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Inactivation of foodborne pathogens influenced by dielectric properties, relevant to sugar contents, in chili sauce by 915 MHz microwaves

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ABSTRACT

The objective of this study was to investigate the effect of sugar content on dielectric properties of chili sauce, and inactivation efficiency when exposed to microwave energy. Heating history showed sugar content was an important factor influencing heating rate when chili sauce was exposed to microwave energy. Also, chili sauce of lower sugar content had a higher dielectric constant and dielectric loss factor. This trend was linked to inactivation efficiency of chili sauce inoculated with foodborne pathogens. As sugar content decreased, the time required to inactivate foodborne pathogen was reduced. Also, the inactivation efficiency of microwave heating was better since conventional heating took much longer to inactivate foodborne pathogens to under the detection limit. Also, our results showed that there was no significant difference in color, except for 25% and 40% sugar content exposed to 915 MHz microwave at 3.0 kW. Even though decreased water activity was observed, there was no significant difference between conventional heating and microwave heating at 1.5 kW and 3.0 kW. These results show not only that microwave heating can inactivate foodborne pathogens without generating significant quality change but also that the effect relies on dielectric properties associated with the sugar content of chili sauce.

1. Introduction

Sauce products are widely consumed as they are essential for food moisture, flavor, and visual effect. In the Korean food industry, the sales value of various sauces accounts for a considerable part of their profit, which is approximately 1.37 billon U.S dollars (Statista, 2017). Also, sales for chili sauce in the U.S rose by approximately 8.1 percent in 2011 (Statista, 2016). However, in spite of advances in food science and technology for ensuring food safety, foodborne illnesses continue to occur worldwide. Unfortunately, sauces are not an exception, and several cases of sauce-related foodborne diseases have been reported. Salsa had been implicated in 70 foodborne illness outbreaks, and 2280 illness cases occurred between 1990 and 2006 (Franco & Simonne, 2009). Also, The U.S Centers for Disease Control and Prevention (CDC) reported 15 foodborne outbreaks related to sauces between 2010 and 2015 (CDC, 2017).

In general, acidic or acidified food products have been regarded as biologically safe since many bacteria cannot grow under acidic conditions (below pH 4.6, which is the minimum hydrogen ion concentration supporting growth of *Clostridium botulinum*) (van Schothorst, Zwietering, Ross, Buchanan, & Cole, 2009). However, this does not mean that an acidic environment fully inactivates foodborne pathogens. This is because *Escherichia coli* O157:H7 can survive at pH 4 (Glass, Loeffelholz, Ford, & Doyle, 1992). Also, a chili sauce-related foodborne outbreak caused by *Salmonella enteritica* occurred in 2013 and 2015 (CDC, 2017), even though chili sauce is very acidic, implying that an acidic condition below pH 4.6 cannot ensure biologically safety. Moreover, jalapeño and serrano peppers, which are primary ingredients of chili sauces, were involved in a multi-state foodborne outbreak associated with *Salmonella* spp. (CDC, 2008) . Additionally, it was reported that fresh produce can contain several foodborne pathogens such as *Listeria monocytogenes* (Harris et al., 2003). As hot chili sauce can be prepared from fresh produce it can harbor foodborne pathogens.

Salmonella enterica serovar Typhimurium is the main cause of non-typhoidal salmonellosis, involving diarrhea, abdominal cramping, and fever within 72 h of infection (Baird-Parker, 1990). Also, *E. coli* O157:H7 causes severe illnesses which include bloody diarrhea and hemolytic uremic syndrome (Besser, Griffin, & Slutsker, 1999). *L. monocytogenes* causes a severe syndrome called Listeriosis involving neonatal death, septicemia, abortion and meningitis, and has a high mortality rate of about 24% Thus, appropriate methods need to be developed to inactivate these foodborne pathogens for the biological safety of hot chili sauce.

For pasteurization, conventional heating is typically utilized by the food industry. Heating occurs through conduction and convection when food is subjected to conventional heating. In this process, the outer part of the food can be over-heated while the interior (cold spot) can be underheated; thus conventional heating results in non-uniform heat distribution and takes more time for proper pasteurization than other methods such as ohmic heating and RF heating. Consequently, pasteurization by means of conventional heating is not effective for inactivating foodborne pathogens and can result in deterioration of food quality.

For these reasons, it is necessary to develop useful alternatives to conventional heating, and microwave heating has been considered as an alternative in several studies. Microwave heating quickly generates volumetric heat inside food as microwaves can penetrate the interior of food, implying that food can processed with better efficiency. Since it can process food products much faster, it can maintain desirable food quality attributes such as nutrition or flavor in comparison to conventional heating treatment

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(Vadivambal & Jayas, 2010; Zhu, Kuznetsov, & Sandeep, 2007). Since microwave heating is a form of dielectric heating and dielectric properties can influence the heating rate, dielectric properties of food products should be considered.

Dielectric properties can be affected by several factors such as salt content, moisture content, frequency of applied electromagnetic waves, and temperature. Among these factors, water is the main factor influencing heating rate of food exposed to microwave energy. Thus, sugar content was selected as a factor for dielectric properties to investigate the effect of microwave heating on chili sauce pasteurization, since the sugar content of chili sauce varies from 10% to 38% in the market and affects water activity (a_w)of chili sauce as sugar binds with water molecules.

