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Research Note

Effect of Power Levels on Inactivation of *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* in Tomato Paste Using 915-Megahertz Microwave and Ohmic Heating

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ABSTRACT

The effect of power levels on inactivation of *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* in tomato paste was investigated using 915-MHz microwave heating (MW) and ohmic heating (OH). Heating uniformity, pathogen inactivation, and quality aspects were determined with 1.8-, 2.1-, 2.4-, and 3.0-kW MW and corresponding OH. GInaFit was used to analyze pathogen inactivation. The heating uniformity of MW-treated samples was inferior to that of OH-treated samples at low power levels of 1.8 to 2.4 kW but improved as the power level increased. Pathogen inactivation of MW-treated samples was significantly higher than that of OH-treated samples at low power levels of 1.8 to 2.4 kW ($P < 0.05$) but was not significantly different at the highest power level of 3.0 kW ($P > 0.05$). Quality aspects (color, pH, and lycopene content), except for L*, of MW-treated samples were not significantly degraded ($P > 0.05$) by increased power levels. Our results indicate that increasing power levels of MW ensures heating uniformity and microbiological safety and preserves quality aspects of tomato paste.

Key words: 915-MHz microwave heating; GInaFit; Ohmic heating; Pathogen inactivation; Power levels; Tomato paste

Foodborne illness is a major public health problem, and socioeconomic losses resulting from foodborne outbreaks have been reported worldwide. In particular, foodborne outbreaks associated with raw tomatoes resulted in 1,959 illnesses, 384 hospitalizations, and three deaths from 1990 through 2010 *(3)*. Tomatoes are enjoyed worldwide in the form of processed products such as juice, ketchup, paste, puree, sauce, passata, and tomato chips *(16)*. Among these products, tomato paste is a significant component of the human diet and an important source of antioxidants *(4)*. Tomato paste contains 24% or more natural tomato soluble solids and is made from concentrated tomato pulp after the removal of skins and seeds *(13)*. Even though tomato paste has been considered a safe food because of its low pH (3.5 to 4.7), some acid-resistant bacteria and bacterial spores can survive in an acidic environment *(19, 22, 30)*. Because *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* are known to be acid resistant *(21, 24, 29)*, these pathogens must be inactivated completely during processing.

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Thermal treatment is an important step in tomato paste processing that inactivates foodborne pathogens and enhances the nutritional value *(9)*. Nevertheless, high temperatures and long treatment times characteristic of conventional thermal processing can seriously degrade quality aspects of the product *(14)*. Thus, advanced thermal technologies such as microwave heating (MW) and ohmic heating (OH) have been proposed as alternative thermal technologies for reducing tomato paste processing time *(4, 11, 17, 31)*. Power level is an important factor in both MW and OH during food processing. The power level of OH is determined by electric field strength and can be changed by changing the voltage or electrode gap *(10, 32)*. In contrast, the power level of MW is designated in units of electric power *(35)*. Processing time would be too long at very low power levels, whereas quality degradation could occur at very high power levels. Therefore, selection of an adequate power level is necessary to ensure microbiological safety while minimizing quality degradation of foods. For these reasons, optimization studies of power levels in food processing have been conducted in recent years *(2, 8, 33, 34)*.

Thermal inactivation of foodborne pathogens generally follows a non–log-linear trend. GInaFit is a freeware tool

used to assess non–log-linear microbial survivor curves, helping researchers develop predictive modelling approaches for the food industry *(12)*. Among several models in GInaFit, the Weibull and shoulder log-linear models are the most frequently used to analyze the inactivation of microorganisms because these models provide optimal fitting. Inactivation curves of an indicator microorganism (nonpathogenic *E. coli*) and pathogenic microorganisms (*E. coli* O157:H7, *Salmonella* Typhimurium, and *L. monocytogenes*) were suitably analyzed by Weibull and shoulder log-linear models in previous studies *(5, 27, 28)*. Even though tomato paste has been of interest as a model food for evaluating OH and MW processing recently, research about the effect of power levels in tomato paste processing has been limited.

In the present study, we investigated the effect of power levels on tomato paste processing using MW and OH. Heating uniformity in microwave- and ohmic-heated tomato paste was compared at different power levels, and pathogen inactivation was analyzed by GInaFit using Weibull and shoulder log-linear models. Quality aspects of MW-treated tomato paste also were assessed at different power levels.

MATERIALS AND METHODS

Bacterial cultures and cell suspension. Three strains each of *E. coli* O157:H7 (ATCC 35150, ATCC 43889, and ATCC 43890), *Salmonella* Typhimurium (ATCC 19585, ATCC 43971, and DT 104), and *L. monocytogenes* (ATCC 19111, ATCC 19115, and ATCC 15313) were obtained from the bacteria culture collection of Seoul National University (Seoul, South Korea). Stock cultures and working cultures were prepared by the method described elsewhere *(6, 18)*. The final pellets were resuspended in 9 ml of sterile 0.2% peptone water, corresponding to approximately 10^8 to 10^9 CFU/ml. Suspended pellets of the three pathogens were combined to create a mixed culture cocktail containing approximately equal numbers of cells of each strain of *E. coli* O157:H7 (10^7 CFU/ml), *Salmonella* Typhimurium (10^7 CFU/ml), and *L. monocytogenes* (10^6 CFU/ml).

