwave processes; accurate simulations of model foods would be difficult without these properties. For these reasons, the dielectric properties of developed model food systems were measured in this study.

Previous work on model food system development for microwave process evaluation focused on process lethality applications (Lau and others 2003; Pandit and others 2006, 2007b; Zhang 2014; Zhang and others 2014), with a few more recent studies examining potential applications of these types of models for quality assessment (Bornhorst and others 2017a; Bornhorst and others 2017b). Model foods developed to evaluate process lethality are not ideal to evaluate food quality because of the differing temperature sensitivity and reaction rates of each application (pathogens vs. quality attributes). Foodborne pathogens, such as vegetative cells, spores, and viruses, usually have a higher thermal sensitivity with typical *z*-values of 4 to 20 °C, compared to quality attributes, such as vitamins, proteins, texture degradation, color change, and overall sensory quality with typical *z*-values of 15 to 50 °C (Holdsworth 1997; Peng and others 2017). Previously mentioned studies on model food development for microwave pasteurization evaluation all utilized Maillard reaction products (that is, chemical marker and brown color formation) as the time–temperature integrators, reporting *z*-values between 10 and 29 °C (Bornhorst and others 2017b). This *z*-value range is applicable to the temperature sensitivity of many food pathogens and some quality attributes with smaller *z*-values. However, these previously developed model foods are not applicable to many quality attributes that are less sensitive to temperature change, with z-values greater than 30 °C. Therefore, it is of interest to develop additional model foods with different time-temperature integrators and varying color formation mechanisms to expand the range of temperature sensitivities in the model food systems to include larger *z*-values.

According to Tucker and others (2009), a TTI is any property that changes during heating in a predictable way, including physical properties, enzymes, nutrients, and colors. Color was selected as the desired TTI for model food development; this is based on the principle that color change in food during heating is an indicator of a decrease in food quality perception. Various fruit and vegetable purees were considered during a preliminary study to determine those that would be most relevant for pasteurization quality assessment. Based on the initial results, green pea and garlic purees were selected as the most relevant because both samples showed significant color change during heating at 90 °C. Both green pea and garlic puree model foods are unique and have not been previously studied for pasteurization process quality evaluation or in evaluating microwave processes. Previous work has utilized whole green peas as a model food for canning processes at sterilization temperatures (Smout and others 2003; Simpson and others 2008), but these studies did not consider pasteurization or microwave processes. The objectives of this study were to (1) develop green pea and garlic model foods for use in MAPS process quality evaluation, (2) determine the models' dielectric properties and color change kinetics at pasteurization temperatures, and (3) perform a validation with the optimal model food using MAPS and hot water pasteurization processes.

Materials and Methods

Model food preparation

The green pea model food was prepared by thawing frozen green peas (Better Living Brands LLC, Pleasanton, Calif., U.S.A.) in 40 °C water, pureeing the green peas using a Vitamix blender (Vitamix 7500 machine, Vitamix Corp., Cleveland, Ohio, U.S.A.), and adding 1% low acyl gellan gum (Kelcogel® F Food grade gellan gum, supplied by CP Kelco Inc., Atlanta, Ga., U.S.A.). The garlic model food was prepared by pureeing fresh garlic (Christopher Ranch Co., Gilroy, Calif., U.S.A.) using a Vitamix blender, and adding 2% low acyl gellan gum. Low acyl gellan was added to the green pea and garlic purees in order to produce model foods with a firm texture after heating and cooling to ambient temperature.

Low acyl gellan was selected instead of other gels because it is effective with low concentrations and in the presence of cations, it forms a strong, brittle, and stable gel (Tang and others 1994; Morris and others 2012). After heating low acyl gellan in water to approximately 90 °C, the gellan dissolves into solution and cations are added to facilitate the gel setting, which typically occurs upon cooling to 30 to 50 °C (Tang and others 1997; CP Kelco 2007; Morris and others 2012). Firm gels formed with low acyl gellan are heat stable and not thermally reversible; gels can withstand heating processes, such as thermal pasteurization (CP Kelco 2007; Morris and others 2012). Heat stability was essential for the gum added to the puree model food systems; the prepared model foods had to maintain the consistency of a firm gel before, during, and after thermal pasteurization for accurate heating pattern determination. Additionally, previous work (Zhang and others 2015; Bornhorst and others 2017a) on the development of model foods with Maillard reaction products for pasteurization applications showed promising results using low acyl gellan gum in model food formulations.