There have been several studies investigating the efficiency of microwave heating for inactivation of foodborne pathogens depending on the water activity of food products (Song & Kang, 2016b). However, it has not been reported how dielectric properties of food products affect the pasteurization of food under microwave energy. Thus, in this study, we compared the efficiency of microwave heating and conventional heating and investigated how dielectric properties of food affect the inactivation of foodborne pathogens in chili sauce.

2. Materials and methods

2.1. Bacterial strains and culture preparation

Strains of *E. coli* O157:H7 (ATCC 35150, ATCC 43889, ATCC 43890), *S.* Typhimurium (ATCC 19585, ATCC 19115, DT 104), and *L. monocytogenes* (ATCC 15313, ATCC 19111, ATCC 19115) were obtained from the bacterial cell culture collection of Seoul National University (Seoul, Republic of Korea) for study. Stock cultures were stored frozen at −80 °C in 0.7 ml of Tryptic Soy Broth (TSB; Difco, BD, Sparks, MD) and 0.3 ml of sterile 50% (V/V) glycerol. Cultures for this study were streaked onto Tryptic Soy Agar (TSA; Difco, BD), incubated at 37 °C for 24 h h and stored at 4 °C. A single colony of each strain was transferred to 5 ml of TSB and incubated at 37 °C for 24 h. Then, 1 ml of the overnight culture of each strain was spread onto TSA, followed by 37 °C incubation for 24 h. Five ml of sterile 0.2% peptone water (PW) was added to each plate to harvest the bacterial cells, and the cell suspensions were collected by scrubbing the agar surfaces with sterile cotton swabs (3M pipette swab, 3M Korea Ltd) to remove cells. Cell pellets were obtained by centrifugation of the cell suspension at 4000 g for 20 min at 4 °C and washing three times with 0.2% peptone water (PW; Bacto, Sparks, MD) The final cell pellets were resuspended in PW and the population of *E. coli* O157:H7, *S.* Typhimurium, and *L. monocytogenes* was 10^8–10^9 CFU/ml.

2.2. Sample preparation and inoculation

Experiments were performed using commercially processed hot chili sauce. Shelf-stable chili sauce of 10% sugar content was purchased at a local grocery store (Seoul, Republic of Korea) for this study and stored at room temperature (22 ± 1 °C). Sugar content was adjusted by addition of sucrose. Twenty-five g of chili sauce sample were aseptically placed in sterile 100 ml Pyrex beakers. For inoculation, one ml of bacterial cell culture was inoculated into each sample and thoroughly mixed for 1 min with a sterile spoon to ensure even distribution of bacterial cells. The populations of *E. coli* O157:H7, *S.* Typhimurium, and *L. monocytogenes* recovered from inoculated samples were 10^7–10^8 CFU/ml.

2.3. Microwave heating treatment

Microwave treatment was performed in a previously described apparatus (Sung & Kang, 2014) for 915 MHz treatment, or in a domestic microwave oven for 2450 MHz treatment(700 W). A beaker containing 25 g of chili sauce sample was located at the center of the turntable, and subjected to microwave heating. For inactivation of pathogens and quality evaluation, samples were treated at 2 different power levels (1.5 kW, 3.0 kW) only for the 915 MHz treatment.

2.4. Conventional heating treatment

For conventional heating, a constant-temperature water bath (BW-10G; Jeio Tech, Seoul, South Korea) was utilized in this study. The conventional heating chamber was made of stainless steel (2 × 15 × 6 cm) of 0.2 cm thickness. Temperature of the water bath was fixed at 100 °C. Samples were prepared as above and treated for up to 6 min.

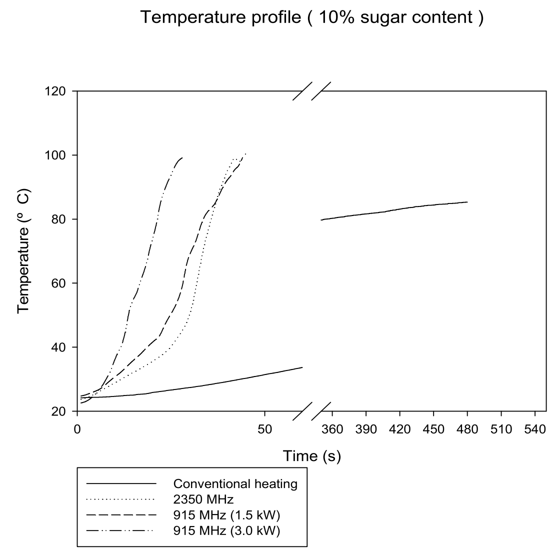


Fig. 1. Temperature curve of 10% sugar content chili sauce of during conventional heating, 2450 MHZ microwave heating, and 915 MHz microwave heating at 1.5 kW and 3.0 kW. The results are the mean of three experiments.

2.5. Temperature measurement

For temperature measurement of microwave heating and conventional heating, the geometric center temperature of a non-inoculated sample adjusted to 10%, 25%, and 40% sugar content in a beaker was measured with a fiber optic sensor (FOT-L; FISO Technologies INC, Quebec, Canada) connected to a temperature signal conditioner. This optic sensor measures real-time temperature in samples during microwave heating and conventional heating and was recorded at 1 s intervals. The rate of temperature increase was calculated by dividing the difference in temperature between the beginning and the end by the treatment time.