Sample preparation and inoculation. Canned tomato paste made from organic tomatoes was purchased at a local grocery store (Seoul, South Korea) and stored at room temperature out of direct sunlight. Twenty-five grams of tomato paste was inoculated with 0.2 ml of the culture cocktail and thoroughly stirred with a spatula for 1 min. The final cell levels were 10^6 to 10^7 CFU/g for *E. coli* O157:H7 and *Salmonella* Typhimurium and 10^5 to 10^6 CFU/g for *L. monocytogenes*.

MW treatment. MW treatments were performed in a previously described apparatus *(34)*. The microwave system consisted of a high frequency power generator, magnetron head, waveguide system (WR-975), microwave cavity (Korea Microwave Instrument Co., Gyeonggi-do, South Korea), fiber optic temperature sensors, and signal conditioner (FOT-L, TMI-4, FISO Technologies Inc., Quebec City, Quebec, Canada). The initial preheating time was 30 min for this system. For treatment, 25 g of tomato paste was dispensed into a microwavable cylindrical polypropylene container, which was placed at the center of the turn table inside the cavity and subjected to MW at four power levels (1.8, 2.1, 2.4, and 3.0 kW). Tomato paste inoculated with pathogens was treated with MW for a maximum of 110, 85, 70, and 55 s at 1.8, 2.1, 2.4, and 3.0 kW, respectively. Fiber optic temperature sensors were inserted at the center and side of the chamber through a hole at the top wall of the cavity, and a signal conditioner connected to a personal computer recorded real-time sample temperatures at 1-s intervals. The side temperature was obtained with a fiber optic sensor close to the wall of the container in contact with the sample. The turn table was not operated while the temperature was measured, and a stirrer was used instead of the turn table to ensure uniformity of microwave penetration.

OH treatment. OH treatments were carried out in a previously described apparatus *(26)*. The system consisted of a function generator (no. 33210A, Agilent Technologies, Palo Alto, CA), a precision power amplifier (no. 4510, NF Corp., Yokohama, Japan), a two-channel digital-storage oscilloscope (no. TDS2001C, Tektronix, Inc., Beaverton, CO), a data logger (no. 34970A, Agilent Technologies), and an OH chamber. The OH electric field was regulated at 8.3 to 27.8 V_{rms}/cm to match the central temperature of the OH-treated tomato paste with that of the MW-treated tomato paste. K-type thermocouples were inserted at the center and side of the OH chamber, and temperatures were recorded at 0.6-s intervals with a data logger. All other conditions were the same as those described for MW.

Bacteriological analysis. For microbial enumeration, each treated 25-g sample was immediately transferred into a sterile stomacher bag (Labplas, Inc., Sainte-Julie, Quebec, Canada) containing 225 ml of sterile 0.2% peptone water and homogenized for 2 min with a stomacher (Easy Mix, AES Chemunex, Rennes, France). After homogenization, 1-ml samples were 10-fold serially diluted with 9 ml of sterile 0.2% peptone water, and 0.1 ml of stomached samples or diluents was spread plated onto each selective medium: sorbitol MacConkey agar (Difco, BD, Sparks, MD) for *E. coli* O157:H7, xylose lysine desoxycholate agar (Difco, BD) for *Salmonella* Typhimurium, and Oxford agar base with antimicrobial supplement (MB Cell, Los Angeles, CA) for *L. monocytogenes*. All plates were incubated at 37°C for 24 to 48 h, and colonies characteristic of the pathogens were counted.

Inactivation parameters. Survival curves were analyzed by the Weibull and shoulder log-linear models. The parameters of the Weibull model (δ and p) are calculated from the following equation:

$$\log(N) = \log(N_0) - \left(\frac{t}{\delta}\right)^p \quad (1)$$

where N (CFU/ml) is the population of the microorganisms, N_0 is the initial population, t (minutes) is the treatment time, δ (minutes) is the time for the first decimal reduction, and p is the parameter related to the scale and shape of the survival curve. The Weibull distribution corresponds to a concave downward survival curve when $p > 1$ and a concave upward curve when $p < 1$ *(36)*. The time required to achieve a 3-log reduction (t_{3d}) and a 5-log reduction (t_{5d}) was calculated using equation 2:

$$t_x d = \delta \times (x)^{\frac{1}{p}} \quad (2)$$

The parameters of the shoulder log-linear model are

$$\log(N) = \log(N_0) - \frac{k_{\max}(t)}{\ln(10)} + \log\left(\frac{e^{k_{\max} S_l}}{1 + (e^{k_{\max} S_l} - 1)e^{-k_{\max} t}}\right) \quad (3)$$

where S_l is the shoulder length and k_{max} is the inactivation rate (per minute). The time required to achieve a 3-log reduction and a 5-log reduction was calculated using equation 4:

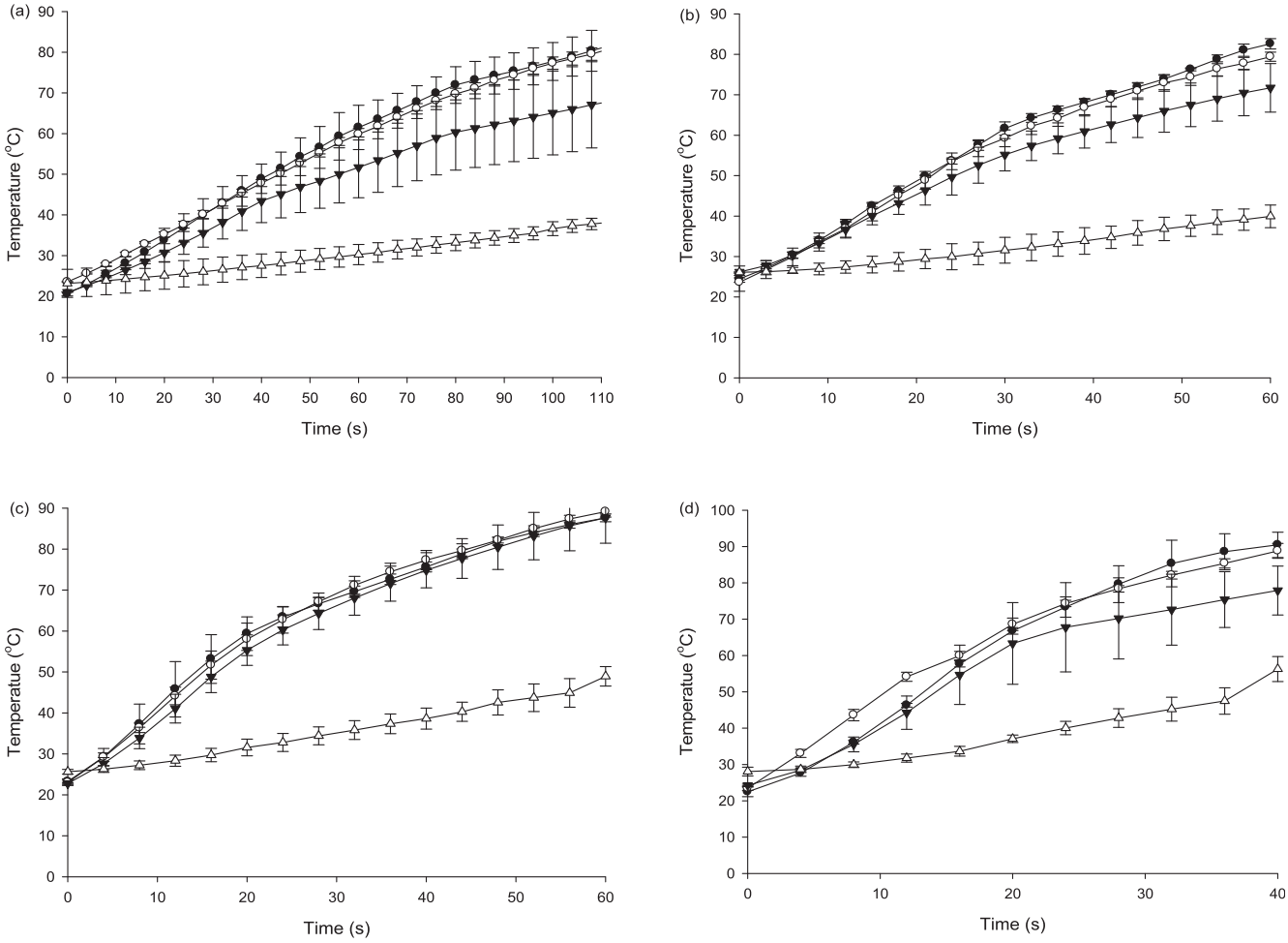

FIGURE 1. *Time-temperature profiles of tomato paste at power levels of (a) 1.8, (b) 2.1, (c) 2.4, and (d) 3.0 kW. Center temperatures of ohmic-heated (●) and microwave-heated (○) samples and side temperatures of ohmic-heated (▼) and microwave-heated (△) samples are shown. The results are means from three experiments; error bars indicate standard errors.*

$$t_x d = S_1 + (x)\frac{\ln(10)}{k_{\max}} \tag{4}$$

Measurement of color, pH, and lycopene concentration. Color, pH, and lycopene concentration of treated and untreated (control) samples were measured. All treated samples were cooled in crushed ice immediately after treatment. Color values were measured with a Minolta colorimeter (CR400, Minolta Co., Osaka, Japan). The values for L*, a*, and b* were measured to evaluate the color changes of tomato paste after each heating treatment, where L* is a measure of lightness, a* is a measure of redness, and b* is a measure of yellowness. The pH of treated and untreated samples was measured with a pH meter (Seven Multi 8603, Mettler Toledo, Greifensee, Switzerland). Lycopene concentration in tomato paste was measured according to a method described previously *(23)*. The absorbance of the upper hexane layer was measured with a spectrofluorophotometer (Spectramax M2e, Molecular Devices, Sunnyvale, CA) at 503 nm. The concentrations of lycopene in tomato paste (milligrams per kilograms of tissue) were determined using absorbance and sample weight with equation 5:

$$\text{lycopene} = A_{503} \times 0.0312 \text{ kg/sample} \tag{5}$$

Statistical analysis. All experiments were replicated three times. All data were analyzed by the analysis of variance procedure of the Statistical Analysis System (version 9.3, SAS Institute, Cary, NC), and mean values were separated using Duncan's multiple range test. Significant differences in the processing treatments were determined at a significance level of $P = 0.05$.