Dielectric properties

Dielectric properties (constant and loss factor) of the model foods were measured using the system set-up and method from Wang and others (2003) and Zhang and others (2013). The system included an 8752 C network analyzer with a frequency range of 300 to 3000 MHz (Hewlett Packard Inc., Palo Alto, Calif., U.S.A.), 85070B dielectric probe (Agilent Technologies, Santa Clara, Calif., U.S.A.), high temperature coaxial cable, custom-designed, jacketed stainless steel test cell with 20 mm inner diameter and 94 mm inner height, and desktop computer with custom-designed software for data logging and impedance analysis (DMS 85070, Innovative Measurement Solutions Inc., Milford, Conn., U.S.A.). The system was warmed up for a minimum of 30 min and calibrated before each sample measurement using an open circuit with air, a short circuit with a gold plated shorting block, and a known load with DDI water at 25 °C (Wang and others 2003). The temperature of the center of the test cell was measured with a calibrated type-T thermocouple and the temperature was controlled using a recirculating liquid bath with 90% ethylene glycol and 10% water that supplied warm liquid to the test cell jacket. Four replicate measurements were taken for each model food from 20 to 100 °C in 10 °C steps and at each temperature, the dielectric properties from 300 to 3000 MHz were recorded in 7.5 MHz steps. However, only 915 MHz data were reported in this study because this is the only frequency used in the MAPS.

The penetration depth of the microwaves into a food sample is typically defined as the depth where the electromagnetic wave's

power has decayed to $1/e \approx 37\%$ of the power at the surface (Schubert and Regier 2005). Penetration depth, d_p (m), of microwaves into the model food samples was calculated by (Schubert and Regier 2005):

$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon' \left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]}} \quad (1)$$

where c is the speed of light in free space (3×10^8 m/s), f is the frequency (Hz), ε' is the dielectric constant (dimensionless), and ε'' is the dielectric loss factor (dimensionless).

Kinetic study

Model food samples were heated in small, cylindrical, aluminum test cells with 1 mL capacity (Chung and others 2008) using a water bath at 70, 80, and 90 °C and an ethylene glycol bath at 100 °C (Haake DC 30, Thermo Fisher Scientific Inc., Newington, N.H., U.S.A.). The come-up time (CUT), or the time for the coldest spot of the sample to reach within 0.5 °C of the target temperature (Zhang and others 2014), was measured to be 1.75 min by a calibrated type-T thermocouple for all temperatures. The CUT was within 15 s for all model foods and temperatures, likely due to the small sample size (1 mL) and the test cells that were custom designed to minimize CUT. Following heat treatment, the samples were cooled in ice water (0 °C). Both model foods were heated at 70 °C from 5 to 180 min, 80 °C from 5 to 150 min, 90 °C from 5 to 120 min, and 100 °C from 5 to 90 min; all times were excluding CUT and tests were performed in triplicate. The times were chosen to encompass shorter MAPS and conventional pasteurization methods, as well as longer times to determine the color change saturation at each temperature.

The color of each model food sample was measured with a computer vision system in $L^*a^*b^*$ or CIELAB color space. The computer vision system included controlled lighting using a light pod and compact fluorescent light bulbs, a camera connected to a computer, and image analysis using MATLAB R2013a to apply a color correction and analyze 37695 pixel values of each sample (Pandit and others 2007a; Bornhorst and others 2017a). These pixel values were averaged to obtain the color of each model food sample; 3 separate samples (3 replicates) were analyzed for all time points. Pictures were taken using fixed camera settings of 15 frames per second speed, 200 ISO, and F 11 (aperture value). A standard color card (QPcard 203, QPcard AB is Helsingborg, Sweden.) was employed in the color correction and transformation of images from RGB to $L^*a^*b^*$ using a quadratic model with a nonlinear least squares fitting approach (Leon and others 2006).

Data analysis—kinetic study

SAS® 9.2 was utilized for data analysis. At each temperature, correlation analysis was performed using Pearson correlation coefficients to determine the correlation strength between color or L^*, a^*, and b^* values, and heating time. Strong correlation was defined as a Pearson correlation coefficient >0.7, moderate correlation was 0.5 to 0.7, and weak correlation was <0.5, with p-value <0.05 for significance. Color parameters with strong, significant correlations to heating time were utilized in regression analysis.

As described in Lau and others (2003), a modified 2-step regression method was employed to calculate the color change reaction kinetics for both model foods. This regression method was selected over other techniques based on the results presented in Lau and others (2003). Briefly, this method consisted of 2 steps: step one was to determine the reaction order and rate constants for color change at each temperature and step 2 was to model the effect of temperature on the reaction rate. In step one, zero-, first-, and second-order rate equations were fit to the color data using non-linear regression. As an example, the generalized first order equation was expressed as (Lau and others 2003):

$$C = C_\infty - (C_\infty - C_0)\exp(-kt) \quad (2)$$

where C is the color (a^*) at time t (min), C_0 is the initial color (a_0^*), C_∞ is the color at saturation (a_∞^*), and k is the reaction rate constant (min^{-1}). At each temperature, nonlinear regression fitting was conducted using the Newton algorithm in order to determine C_0, C_∞, and k for the color components (a^*). To find the best fitting rate equation, coefficients of determination (R^2) were calculated during regression analysis.

In step 2, the influence of temperature change on reaction rate was described using the Arrhenius equation (Toledo 2007):

$$k = A_0 \exp\left(-\frac{E_a}{RT}\right) \quad (3)$$

where k is the reaction rate (min^{-1}) at temperature T (K), E_a is the activation energy (kJ/mol^{-1}), A_0 is the rate constant (min^{-1}) as T approaches infinity, and R is the universal gas constant ($kJ/K/mol^{-1}$).