2.6. Dielectric properties measurement

Dielectric properties of chili sauce of varying sugar content were measured using a network analyzer coupled with a dielectric probe kit (85070E, Agilent Technologies). Calibration was conducted using three standards: air, a standard shorting block (85070-60003, Agilent Technologies), and distilled water at 25 °C. During measurement, room temperature was maintained at 25 °C.

2.7. Bacterial cell enumeration

After conventional heating treatment and microwave heating treatment at 915 MHz, 25 g of sample was immediately mixed with 25 ml of 4.0 °C 0.2% sterile peptone water (PW) to cool the sample and arrest thermal inactivation. Then, the mixture was poured into a stomacher bag containing 200 ml of PW and homogenized for 2 min in a stomacher (EASY MIS, AES Chemunex, Rennes, France). After homogenization, one ml aliquots of samples were 10-fold serially diluted in 9 ml of 0.2% sterile peptone water and then 0.1 ml of diluent was spread-plated onto Sorbitol MacConkey agar (SMAC; Difco), Xylose Lysine Deoxycholate agar (XLD; Difco), and Oxford Agar Base with antimicrobial supplement (OAB; MB cell) for enumeration of *E. coli* O157:H7, *S.* Typhimurium, and *L. monocytogenes*, respectively. In order to enumerate sub-lethally injured cells of *E. coli* O157:H7, the same volume of diluents were spread-plated onto phenol red agar base with 1% sorbitol (SPRAB; Difco) (Rocelle, Clavero, & Beuchat, 1995). For enumeration of injured cells of *S.* Typhimurium and L. *monocytogenes*, the overlay (OV) method was used (Lee & Kang, 2001). TSA was utilized as a nonselective agar to resuscitate injured bacteria. One hundred μl of selected dilutions were spread-plated onto TSA medium, incubated for 2 h at 37 °C, then overlaid with 10 ml selective medium such as XLD or OAB for *S.* Typhimurium or L. *monocytogenes*, respectively. After solidification of the medium, overlaid plates were further incubated for 22 h at 37 °C.

2.8. Color and water activity measurement

To measure the effect of conventional heating and microwave heating on the color of chili sauce of varying sugar content, a Minolta colorimeter

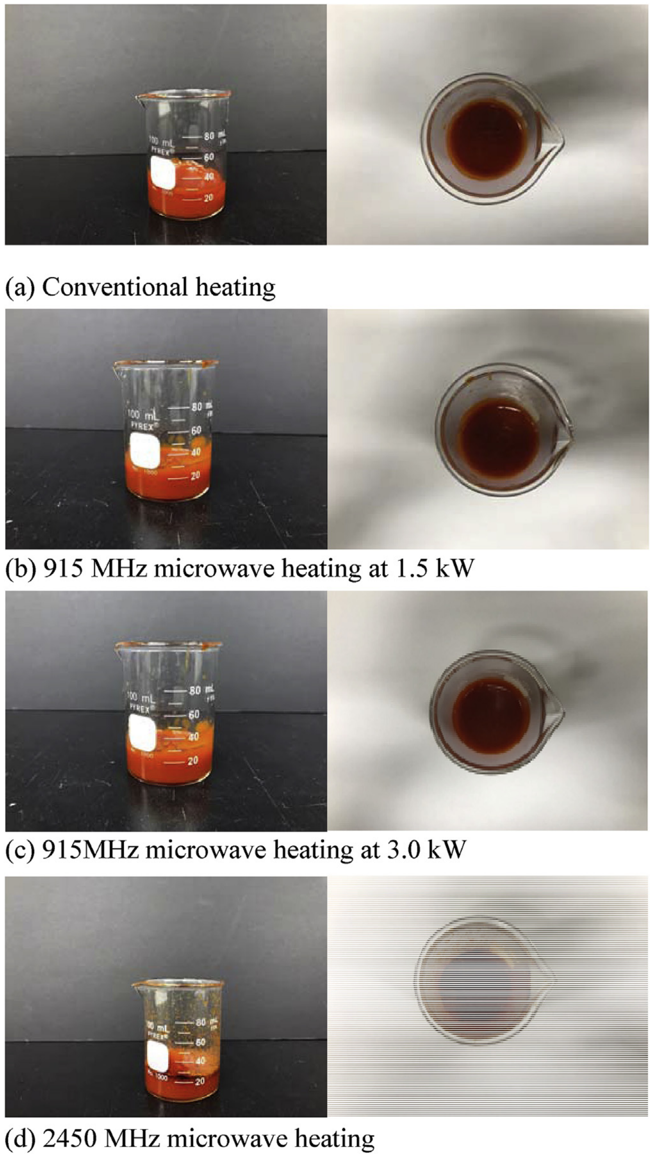


Fig. 2. Appearance of 10% sugar content chili sauce after (a) conventional heating treatment, (b) 915 MHz microwave heating at 1.5 kW, (c) 915 MHz microwave heating at 3.0 kW, and (d) 2450 MHz microwave heating.

Table 1
Color values and water activity of chili sauce of 10% sugar content after heating to 85 °C.