The fitness of the models was evaluated by the root mean squared error (RMSE) and the regression coefficient (R^2):

$$\text{RMSE} = \sqrt{\sum_{i=1}^{n_t} \frac{(y_{\text{expi}} - y_{\text{pre}})^2}{n_t - n_p}}$$

where y_{expi} is the experimental observation, y_{pre} is the model prediction, n_t is the number of data points, and n_p is the number of parameters.

RESULTS AND DISCUSSION

Heating uniformity is an important factor for ensuring microbiological safety in food processing. In the present study, tomato paste exposed to MW was less uniformly heated than were OH samples (Fig. 1). The temperature differences between center and side were larger for MW than for OH samples. The side temperatures of MW samples were 37 to 43°C when the center temperature reached 80°C. In contrast, the side temperatures of OH samples were 67 to 77°C when the center temperature reached 80°C. Temper-

TABLE 1. *Parameters of the Weibull and shoulder log-linear models for inactivation of* E. coli *O157:H7,* Salmonella *Typhimurium, and* L. monocytogenes *subjected to microwave heating (MW) and ohmic heating (OH) corresponding to temperature profiles of 1.8 kW*[a]

	Weibull						Shoulder log-linear					
Heating method	δ (mean ± SE) (min)	p (mean ± SE)	RMSE	R^2	t_{3d} (mean ± SD) (min)	t_{5d} (mean ± SD) (min)	S_l (mean ± SE) (min)	k_{max} (mean ± SE)	RMSE	R^2	t_{3d} (mean ± SD) (min)	t_{5d} (mean ± SD) (min)
E. coli O157:H7												
MW	1.35 ± 0.05	2.98 ± 0.31	0.10	0.99	1.94 ± 0.04 A	2.29 ± 0.07 A	1.03 ± 0.04	6.91 ± 0.45	0.09	0.99	2.07 ± 0.16 A	2.63 ± 0.03 A
OH	0.72 ± 0.13	1.58 ± 0.28	0.30	0.97	1.45 ± 0.15 B	1.99 ± 0.14 B	0.51 ± 0.10	7.24 ± 0.60	0.22	0.98	1.46 ± 0.14 B	2.09 ± 0.20 B
Salmonella Typhimurium												
MW	1.36 ± 0.03	3.23 ± 0.24	0.08	0.99	1.90 ± 0.06 A	2.23 ± 0.17 A	1.06 ± 0.06	7.52 ± 0.65	0.12	0.99	1.96 ± 0.10 A	2.58 ± 0.28 A
OH	0.78 ± 0.06	1.65 ± 0.14	0.14	0.99	1.65 ± 0.22 A	2.28 ± 0.37 A	0.54 ± 0.03	6.93 ± 0.16	0.06	1.00	1.67 ± 0.24 A	2.45 ± 0.45 A
L. monocytogenes												
MW	1.32 ± 0.03	2.35 ± 0.12	0.05	1.00	2.03 ± 0.04 A	2.38 ± 0.23 A	0.87 ± 0.03	5.05 ± 0.16	0.04	1.00	2.17 ± 0.05 A	2.89 ± 0.27 A
OH	0.82 ± 0.09	1.29 ± 0.15	0.13	0.99	1.94 ± 0.09 A	2.90 ± 0.36 A	0.33 ± 0.10	4.25 ± 0.28	0.11	0.99	1.97 ± 0.07 B	3.08 ± 0.23 A

[a] SE, standard error; R^2, regression coefficient; SD, standard deviation. Within each column for each pathogen, values followed by the same letter are not significantly different ($P > 0.05$).

TABLE 2. *Parameters of the Weibull and shoulder log-linear models for inactivation of* E. coli *O157:H7,* Salmonella *Typhimurium, and* L. monocytogenes *subjected to microwave heating (MW) and ohmic heating (OH) corresponding to temperature profiles of 2.1 kW*[a]