The sensitivity of quality attributes to heat is commonly reported using the Bigelow model. Decimal reduction time (D-value), the time required for the color to change by one log at a constant temperature, was determined from the reaction rate constant (Toledo 2007). Thermal resistance constant (z-value), the temperature difference required for the D-values to change by one log, was determined from the activation energy (Toledo 2007). D- and z-values were calculated to expedite comparison to previous studies and improve the ease of using results from this study in future work.

Accumulated cook value, C_{100}, is a common food quality indicator used by thermal processors and was calculated by (Toledo 2007):

$$C_{100} = \int_0^t 10^{(T-100)/z} dt \quad (4)$$

where C_{100} is the equivalent thermal treatment time (minutes) at 100 °C, T is the temperature (°C) at time t (min), and z is the thermal resistance constant (deg C)(Toledo 2007). Experimentally determined z-values were used in the cook value calculation; 39.9 and 36.8 °C for the green pea and garlic model foods, respectively. Correlation analysis was also performed using Pearson correlation coefficients to calculate the strength of correlation between color (a^* value) and accumulated cook value (C_{100}). Correlation analysis utilized temperature measurement data from calibrated type-T thermocouples placed at the cold spot of the test cells (geometric center). Initial correlation assessment utilized temperature and color data for cook values 0 to 50 min, which included 0 to 180 min at 70 °C, 0 to 150 min at 80 °C for, 0 to 75 min at 90°C, and 0 to 45 min at 100 °C. Secondary correlation analysis restricted the data analyzed to a maximum cook value of 20 min. A maximum cook value of 20 minutes was selected to be relevant for pasteurization quality evaluation because preliminary results

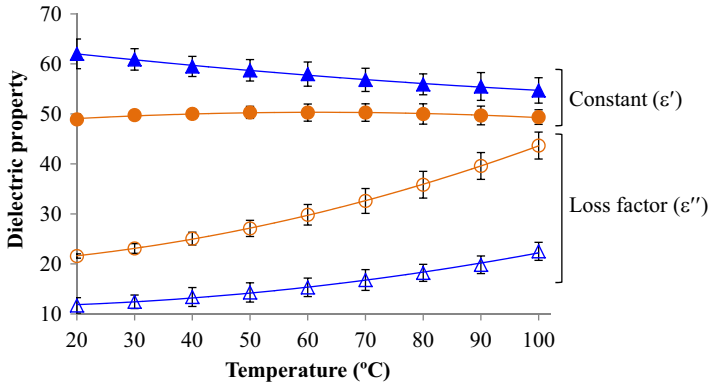


Figure 1–Experimental dielectric properties during heating at 915 MHz with 95% confidence intervals (4 replicates). The dielectric constant (ε') for green pea (▲) and garlic (●) and dielectric loss factor (ε'') for green pea (△) and garlic (○) are shown. Second-order polynomial correlations for the data are shown (——).

during pilot-scale pasteurization tests showed a maximum 20-min cook value for the hot spot.

Validation

The green pea model was selected as the optimal model for the target process in this study (90 °C for 10 min to control nonproteolytic *C. botulinum* spores). The kinetic study results indicated that garlic would not be an ideal model for a 90 °C for 10 min process because the garlic model food color change was too rapid during heating at 90 °C.

Three pasteurization processes were utilized to validate the green pea model: MAPS and 2 different conventional hot water methods, one with a preheating step and another process that did not include preheating. The MAPS is a pilot-scale design that uses both hot water heating and microwave heating with a 915 MHz generator and single mode cavities (Tang 2015). The system has no overpressure and includes 4 sections: preheating, microwave heating, holding, and cooling. The conventional, hot water method also did not include overpressure and utilized recirculating hot water baths and ice water for cooling.

The validation was conducted in duplicate according to the methods described in Bornhorst and others (2017b). Briefly, 280 g of the green pea model food was packaged under 150 mbar vacuum in rectangular polypropylene trays with an ethylene vinyl alcohol barrier layer (tray dimensions: 161 mm length, 116 mm width, and 32 mm depth) and plastic lid-stock (Printpack, Inc., Atlanta, Ga., U.S.A.). Preliminary tests were performed to measure the cold spot temperature for each process to determine the appropriate heating and holding times to yield processes with a minimum 90 °C for 10 min thermal treatment equivalent or F_{90} of 10 min. Accumulated thermal lethality for the target pathogen, F_{90}, was calculated for nonproteolytic *C. botulinum* using (Toledo 2007):

$$F_{90} = \int_0^t 10^{(T-90)/z}\,dt \qquad (5)$$

where F_{90} is the equivalent thermal treatment time (minutes) at 90 °C, T is the temperature (°C) at time t (min), and z is the thermal resistance constant (10 °C for this target pathogen) (ECFF 2006; FDA 2011).