Treatment	Color[a,b]		
	L*	a*	b*
Control	30.92 ± 0.14a	11.56 ± 1.20a	12.72 ± 1.45a
Conventional heating	33.11 ± 0.31a	10.29 ± 1.14a	10.09 ± 1.37a
915 MHz at 1.5 kW	32.57 ± 1.72a	11.06 ± 1.54a	10.39 ± 1.45a
915 MHz at 3.0 kW	31.51 ± 1.56a	10.95 ± 1.11a	11.30 ± 1.61a
2450 MHz	26.08 ± 2.86b	16.45 ± 3.48b	20.97 ± 6.70b

[a] Means ± standard deviation from three replications. Values followed by the same letters within the same column are not significantly different ($P > 0.05$).
[b] Color parameters are L*(Lightness), a*(Redness), b*(Yellowness).

(CR400; Minolta Co., Osaka, Japan) was used to measure the color changes of heat-treated samples. The value of L*, a*, and b* were utilized to quantify color attributes. L*, a*, and b* indicate color lightness, redness, and yellowness of sample, respectively. For measurement of the influence of sugar content on water activity of chili sauce, an Aqualab model 4 TE a_w meter

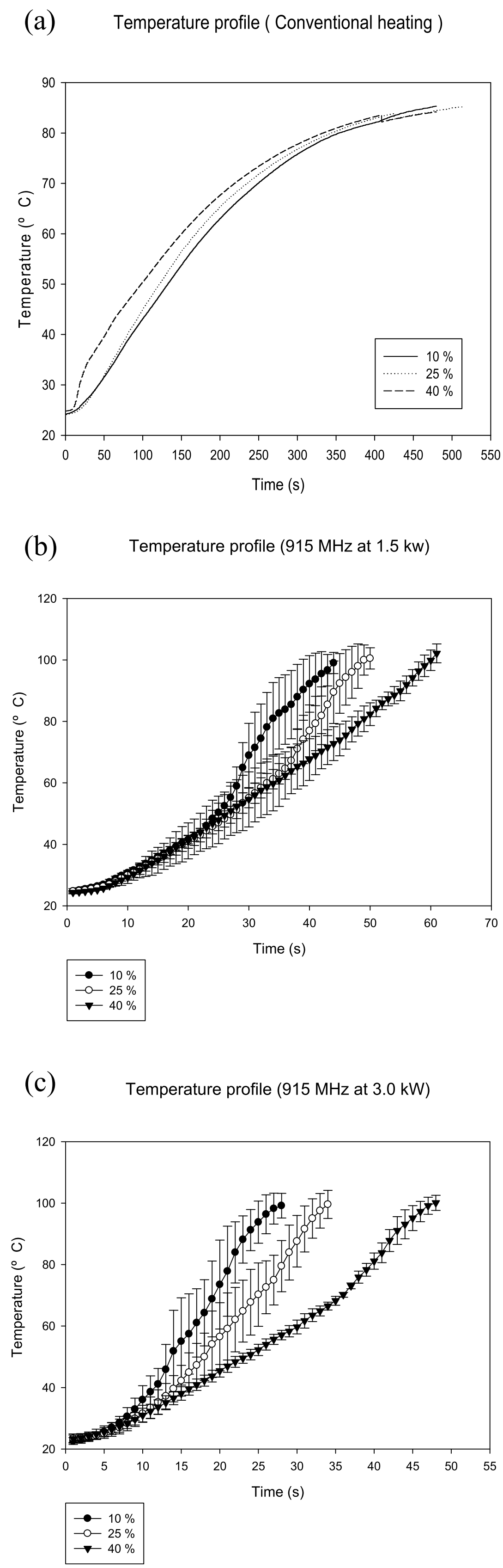


Fig. 3. Temperature curves of 10%, 25%, and 40% sugar content chili sauce after (a) conventional heating, (b) 915 MHz microwave heating at 1.5 kW, and (c) 915 MHz microwave heating at 3.0 kW.

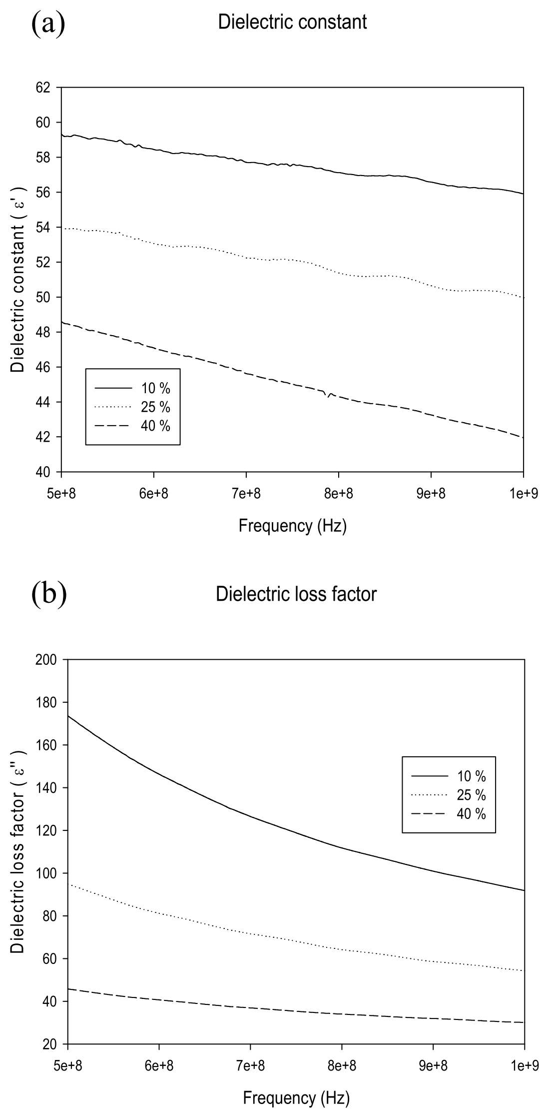


Fig. 4. Dielectric properties from 500 MHz to 1 GHz of chili sauce of varying sugar content: (a) Dielectric constant, (b) Dielectric loss factor.