	Weibull						Shoulder log-linear					
Heating method	δ (mean ± SE) (min)	p (mean ± SE)	RMSE	R^2	t_{3d} (mean ± SD) (min)	t_{5d} (mean ± SD) (min)	S_l (mean ± SE) (min)	k_{max} (mean ± SE)	RMSE	R^2	t_{3d} (mean ± SD) (min)	t_{5d} (mean ± SD) (min)
E. coli O157:H7												
MW	0.89 ± 0.03	2.30 ± 0.14	0.07	1.00	1.44 ± 0.06 A	1.80 ± 0.17 A	0.63 ± 0.06	8.07 ± 0.67	0.13	0.99	1.47 ± 0.07 A	2.04 ± 0.20 A
OH	0.46 ± 0.11	1.15 ± 0.22	0.27	0.97	1.23 ± 0.06 B	1.86 ± 0.12 A	0.10 ± 0.15	6.39 ± 0.73	0.27	0.97	1.22 ± 0.06 B	1.95 ± 0.11 A
Salmonella Typhimurium												
MW	0.94 ± 0.01	2.46 ± 0.05	0.02	1.00	1.48 ± 0.10 A	1.82 ± 0.13 A	0.67 ± 0.03	7.97 ± 0.47	0.08	0.99	1.54 ± 0.13 A	2.11 ± 0.19 A
OH	0.38 ± 0.10	0.97 ± 0.17	0.24	0.97	1.14 ± 0.03 B	1.87 ± 0.13 A	0.03 ± 0.15	5.80 ± 0.63	0.24	0.97	1.15 ± 0.01 B	1.89 ± 0.06 A
L. monocytogenes												
MW	0.99 ± 0.04	2.15 ± 0.21	0.08	0.99	1.64 ± 0.07 A	2.09 ± 0.09 A	0.60 ± 0.06	5.98 ± 0.45	0.09	0.99	1.75 ± 0.08 A	2.52 ± 0.09 A
OH	0.36 ± 0.15	0.77 ± 0.20	0.29	0.94	1.50 ± 0.07 A	2.90 ± 0.10 B	-0.23 ± 0.32	4.00 ± 0.80	0.30	0.94	1.49 ± 0.07 B	2.64 ± 0.06 A

[a] SE, standard error; R^2, regression coefficient; SD, standard deviation. Within each column for each pathogen, values followed by the same letter are not significantly different ($P > 0.05$).

TABLE 3. *Parameters of the Weibull and shoulder log-linear models for inactivation of* E. coli *O157:H7,* Salmonella *Typhimurium, and* L. monocytogenes *subjected to microwave heating (MW) and ohmic heating (OH) corresponding to temperature profiles of 2.4 kW*[a]

	Weibull						Shoulder log-linear					
Heating method	δ (mean ± SE) (min)	p (mean ± SE)	RMSE	R^2	t_{3d} (mean ± SD) (min)	t_{5d} (mean ± SD) (min)	S_l (mean ± SE) (min)	k_{max} (mean ± SE)	RMSE	R^2	t_{3d} (mean ± SD) (min)	t_{5d} (mean ± SD) (min)
E. coli O157:H7												
MW	0.88 ± 0.02	3.85 ± 0.32	0.09	1.00	1.23 ± 0.14 A	1.44 ± 0.19 A	0.76 ± 0.04	16.40 ± 2.09	0.16	0.99	1.33 ± 0.29 A	1.76 ± 0.51 A
OH	0.31 ± 0.10	1.01 ± 0.23	0.33	0.96	0.91 ± 0.11 B	1.49 ± 0.14 A	0.05 ± 0.15	7.83 ± 1.08	0.32	0.96	0.94 ± 0.09 A	1.51 ± 0.12 A
Salmonella Typhimurium												
MW	0.77 ± 0.03	2.89 ± 0.28	0.12	0.99	1.13 ± 0.01 A	1.35 ± 0.04 A	0.60 ± 0.04	12.76 ± 1.07	0.14	0.99	1.20 ± 0.09 A	1.48 ± 0.05 A
OH	0.42 ± 0.09	1.31 ± 0.25	0.27	0.98	0.97 ± 0.07 B	1.42 ± 0.11 A	0.21 ± 0.10	9.10 ± 0.93	0.24	0.98	0.98 ± 0.07 B	1.48 ± 0.13 A
L. monocytogenes												
MW	0.86 ± 0.03	3.08 ± 0.33	0.10	0.99	1.22 ± 0.05 A	1.46 ± 0.14 A	0.64 ± 0.07	10.71 ± 1.48	0.17	0.98	1.27 ± 0.06 A	1.66 ± 0.19 A
OH	0.48 ± 0.05	1.12 ± 0.11	0.10	0.99	1.28 ± 0.09 A	2.05 ± 0.35 A	0.08 ± 0.08	5.73 ± 0.40	0.10	0.99	1.29 ± 0.08 A	2.11 ± 0.22 A

[a] SE, standard error; R^2, regression coefficient; SD, standard deviation. Within each column for each pathogen, values followed by the same letter are not significantly different ($P > 0.05$).