After processing and cooling the model food trays to ambient temperature (22 °C), the trays were horizontally cut at the quarter and middle layers, that is one-fourth and half of the sample thickness; the color was analyzed using the computer vision system described previously in the section "kinetic study." Color mapping was conducted as part of the image analysis, as described in Bornhorst and others (2017b). Briefly, MATLAB R2013a was employed to convert the images a^* values to a jet color scale using an a^* value range of −22 to 1, which was based on the initial and saturation kinetic study color results. This approach to data analysis of green pea model foods using computer vision, color mapping, and image visualization was unique and differed from the approach employed by Smout and others (2003) in analysis of whole green peas as a model food in canning processes. Images were further analyzed statistically by developing normalized histograms using the total number of pixels in each image.

Table 1–Relationship of the dielectric constant (ε′) and dielectric loss factor (ε″) with temperature, T (°C) at 915 MHz for green pea and garlic model foods was described by a second-order polynomial (ε' or $\varepsilon'' = A \times T^2 + B \times T + C$). Model coefficients A, B, and C with the estimated standard error are shown.

		Polynomial coefficients			
Model food		$A \times 10^{-4}$	$B \times 10^{-2}$	C	R^2
Green pea	ε'	3.9 ± 0.9	−13.8 ± 1.1	64.6 ± 2.1	0.99
	ε''	10.5 ± 1.3	0.4 ± 1.6	11.4 ± 1.5	0.91
Garlic	ε'	−7.2 ± 0.7	8.9 ± 0.8	47.6 ± 1.3	0.95
	ε''	18.1 ± 0.5	5.8 ± 0.6	19.7 ± 1.8	0.97

Results and Discussion

Dielectric properties

The dielectric constant (ε') and dielectric loss factor (ε'') were measured for the green pea and garlic model foods at 915 MHz from 20 to 100 °C (Figure 1). The dielectric constant decreased and the loss factor increased with increasing temperature. The relationship between the dielectric properties and temperature at 915 MHz was correlated using second-order polynomial regression (Table 1). Polynomial correlations were developed to facilitate use of these data in future research, especially during the application of the model foods in processes using 915 MHz microwaves, such as MAPS.

The garlic model food had significantly larger dielectric loss factors at all temperatures, which suggested that the garlic model food would heat faster than the green pea model food when exposed to electromagnetic energy with a frequency of 915 MHz. At temperatures ranging from 20 to 100 °C, the penetration depth of 915 MHz microwaves ranged from 14.5 to 35.2 mm for the green pea model and 9.1 to 17.3 mm for the garlic model food. Penetration depth helps give a practical interpretation of the dielectric property

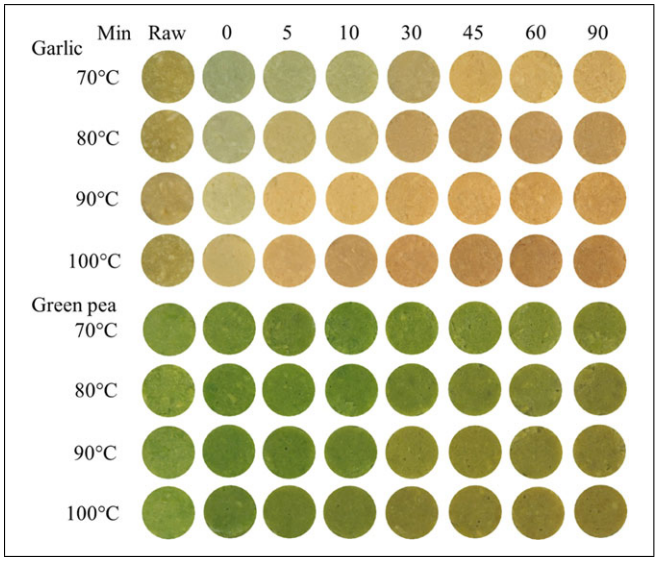


Figure 2–Color change of green pea and garlic model food samples during heating (0 to 90 min) at 70, 80, 90, and 100 °C. The raw samples were unheated and the 0 min time point is equivalent to the come-up time.

values; these results showed that 915 MHz microwaves had a greater penetration depth into the green pea model food compared to the garlic model. This is important information to have when designing processes and packages for a MAPS application.

Dielectric properties for the green pea model food at 915 MHz found in this study from 20 to 100 °C (ε': 54.7 to 62.0, ε'': 11.7 to 22.5) were within the range of values reported by Kumar and others (2007) for green pea puree at 20 to 130 °C (ε': 49 to 67, ε'': 15 to 31) and were also similar to results from Tong and others (1994) for sweet pea puree at 25 to 125 °C (ε': 47 to 64, ε'': 13 to 28). Previous research on the dielectric properties of garlic is very limited, with only one published work for garlic during drying at 2450 MHz. In this study, the dielectric properties of the garlic model food at 2450 MHz from 20 to 100 °C (ε': 41.0 to 43.8, ε'': 17.9 to 22.5) differed from the results of Sharma and Prasad (2002), who reported dielectric properties ranges for dried garlic with 185% dry basis moisture content at 35 to 75 °C of 51 to 55 for ε' and 6.9 to 8.5 for ε''. Differences in garlic dielectric property data between this study and Sharma and Prasad (2002) could be explained by differing formulas, moisture contents, and measurement temperatures.