(METER Group, Pullman, WA) was used to measure the water activity of treated samples.

2.9. Statistical analysis

All experiments were repeated at least three times with independently prepared samples. Data were analyzed by analysis of variance (ANOVA) and *t*-test (LSD) using the Statistical Analysis System (SAS Institute, Cary, NC, USA). A *p* value of < 0.05 was used to indicate significant difference.

3. Results

3.1. Comparison of temperature profile and visual quality of 10% sugar content chili sauce

Fig. 1 shows the temperature increase of 10% sugar content chili sauce. In this experiment design, a difference in temperature history was observed. The temperature attained 85 °C after 470 s of conventional heating treatment, while the temperature of samples treated with 2450 MHz microwave and 915 MHz microwave at 1.5 kW reached 100 °C after 45 s of heating treatment. The fastest rate of temperature increase was with 915 MHz treatment at 3.0 kW, reaching 100 °C in 28 s. The visual appearance of chili sauce after each treatment is shown in Fig. 2, and compared in Table 1. When subjected to 2450 MHz microwave heating, quality deterioration was evident. However, there was no clear visual effect on quality following conventional heating and 915 MHz microwave heating at 1.5 kW and 3.0 kW. Color values also showed similar results. Table 1 reveals no significant color value differences in samples treated with conventional heating and 915 MHz microwave heating, whereas samples treated with 2450 MHz microwaves showed decreased L* and increased a* and b* values.

Since the peripheral parts of samples treated with 2450 MHz microwave heating were blackened, we conducted further study using only conventional heating and 915 MHz microwave heating.

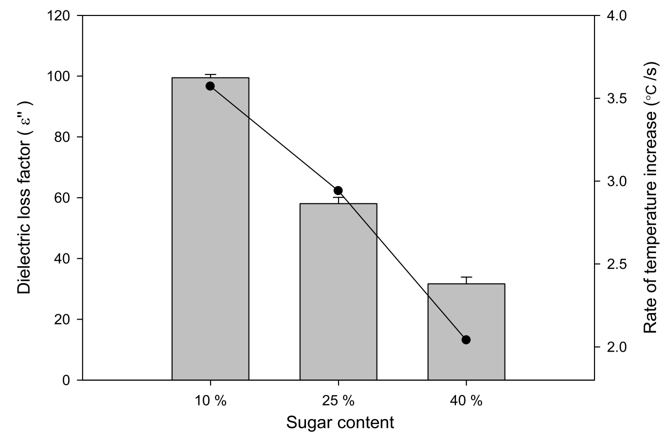


Fig. 5. Relationship between dielectric loss factor of chili sauce of varying sugar content and rate of temperature increase during microwave heating at 3.0 kW, rate of temperature increase;, dielectric loss factor.

3.2. Influence of sugar content on conventional heating and 915 MHz microwave heating treatment

The average temperatures of chili sauce of varying sugar content (10%–40%) during conventional heating and 915 MHz microwave heating at 1.5 kW and 3.0 kW are shown in Fig. 3. Among different sugar levels, there was no significant difference in the rate of temperature increase when treated with conventional heating ($P > 0.05$). On the other hand, the rate of increase was dependent on sugar content when exposed to microwave energy. Following 915 MHz microwave heating treatment at 1.5 kW, the temperature of 10%, 25%, and 40% sugar content chili sauce increased from ca. 20 °C to 100 °C after 44 s, 50s, and 61s, respectively. Also, it took 28 s, 34 s, and 48 s, respectively, to reach 100 °C when chili sauce of 10%, 25%, 40% sugar content was treated with 915 MHz microwave heating at 3.0 kW. Lower sugar content combined with a higher power level of microwave heating accelerated the rate of temperature increase.

3.3. Influence of sugar content on dielectric properties of chili sauce

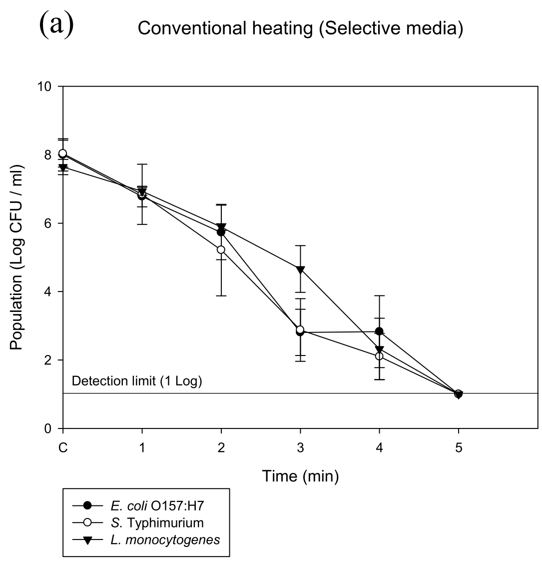
The dielectric properties of chili sauce at each of the three sugar levels were analyzed from 500 MHz to 1 GHz as shown in Fig. 4. Both dielectric constant and dielectric loss factor of chili sauce significantly increased with decreasing sugar content. At 915 MHz, the dielectric constant of chili sauce of 10%, 25%, and 40% sugar content were 56.4, 50.4, and 43.1, respectively. Also, the dielectric loss factor of chili sauce of these sugar contents were 99.5, 58.0, and 31.7.