TABLE 4. *Parameters of the Weibull and shoulder log-linear models for inactivation of* E. coli *O157:H7,* Salmonella *Typhimurium, and* L. monocytogenes *subjected to microwave heating (MW) and ohmic heating (OH) corresponding to temperature profiles of 3.0 kW*[a]

	Weibull						Shoulder log-linear					
Heating method	δ (mean ± SE) (min)	p (mean ± SE)	RMSE	R^2	t_{3d} (mean ± SD) (min)	t_{5d} (mean ± SD) (min)	S_l (mean ± SE) (min)	k_{max} (mean ± SE)	RMSE	R^2	t_{3d} (mean ± SD) (min)	t_{5d} (mean ± SD) (min)
E. coli O157:H7												
MW	0.25 ± 0.06	1.41 ± 0.25	0.40	0.98	0.59 ± 0.06 A	0.82 ± 0.03 A	0.21 ± 0.05	19.34 ± 1.60	0.30	0.99	0.56 ± 0.06 A	0.80 ± 0.05 A
OH	0.34 ± 0.01	1.76 ± 0.07	0.08	1.00	0.62 ± 0.10 A	0.83 ± 0.03 A	0.26 ± 0.04	19.37 ± 1.49	0.25	0.99	0.62 ± 0.09 A	0.85 ± 0.03 A
Salmonella Typhimurium												
MW	0.40 ± 0.06	2.19 ± 0.40	0.40	0.98	0.66 ± 0.03 A	0.84 ± 0.02 A	0.41 ± 0.04	26.29 ± 2.91	0.36	0.99	0.61 ± 0.12 A	0.88 ± 0.05 A
OH	0.35 ± 0.08	1.67 ± 0.36	0.39	0.98	0.68 ± 0.09 A	0.92 ± 0.08 A	0.18 ± 0.12	15.20 ± 2.65	0.50	0.96	0.64 ± 0.09 A	0.95 ± 0.12 A
L. monocytogenes												
MW	0.41 ± 0.07	2.04 ± 0.38	0.35	0.98	0.71 ± 0.03 A	0.91 ± 0.03 A	0.37 ± 0.04	20.49 ± 1.61	0.21	0.99	0.71 ± 0.02 A	0.93 ± 0.04 A
OH	0.38 ± 0.07	1.74 ± 0.35	0.33	0.98	0.72 ± 0.04 A	0.97 ± 0.05 A	0.21 ± 0.12	14.12 ± 2.51	0.45	0.96	0.70 ± 0.03 A	1.02 ± 0.05 A

[a] SE, standard error; R^2, regression coefficient; SD, standard deviation. Within each column for each pathogen, values followed by the same letter are not significantly different ($P > 0.05$).

TABLE 5. *Color, pH, and lycopene concentration of microwave-treated tomato paste at different power levels*[a]

Power level (kW)	Color			pH	Lycopene (mg/kg)
	L*	a*	b*		
0	31.73 ± 0.07 A	26.81 ± 0.41 A	26.71 ± 1.26 A	3.87 ± 0.17 A	64.41 ± 5.54 A
1.8	31.29 ± 0.09 B	26.97 ± 0.31 A	26.57 ± 0.28 A	3.86 ± 0.15 A	56.66 ± 5.11 A
2.1	31.06 ± 0.11 B	26.65 ± 0.53 A	26.99 ± 0.22 A	3.86 ± 0.15 A	61.05 ± 3.97 A
2.4	31.07 ± 0.20 B	26.32 ± 0.27 A	26.77 ± 0.07 A	3.92 ± 0.16 A	63.41 ± 7.30 A
3.0	31.25 ± 0.31 B	26.64 ± 0.59 A	26.96 ± 0.36 A	3.84 ± 0.17 A	58.92 ± 6.21 A

[a] Values are means ± standard deviations. Within a column, means followed by different letters are significantly different ($P < 0.05$).

atures at the geometric center of MW samples were higher than those at the side, a phenomenon reported by other researchers who suggested that the center concentration effect of 915-MHz MW is a reason for nonuniformity *(7, 25)*. The center concentration effect could also have resulted in the nonuniformity of heating in our MW samples. The problems of nonuniformity have been pointed out by numerous researchers, but solutions have been confined to specific conditions *(35)*. Our results indicate that increasing the power levels could be one way to mitigate the nonuniformity of MW.

Differences in heating uniformity between OH and MW led to differences in inactivation parameters of the foodborne pathogens (Tables 1 through 4). At first, high R^2 ($\geq$0.94) and low RMSE ($\leq$0.50) were observed in both the Weibull and shoulder log-linear models, which indicated that these two models fit well for inactivation of *E. coli* O157:H7, *Salmonella* Typhimurium, and *L. monocytogenes*. The k_{max} parameter, which indicates the inactivation rate, increased as the power level increased regardless of heating method (Tables 1 through 4). We assumed that more time would be needed for MW samples because the side temperature lagged behind the center temperature. The parameters δ and S_l, which represent time needed in the early stage of inactivation, were larger in MW than OH samples as we predicted (Tables 1 through 3). The same tendency was observed for t_{3d} and t_{5d}, which indicate the time needed for 3-log and 5-log reductions, respectively, of the pathogens. Significant differences ($P < 0.05$) between OH and MW samples were found for the t_{3d} and t_{5d} values, which indicates that MW is less effective for inactivation of pathogens than OH at low power levels (1.8 to 2.4 kW). However, significant differences between OH and MW samples were not found for δ, S_l, t_{3d}, and t_{5d} at the highest power level (3.0 kW) (Table 4). The differences in the inactivation parameters between MW and OH decreased as the power level increased because the temperature difference between center and side of MW samples decreased as the power level increased. Thus, heating uniformity achieved by increasing power levels would result in more thorough inactivation of pathogens in MW samples.