Color change

Both green pea and garlic model foods showed increased color change with increasing heating time, up until the apparent saturation (Figure 2 and 3). For all temperatures, a^* values were significantly and strongly correlated to heating time, with correlation coefficients ranging from 0.74 to 0.95 with an average among all treatments of 0.85. For L^* and b^* values, correlation with heating time was less consistent across all temperatures, with correlation coefficients for L^* value ranging from 0.09 to 0.79 with an average among all treatments of 0.58 and b^* value correlation coefficients ranging from 0.03 to 0.59 with an average of 0.35. Based on these results, a^* value was selected as the TTI for these model food systems and nonlinear regression analysis was employed to determine the reaction kinetics. The use of a^* value as the optimal indicator of color change in green pea agreed with previous work (Steet and Tong 1996; Smout and others 2003).

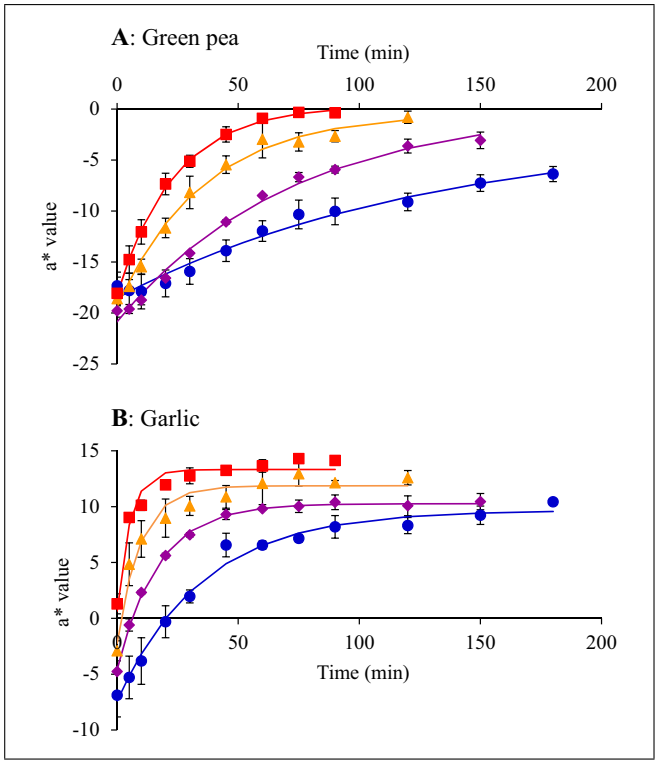


Figure 3–Experimental a^* value color change (3 replicates) during heating at 70 °C (●), 80 °C (◆), 90 °C (▲), and 100 °C (■) for green pea (A) and garlic (B). Predicted a^* values using first-order kinetic models are shown (——).

In both model foods, color change (a^* value) fit best to first-order reaction kinetics (Figure 3); the R^2 for zero-order ranged from 0.50 to 0.87 with an average among all treatments of 0.65, for first-order R^2 ranged from 0.75 to 0.99 with an average of 0.94, and for second order R^2 ranged from 0.51 to 0.89 with an average of 0.74. A first-order kinetic modeling approach agreed with previous work on green pea and garlic kinetics (Steet and Tong 1996; Ahmed and Shivhare 2001; Smout and others 2003). At each temperature, the garlic model food had faster reaction rates, ranging from 28.3 to 187.8 $\times$ 10^{-3} min^{-1} (D-values: 12 to 81 min) compared to 7.8 to 42.1 $\times$ 10^{-3} min^{-1} (D-values: 55 to 296 min) for the green pea model food (Table 2). The garlic model food reaction rate at 90 °C was 104.5 $\pm$ 17.4 $\times$ 10^{-3} min^{-1} (D-value 22 $\pm$ 4 min), which was almost 4 times faster than the green pea reaction rate of 28.0 $\pm$ 2.6 $\times$ 10^{-3} min^{-1} (D-value 82 $\pm$ 8 min). This result implied that the green pea model food would be a superior model for the target pasteurization process in this study (90 °C for 10 min to control nonproteolytic *C. botulinum* spores), whereas the garlic model food was not ideal because of the rapid color reaction rate. However, the garlic model food may be more appropriate for a less severe thermal process, such as a process targeting control of *L. monocytogenes* (70 °C for 2 min).

The difference in reaction speeds could be explained by differences in the color change mechanisms in each model system. The primary reason for color change in the green pea model food is due to degradation of chlorophyll compounds (Schwartz and Vonelbe 1983). In the garlic model food, color change could be attributed to several mechanisms, including enzymatic and nonenzymatic browning and thermal interactions and rearrangements of sulfur

Table 2–Predicted a_0^*, a_∞^*, k, D-value, E_a, and z-value for a^* values with estimated standard error (3 replicates) for green pea and garlic model food samples heated at 70, 80, 90, and 100 °C. Coefficients of determination (R^2) are shown for each model.