3.4. Relationship between the rate of temperature increase, dielectric loss factor, and sugar content of chili sauce

The results of the rate of temperature increase, dielectric loss factor, and sugar content of chili sauce were analyzed for the relationships among them and shown in Fig. 5. Our results revealed that the dielectric loss factor was inversely proportional to sugar content as shown in Fig. 6. Also, the rate of temperature increase highly relied on the sugar content of chili sauce, since the rate of temperature increase fell as sugar content of chili sauce increased.

3.5. Inactivation of foodborne pathogens in chili sauce by conventional heating and microwave heating

Since Fig. 3 shows that there was no significant difference in the rate of temperature increase when samples were subjected to conventional heating, we conducted an inactivation study only using chili sauce of 10% sugar content. The reduction of foodborne pathogens increasedas treatment time



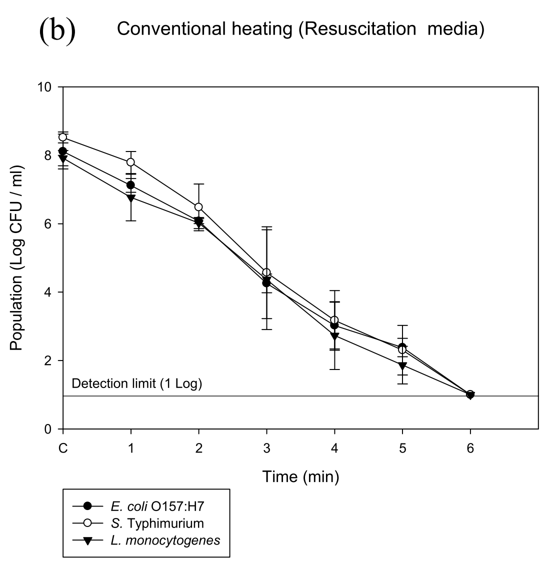


Fig. 6. Population curve of *E. coli* O157:H7(●), *S.* Typhimurium (○), and *L. monocytogenes* (▼) in chili sauce of 10% sugar content during conventional heating as enumerated on selective media (a) and on resuscitation media (b) to recover sub-lethally injured bacterial cells. Detection limit was 1.0 log CFU/ml.

increased as shown in Fig. 6. When treated with conventional heating for 5 min, all pathogens were reduced to under the detection limit (1 Log CFU/ml) whereas sub-lethally injured cells were not detected after 6 min of treatment. All three pathogens showed a similar reduction tendency, except for the 3 min time point in which *L monocytogenes* showed a slightly higher population than the other pathogenic bacteria as shown in Fig. 6-(a) ($P < 0.05$). Microwave heating showed much higher inactivation efficiency. When samples of 10%, 25%, and 40% sugar content were exposed to 915 MHz microwave energy at 1.5 kW, *E. coli* O157:H7 was not detected after 50 s, 60 s, and 70 s treatment, respectively, as shown in Tables 2a–2c. *L. monocytogenes* showed a trend similar to *E. coli* O157:H7, while the population of *S.* Typhimurium in chili sauce of 25% sugar content fell to under the detection limit after 50 s treatment. According to Tables 2a–2c, injured cells also demonstrated a similar trend. Even though they showed a slightly higher population than cells on selective media, there was no significant overall difference between injured cell populations and populations of cells on seletive agar ($P > 0.05$). When increased power was applied, the inactivation efficiency was higher. Tables 3a–3c shows that when samples of 10%, 25%, and 40% sugar content were treated with 915 MHz microwave energy of 3.0 kW, all pathogens on selective media were inactivated to under the detection limit after 20 s, 25 s, and 40 s, respectively. Additionally, Table 3a-3c reveals that sub-lethally injured cells also follow a similar trend, as they likewise were not detected after 20 s, 25 s, and 40 s.

3.6. Measurement of chili sauce quality after conventional heating and microwave heating

Table 4 shows he color and water activity changes of chili sauce samples of varying sugar content after conventional heating and microwave heating treatment at 1.5 kW and 3.0 kW for the treatment times needed to reduce populations of foodborne pathogens to below the detection limit. Overall, there was no significant change in color after heating treatment, except for samples of 25% and 40% sugar content exposed to 915 MHz microwave heating at 3.0 kW a* and b* values were reduced by 0.54 and 0.61 respectively, when chili sauce of 25% sugar content was treated with 915 MHz microwave heating at 3.0 kW, while these values for 40% sugar content chili sauce were reduced by 0.49 and 1.18 log CFU/g, respectively. Water activity was reduced in all heating treatments. However, no significant difference was observed after conventional heating and microwave heating of chili sauce of 10% sugar content. On the other hand, sugar content also influenced the change of water activity. The degree of change was 0.008 a_w and 0.011 a_w when sugar content was 10%, but those changes in chili sauce of 40% sugar content were 0.031 a_w and 0.023 a_w when exposed to microwave energy at 3.0 kW and 1.5 kW, respectively.