Color, pH, and lycopene concentration are major quality aspects of tomato paste. In the present study, L* values of all MW samples decreased significantly ($P < 0.05$) compared with untreated samples and were not significantly different ($P > 0.05$) among MW samples (Table 5). Other quality aspects (a*, b*, pH, and lycopene concentration) were not significantly different between MW and untreated samples ($P > 0.05$). The same tendency was observed for OH samples (data not shown). L* values of OH samples (30.38 to 31.02) decreased significantly ($P < 0.05$) compared with untreated samples (31.91). Similar to MW samples, other quality aspects of OH samples were not significantly different from those of untreated samples ($P > 0.05$). Even though significant quality differences were not observed relative to power levels used in the present study ($P > 0.05$), the lycopene concentration was lowest following treatment at the lowest power level. The effect of power level on the quality of tomato products has also been reported previously. Several researchers have reported that the quality of tomato products was degraded by MW at high power levels *(1, 15, 20)*. However, long processing times at low power levels also can result in quality deterioration *(34)*. Therefore, selection of the appropriate power level is crucial for minimizing quality degradation of food products. Increasing power levels should effectively minimize quality degradation in the range of power levels used in the present study.

In conclusion, increasing the power levels of MW ensured heating uniformity and microbiological safety and preserved quality aspects of tomato paste. Therefore, increasing power levels would be effective for processing tomato paste with MW in the range of power levels used in the present study. Further study should be conducted to identify the overall temperature distribution of MW samples.

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REFERENCES

1. Al-Harahsheh, M., H. Ala'a, and T. Magee. 2009. Microwave drying kinetics of tomato pomace: effect of osmotic dehydration. *Chem. Eng. Process.* 48:524–531.
2. Baysal, A. H., and F. Icier. 2010. Inactivation kinetics of *Alicyclobacillus acidoterrestris* spores in orange juice by ohmic heating: effects of voltage gradient and temperature on inactivation. *J. Food Prot.* 73:299–304.
3. Bennett, S., K. Littrell, T. Hill, M. Mahovic, and C. B. Behravesh. 2015. Multistate foodborne disease outbreaks associated with raw tomatoes, United States, 1990–2010: a recurring public health problem. *Epidemiol. Infect.* 143:1352–1359.
4. Capanoglu, E., J. Beekwilder, D. Boyacioglu, R. Hall, and R. De Vos. 2008. Changes in antioxidant and metabolite profiles during production of tomato paste. *J. Agric. Food Chem.* 56:964–973.
5. Choi, M.-R., Q. Liu, S.-Y. Lee, J.-H. Jin, S. Ryu, and D.-H. Kang. 2012. Inactivation of *Escherichia coli* O157:H7, *Salmonella* Typhi-