Model	Temp. (°C)	a_0^*	a_∞^*	K (10^{-3} min^{-1})	D-value (min)	R^2	E_a (kJ/mol^{-1})[a]	z-value (°C)[b]	R^2
Green pea	70	−18.5 ± 0.4	−2.2 ± 2.4	7.8 ± 2.0	296 ± 76	0.93	61.5 ± 3.6	39.9 ± 2.4	0.99
	80	−20.9 ± 0.3	0.1 ± 0.7	13.9 ± 1.1	166 ± 13	0.99			
	90	−19.4 ± 0.4	-0.4 ± 0.6	28.0 ± 2.6	82 ± 8	0.98			
	100	−18.2 ± 0.4	0.3 ± 0.4	42.1 ± 2.9	55 ± 4	0.99			
Garlic	70	−7.4 ± 0.5	9.7 ± 0.4	28.3 ± 2.6	81 ± 7	0.97	66.5 ± 2.0	36.8 ± 1.1	0.99
	80	−4.6 ± 0.2	10.3 ± 0.1	59.3 ± 2.3	39 ± 1	0.99			
	90	−2.4 ± 0.8	11.9 ± 0.4	104.5 ± 17.4	22 ± 4	0.93			
	100	0.7 ± 0.3	13.3 ± 0.2	187.8 ± 16.1	12 ± 1	0.98			

[a]Rate constant A_0 was 16.7±1.2 and 19.8±0.7 min^{-1} for green pea and garlic models, respectively.
[b]D_{ref} was 52.4±3.8 and 12.5±0.4 min for green pea and garlic models, respectively, with T_{ref} as 100 °C.

containing compounds (Ahmed and Shivhare 2001; Zang and others 2013). Additionally, the green pea and garlic model foods had different moisture contents, which could also have impacted color change kinetics. However, it is not possible to de-couple the effect of color change mechanism and moisture content on color change kinetics using the results from this study.

Reaction rates for the green pea model found in this study were similar to those found by Steet and Tong (1996) who reported 4.2 to 18.7 × 10^{-3} min^{-1} for 70 to 90 °C and Smout and others (2003) who reported D-values of 44.8 to 274.2 min for 70 to 100 °C. The garlic model food color change reaction rates were similar to those found by Ahmed and Shivhare (2001), with a reported reaction rate of 9 × 10^{-3} min^{-1} for a^* value at 70 °C and differed from reaction rates for a garlic browning index (10 to 3581 × 10^{-3} min^{-1} for 80 to 90 °C) from by Fante and Norena (2012). Differences in garlic browning rates between this study and Fante and Norena (2012) could be explained by differing heating methods, heating times, and data analysis techniques. Previous research on garlic also concluded color change was significantly correlated to flavor pungency, an important quality attribute in garlic (Rejano and others 2004); this helped substantiate the relevance of the garlic model food in evaluating the quality of *Allium* vegetables (for example, onion, garlic).

The color change (a^* value) reaction rate of both green pea and garlic models increased with increasing temperature (Table 2) and fit well to the Arrhenius equation (R^2 of 0.99). Both model foods had similar temperature sensitivity, with an activation energy for the green pea model food of 61.5 ± 3.6 kJ/mol^{-1} (z-value 39.9 ± 2.4 °C) and 66.5 ±2.0 kJ/mol^{-1} (z-value 36.8 ± 1.1 °C) for the garlic model food. Temperature sensitivity of the green pea model food was similar to previous work, for example, Smout and others (2003) reported a z-value of 47.5 ± 5.9 °C for a temperature range of 65 to 110 °C. Temperature sensitivity of the garlic model food was similar to the activation energy of a garlic browning index (67.4 kJ/mol 80 to 100 °C) reported by Fante and Norena (2012) and differed slightly from Ahmed and Shivhare (2001), with a reported activation energy for overall color change of 57.6 kJ/mol^{-1} for 70 to 90 °C. Additionally, the temperature sensitivity of these model foods (z-values: 36.9 to 39.9 °C) were significantly higher than the model foods with only Maillard reaction products previously developed for microwave pasteurization applications, with reported z-values (80 to 100 °C) of 20.8 to 28.8 °C for L^* value and 10.3 to 25.6 °C for a^* value (Bornhorst and others 2017b). This implied that the study goal was accomplished; new model foods were developed with temperature sensitivities different from the Maillard reaction products based model foods from Bornhorst and others (2017b).