4. Discussion

Microwave heating treatment is widely used in the food industry and in household appliances. In the USA, most industrial microwave systems operate at 915 MHz, since it penetrates more deeply than 2450 MHz microwave systems (Wang, Wig, Tang, & Hallberg, 2003). In this study, we analyzed the heating rate profile after treatment with conventional heating, 2450 MHz microwave heating, and 915 MHz microwave heating at 1.5 kW and 3.0 kW. Temperature rapidly increased when samples were treated with the 915 MHz microwave system, while it took ca. 480 s to reach 85 °C under conventional heating in this experiment design. Also, there was no significant difference in color values of

Table 2a
Comparison of pathogen populations between surviving cells and cells including heat-injured cells in 10% chili sauce following 915 MHz microwave heating at 1.5 kW.

Time (s)	*E. coli* O157:H7		*S.* Typhimurium		*L. monocytogenes*	
	SMAC	SPRAB	XLD	TSA-XLD	OAB	TSA-OAB
	Population (log CFU/ml)[a]					
0	7.60 ± 0.52a	7.99 ± 0.16a	8.04 ± 0.15a	8.31 ± 0.06b	7.38 ± 0.20a	7.43 ± 0.17a
20	7.02 ± 0.94a	7.23 ± 1.22a	6.90 ± 0.36a	7.70 ± 0.32b	7.21 ± 0.80a	7.24 ± 0.27a
30	5.35 ± 0.23a	5.99 ± 0.16b	5.94 ± 0.25a	6.44 ± 0.58a	6.15 ± 0.25a	5.96 ± 0.76a
40	3.55 ± 1.12a	4.73 ± 0.98a	3.44 ± 0.53a	4.59 ± 0.21b	3.58 ± 0.50a	4.35 ± 0.70a
50	ND	ND	ND	ND	ND	ND

a Means ± standard deviation from three replications. Values followed by the same letters within the row per foodborne pathogen are not significantly different ($P > 0.05$). SMAC: Sorbitol MacConkey agar, SPRAB: Phenol Red Agar Base with 1% sorbitol, XLD: Xylose Lysine Deoxycholate agar, OAB: Oxford Agar Base with antimicrobial supplement, TSA: Tryptic Soy Agar.

Table 2b
Comparison of pathogen populations between surviving cells and cells including heat-injured cells in 25% chili sauce following 915 MHz microwave heating at 1.5 kW.

Time (s)	*E. coli* O157:H7		*S.* Typhimurium		*L. monocytogenes*	
	SMAC	SPRAB	XLD	TSA-XLD	OAB	TSA-OAB
	Population (log CFU/ml)[a]					
0	8.08 ± 0.27a	8.09 ± 0.27a	7.94 ± 0.18a	8.47 ± 0.09b	7.30 ± 0.27a	7.59 ± 0.27a
20	7.27 ± 0.14a	7.56 ± 0.20a	7.53 ± 0.21a	8.02 ± 0.08b	7.24 ± 0.63a	7.06 ± 0.63a
30	6.11 ± 0.70a	6.12 ± 0.09a	5.95 ± 0.25a	6.08 ± 0.67a	6.33 ± 0.45a	6.22 ± 0.45a
40	5.57 ± 1.23a	5.29 ± 0.50a	4.81 ± 0.38a	5.96 ± 0.52a	4.93 ± 0.40a	5.68 ± 0.40a
50	2.42 ± 0.56a	3.38 ± 0.74a	ND	2.46 ± 0.60	1.81 ± 0.58a	2.05 ± 1.00a
60	ND	ND	ND	ND	ND	ND

a Means ± standard deviation from three replications. Values followed by the same letters within the row per foodborne pathogen are not significantly different ($P > 0.05$).
SMAC: Sorbitol MacConkey agar, SPRAB: Phenol Red Agar Base with 1% sorbitol, XLD: Xylose Lysine Deoxycholate agar, OAB: Oxford Agar Base with antimicrobial supplement, TSA: Tryptic Soy Agar.

chili sauce between conventional and 915 MHz heating. However, deteriorating visual quality was observed when samples were exposed to 2450 MHz microwave energy. In this study, we measured the temperature in the geometric center. It is known that in the case of 2450 MHz microwave treatment, the surface heating rate was higher in the peripheral region, while the geometric center of samples reached a higher temperature when heated with a 915 MHz system (Mudgett, 1989). Thus, we can easily assume that deteriorating visual quality was observed due to overheating at the sample surface. As samples subjected to the 2450 microwave system showed degraded visual quality, we chose conventional heating and 915 MHz microwave heating at 1.5 kW and 3.0 kW for further study.