murium and *Listeria monocytogenes* in apple juice with gaseous ozone. *Food Microbiol.* 32:191–195.
6. Choi, W., S. H. Lee, C.-T. Kim, and S. Jun. 2015. A finite element method based flow and heat transfer model of continuous flow microwave and ohmic combination heating for particulate foods. *J. Food Eng.* 149:159–170.
7. Choi, W., L. T. Nguyen, S. H. Lee, and S. Jun. 2011. A microwave and ohmic combination heater for uniform heating of liquid-particle food mixtures. *J. Food Sci.* 76:E576–E585.
8. Demirdöven, A., and T. Baysal. 2014. Optimization of ohmic heating applications for pectin methylesterase inactivation in orange juice. *J. Food Sci. Technol.* 51:1817–1826.
9. Dewanto, V., X. Wu, K. K. Adom, and R. H. Liu. 2002. Thermal processing enhances the nutritional value of tomatoes by increasing total antioxidant activity. *J. Agric. Food Chem.* 50:3010–3014.
10. Fryer, P., A. De Alwis, E. Koury, A. Stapley, and L. Zhang. 1993. Ohmic processing of solid-liquid mixtures: heat generation and convection effects. *J. Food Eng.* 18:101–125.
11. Gaware, T., N. Sutar, and B. Thorat. 2010. Drying of tomato using different methods: comparison of dehydration and rehydration kinetics. *Dry. Technol.* 28:651–658.
12. Geeraerd, A., V. Valdramidis, and J. Van Impe. 2005. GInaFiT, a freeware tool to assess non–log-linear microbial survivor curves. *Int. J. Food Microbiol.* 102:95–105.
13. Hayes, W., P. Smith, and A. Morris. 1998. The production and quality of tomato concentrates. *Crit. Rev. Food Sci.* 38:537–564.
14. Heredia, A., C. Barrera, and A. Andrés. 2007. Drying of cherry tomato by a combination of different dehydration techniques: comparison of kinetics and other related properties. *J. Food Eng.* 80:111–118.
15. Heredia, A., I. Peinado, E. Rosa, and A. Andrés. 2010. Effect of osmotic pre-treatment and microwave heating on lycopene degradation and isomerization in cherry tomato. *Food Chem.* 123:92–98.
16. Hosainpour, A., H. Darvishi, F. Nargesi, and A. Fadavi. 2014. Ohmic pre-drying of tomato paste. *Food Sci. Technol. Int.* 20:193–204.
17. Ikediala, J., J. Tang, L. Neven, and S. Drake. 1999. Quarantine treatment of cherries using 915 MHz microwaves: temperature mapping, codling moth mortality and fruit quality. *Postharvest Biol. Technol.* 16:127–137.
18. Kim, S.-S., and D.-H. Kang. 2015. Comparative effects of ohmic and conventional heating for inactivation of *Escherichia coli* O157:H7, *Salmonella enterica* serovar Typhimurium, and *Listeria monocytogenes* in skim milk and cream. *J. Food Prot.* 78:1208–1214.
19. Kim, S.-S., and D.-H. Kang. 2015. Comparison of pH effects on ohmic heating and conventional heating for inactivation of *Escherichia coli* O157:H7, *Salmonella enterica* serovar Typhimurium and *Listeria monocytogenes* in orange juice. *LWT Food Sci. Technol.* 64:860–866.
20. Koné, K. Y., C. Druon, E. Z. Gnimpieba, M. Delmotte, A. Duquenoy, and J.-C. Laguerre. 2013. Power density control in microwave assisted air drying to improve quality of food. *J. Food Eng.* 119:750–757.
21. Lee, I., J. Slonczewski, and J. Foster. 1994. A low-pH–inducible, stationary-phase acid tolerance response in *Salmonella* Typhimurium. *J. Bacteriol.* 176:1422–1426.
22. Lee, J.-Y., S.-S. Kim, and D.-H. Kang. 2015. Effect of pH for inactivation of *Escherichia coli* O157:H7, *Salmonella* Typhimurium and *Listeria monocytogenes* in orange juice by ohmic heating. *LWT Food Sci. Technol.* 62:83–88.
23. Lee, S.-Y., S. Ryu, and D.-H. Kang. 2013. Effect of frequency and waveform on inactivation of *Escherichia coli* O157:H7 and *Salmonella enterica* serovar Typhimurium in salsa by ohmic heating. *Appl. Environ. Microbiol.* 79:10–17.
24. Lin, J., M. P. Smith, K. C. Chapin, H. S. Baik, G. N. Bennett, and J. W. Foster. 1996. Mechanisms of acid resistance in enterohemorrhagic *Escherichia coli*. *Appl. Environ. Microbiol.* 62:3094–3100.
25. Nguyen, L. T., W. Choi, S. H. Lee, and S. Jun. 2013. Exploring the heating patterns of multiphase foods in a continuous flow, simultaneous microwave and ohmic combination heater. *J. Food Eng.* 116:65–71.
26. Park, I.-K., and D.-H. Kang. 2013. Effect of electropermeabilization by ohmic heating for inactivation of *Escherichia coli* O157:H7, *Salmonella enterica* serovar Typhimurium, and *Listeria monocytogenes* in buffered peptone water and apple juice. *Appl. Environ. Microbiol.* 79:7122–7129.
27. Patil, S., P. Bourke, J. M. Frias, B. Tiwari, and P. J. Cullen. 2009. Inactivation of *Escherichia coli* in orange juice using ozone. *Innov. Food Sci. Emerg. Technol.* 10:551–557.
28. Patil, S., V. Valdramidis, P. J. Cullen, J. Frias, and P. Bourke. 2010. Inactivation of *Escherichia coli* by ozone treatment of apple juice at different pH levels. *Food Microbiol.* 27:835–840.
29. Phan-Thanh, L., F. Mahouin, and S. Aligé. 2000. Acid responses of *Listeria monocytogenes*. *Int. J. Food Microbiol.* 55:121–126.
30. Sagong, H.-G., S.-H. Park, Y.-J. Choi, S. Ryu, and D.-H. Kang. 2011. Inactivation of *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* in orange and tomato juice using ohmic heating. *J. Food Prot.* 74:899–904.
31. Sastry, S. K., and J. T. Barach. 2000. Ohmic and inductive heating. *J. Food Sci.* 65:42–46.
32. Sastry, S. K., and S. Palaniappan. 1992. Mathematical modeling and experimental studies on ohmic heating of liquid-particle mixtures in a static heater. *J. Food Process Eng.* 15:241–261.
33. Song, W.-J., and D.-H. Kang. 2016. Inactivation of *Salmonella* Senftenberg, *Salmonella* Typhimurium and *Salmonella* Tennessee in peanut butter by 915 MHz microwave heating. *Food Microbiol.* 53:48–52.
34. Sung, H.-J., and D.-H. Kang. 2014. Effect of a 915 MHz microwave system on inactivation of *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* in salsa. *LWT Food Sci. Technol.* 59:754–759.
35. Vadivambal, R., and D. Jayas. 2010. Non-uniform temperature distribution during microwave heating of food materials—a review. *Food Bioprocess Technol.* 3:161–171.
36. Van Boekel, M. A. 2002. On the use of the Weibull model to describe thermal inactivation of microbial vegetative cells. *Int. J. Food Microbiol.* 74:139–159.