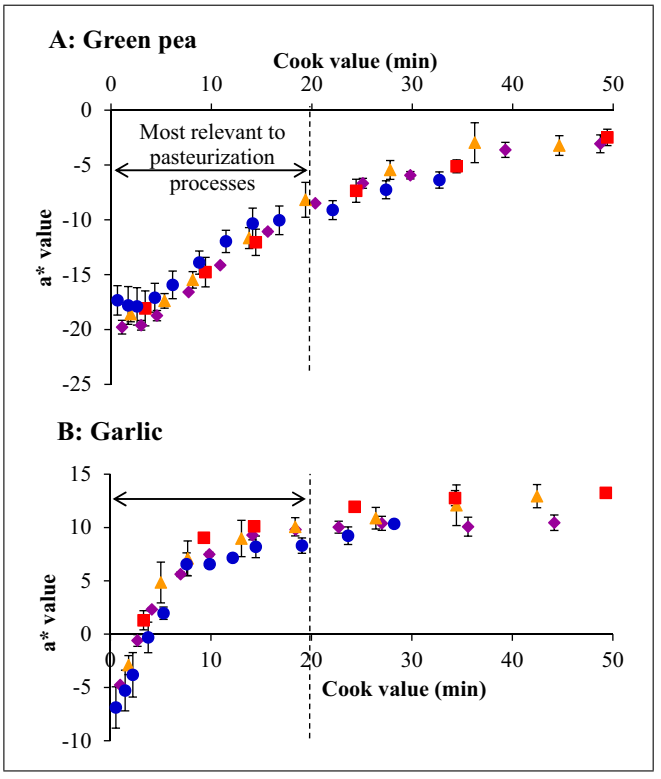
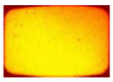
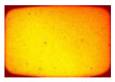
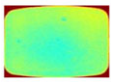
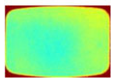
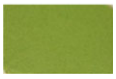
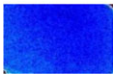


Figure 4–Cook value (C_{100}) correlation to experimental a^* values (3 replicates) during heating at 70 °C (●), 80 °C (◆), 90 °C (▲), and 100 °C (■) for green pea (A) and garlic (B). Cook values up to 20 min were most relevant to pasteurization process quality evaluation.

Color change, described using a^* values, was well correlated to cook values for both green pea and garlic model foods (Figure 4). Pearson correlation coefficients also showed that a^* values were significantly and strongly correlated to cook values up to 50 min, with correlation coefficients of 0.95 for the green pea model food and 0.79 for the garlic model food. When the cook value was restricted to up to 20 min in secondary correlation analysis, the correlation coefficient for the garlic model food improved to 0.87 and the green pea model food maintained a high correlation coefficient of 0.95. These findings implied that a^* value was a good indicator of food quality change and could be applicable for pasteurization process quality quantification and evaluation. The strong correlations from the models developed in this study suggested that the models could be helpful in evaluating the quality of various pasteurization processes between 70 and 100 °C that

Table 3–Example images of trays containing green pea model food after a conventional (hot water) pasteurization with and without preheating, microwave-assisted pasteurization system (MAPS), and an unheated control. Process schedules with times and water temperatures are shown for each pasteurization treatment. For each tray, the middle and quarter layers are depicted by the original colored picture and *a value color map.**

	Processing conditions					
Pasteurization process	Preheating at 60°C	Heating & holding at 93°C	**Middle layer** Original image	a* color map	**Quarter layer** Original image	a* color map
Hot water not preheated	None	38 min				
Hot water preheated	30 min	32.2 min				
MAPS	30 min	2.3 min microwaving 9 min holding				
Unheated control	None	None				

All pasteurization treatments resulted in thermal treatment equivalents (F_{90}) at the cold spots of 90 °C for 10.9 to 11.0 min.

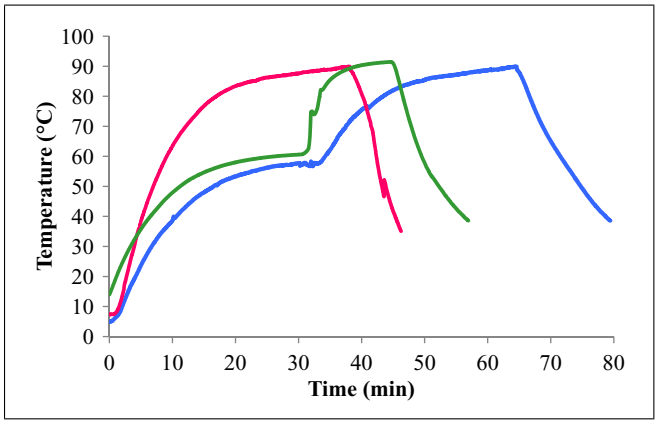


Figure 5–Typical temperature profiles for the cold spot measured during pasteurization of green pea model food trays using the microwave-assisted pasteurization system (MAPS) (——), hot water with preheating (——), and hot water without preheating (——).

have different time-temperature histories. Results from this study agreed with Bornhorst and others (2017b), who concluded color change in model food with Maillard reaction products was a useful tool to evaluate quality changes during pasteurization.

Validation

To produce a safely pasteurized model food product, the MAPS process included 30 min of preheating in 61 °C water, 2.3 min of microwave heating with trays in 93 °C water, 9 min of holding in 93 °C water, and 5 min of cooling in 23 °C water (Figure 5). For the hot water process with preheating, this equated to a process with 30 min of preheating in 61 °C water, 32.2 min of heating in 93 °C water, and 10 min of cooling in 5 °C water. For the hot water process without preheating, this equated to a process with 38 min of heating in 93 °C water and 10 min of cooling in 5 °C water. These process schedules resulted in thermal treatment equivalents (F_{90}) at the cold spots of 90 °C for 10.9 min for MAPS, 11.0 min for the hot water process with preheating, and 10.9 min for the hot water process without preheating.

After pasteurization with MAPS and hot water processing, the color of green pea model food trays were analyzed (Table 3). Both the middle and quarter layers of model foods pasteurized in the MAPS had less color change compared to those from both hot water processes. Comparing the 2 hot water processes, with and without a preheating step, the green pea model food had similar amounts of color change for both methods in both middle and quarter layers. This result suggested that the preheating step did not improve the product quality, even though it was a less severe thermal process than the one without preheating; this differed from the results of the validation performed in Bornhorst and others (2017b) who reported a benefit of the preheating step for mashed potato model food quality. This difference could be explained by differing temperature sensitivity among the models, with the green pea model food color change in this study having a z-value of 39.9 ± 2.4 °C and the mashed potato model foods used in the validation by Bornhorst and others (2017b) having smaller color change z-values of 20.8 to 25.6 °C. The preheating step was conducted at 61 °C, which was 32 °C less than the processing temperature of 93 °C; this temperature decrease would have yielded a much smaller impact on the green pea model (72% increase in D-values) compared to the mashed potato models (112 to 138% increase in D-values). These results demonstrated the importance of performing process quality assessments using multiple model foods with appropriate z-values to cover a range of food quality attributes.

Histograms of model foods' a^* values were compared among the unheated control, MAPS, and hot water processes (Figure 6). Results demonstrated that there was a quantifiable difference between the control, MAPS, and hot water processes with MAPS pasteurized model foods having less color change (smaller a^* values) than both hot water processes. Statistical analysis showed the interquartile range (IQR) or spread of the data were similar for all samples, ranging from 1.3 to 1.6. This showed the amount of

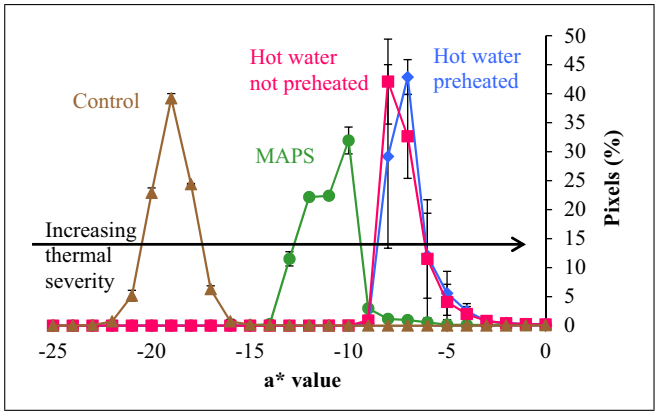


Figure 6–Histograms of experimental, normalized *a value pixel amounts (2 replicates) for the middle layer of green pea model food trays of the control (unheated) sample (▲), microwave-assisted pasteurization system (MAPS) processed (●), and hot water processed with preheating (◆) and without preheating (■). The arrow shows the direction of increasing thermal severity and greater color change compared to the unheated control sample.**

inherent variability in the color of the green pea model food. The median color in the middle layers matched the trends discussed previously; the control had the smallest median a^* value of −18.6, followed by MAPS with −10.7, and the hot water processes (with preheating: −6.8, without preheating: −7.1). The statistical analysis implied the median was a better indicator of color change after pasteurization than IQR, which agreed with the findings from Bornhorst and others (2017b).

Visual and quantitative results indicated that model foods pasteurized using MAPS had less color change than those pasteurized in either hot water process, which matched expectations because MAPS was a less severe thermal process with almost 3 times shorter time in 93 °C water. This suggested that the model foods pasteurized in MAPS may have had a better quality than model foods from the hot water processes. The results of this validation study showed that the image analysis methods and green pea model food may be useful tools to compare food quality after various thermal pasteurization methods. This newly developed model food could be useful in visualizing quality changes in food products volumetrically and optimizing thermal pasteurization processes to obtain safe products, with better quality.

Conclusions

Green pea and garlic model foods were developed for thermal pasteurization quality evaluation. Dielectric property results showed the green pea model would heat slower than garlic when exposed to 915 MHz microwaves and the microwaves would have a deeper penetration into the green pea model compared to the garlic. These data are important to consider when designing food packages for use in microwave processing, especially the penetration depth, which can help put boundaries on the package size. For both model foods, a^* value was selected as the TTI; a^* value increased during heating, following first-order reaction kinetics and an Arrhenius relationship. a^* value reaction rates for the green pea model food were about 4 times slower than the garlic model; this was the main reason that green pea was selected as the optimal model food for the target pasteurization process in this study (90 °C for 10 min).

Validation studies conducted with the green pea model food showed that the unheated control, hot water pasteurization, and MAPS all yielded different amounts of color change that was quantified with image analysis. In the future, the green pea and garlic model foods could both be utilized for quality assessment and optimization of various thermal pasteurization processes. A larger range of processing temperatures can be covered by these model foods because each model has significantly different reaction rates; the green pea model food would be most applicable for quality evaluation for a target process of 90°C for 10 min to control nonproteolytic *C. botulinum* spores, while the garlic model would be more appropriate for a process aiming to control *L. monocytogenes* (70 °C for 2 min).

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