We observed the temperature increase of chili sauce of 10–40% sugar content. In the case of conventional heating, there was no significant difference in heating rate among chili sauces of differing sugar content. However, chili sauce exposed to 915 MHz microwave energy showed a different tendency. Chili sauce of 10% sugar content exhibited the highest rate of temperature increase, whereas the heating rate was slowest for chili sauce of 40% sugar content. Water activity is one major factor influencing microwave heating rate. The study conducted by Song and Kang (2016a,b) showed that peanut butter of differing water activity revealed different heating rates, and the sample of highest water activity had the highest rate of temperature increase (Song & Kang, 2016b). Our results also showed positive correlation with water activity and rate of temperature increase. Also, as there was no significant difference in heating rate when treated with conventional heating, we conducted further study with only 10% sugar content chili sauce in the case of conventional heating treatment.

Microwaves are a form of dielectric heating, and thus dielectric properties should be taken into consideration in order to explain the different tendencies in heating rate. Dielectric properties can be described by dielectric constant and dielectric loss factor. Dielectric constant describes the ability of a material to

Table 2c
Comparison of pathogen populations between surviving cells and cells including heat-injured cells in 40% chili sauce following 915 MHz microwave heating at 1.5 kW.

Time (s)	*E. coli* O157:H7		*S.* Typhimurium		*L. monocytogenes*	
	SMAC	SPRAB	XLD	TSA-XLD	OAB	TSA-OAB
	Population (log CFU/ml)[a]					
0	7.93 ± 0.34a	8.09 ± 0.27a	7.99 ± 0.39a	8.47 ± 0.26a	7.35 ± 0.35a	7.77 ± 0.25a
20	7.47 ± 0.15a	7.61 ± 0.42a	7.94 ± 0.13a	7.85 ± 0.65a	7.20 ± 0.49a	6.97 ± 0.33a
30	7.11 ± 0.41a	7.31 ± 0.17a	6.96 ± 0.37a	7.75 ± 0.44b	6.61 ± 0.47a	6.66 ± 0.40a
40	5.68 ± 0.32a	6.22 ± 0.28a	5.60 ± 0.84a	7.02 ± 0.28b	6.32 ± 0.21a	6.35 ± 0.26a
50	4.68 ± 0.67a	5.45 ± 0.19a	4.11 ± 0.79a	6.04 ± 1.24a	5.60 ± 0.39a	5.48 ± 0.52a
60	3.12 ± 1.02a	3.38 ± 0.47a	2.93 ± 0.73a	3.60 ± 1.26a	3.36 ± 1.05a	3.01 ± 0.96a
70	ND	ND	ND	ND	ND	ND

a Means ± standard deviation from three replications. Values followed by the same letters within the row per foodborne pathogen are not significantly different ($P > 0.05$).
SMAC: Sorbitol MacConkey agar, SPRAB: Phenol Red Agar Base with 1% sorbitol, XLD: Xylose Lysine Deoxycholate agar, OAB: Oxford Agar Base with antimicrobial supplement, TSA: Tryptic Soy Agar.

Table 3a
Comparison of pathogen populations between surviving cells and cells including heat-injured cells in 10% chili sauce following 915 MHz microwave heating at 3.0 kW.

Time (s)	*E. coli* O157:H7		*S.* Typhimurium		*L. monocytogenes*	
	SMAC	SPRAB	XLD	TSA-XLD	OAB	TSA-OAB
	Population (log CFU/ml)[a]					
0	7.43 ± 0.14a	7.83 ± 0.28a	7.73 ± 0.27a	8.22 ± 0.13b	7.25 ± 0.11a	7.65 ± 0.13b
10	5.30 ± 0.40a	7.51 ± 0.36b	6.29 ± 0.13a	7.53 ± 0.37b	6.60 ± 0.42a	6.75 ± 0.48a
15	3.31 ± 0.77a	3.35 ± 0.99a	2.89 ± 0.86a	4.43 ± 1.35a	3.28 ± 0.70a	3.81 ± 0.66a
20	ND	ND	ND	ND	ND	ND

a Means ± standard deviation from three replications. Values followed by the same letters within the row per foodborne pathogen are not significantly different ($P > 0.05$).
SMAC: Sorbitol MacConkey agar, SPRAB: Phenol Red Agar Base with 1% sorbitol, XLD: Xylose Lysine Deoxycholate agar, OAB: Oxford Agar Base with antimicrobial supplement, TSA: Tryptic Soy Agar.

Table 3b
Comparison of pathogen populations between surviving cells and cells including heat-injured cells in 25% chili sauce following 915 MHz microwave heating at 3.0 kW.

Time (s)	*E. coli* O157:H7		*S.* Typhimurium		*L. monocytogenes*	
	SMAC	SPRAB	XLD	TSA-XLD	OAB	TSA-OAB
	Population (log CFU/ml)[a]					
0	7.60 ± 0.42a	7.82 ± 0.17a	7.93 ± 0.13a	8.06 ± 0.04a	7.24 ± 0.10a	7.64 ± 0.33a
10	5.80 ± 0.34a	6.73 ± 1.20a	7.18 ± 0.52a	7.59 ± 0.20a	6.74 ± 0.48a	6.84 ± 0.06a
15	4.61 ± 0.90a	6.23 ± 0.55a	4.64 ± 0.88a	6.70 ± 0.52b	5.50 ± 1.41a	5.18 ± 0.82a
20	2.19 ± 0.77a	2.43 ± 0.42a	2.40 ± 1.17a	3.18 ± 1.37a	3.48 ± 1.06a	3.53 ± 0.88a
25	ND	ND	ND	ND	ND	ND

a Means ± standard deviation from three replications. Values followed by the same letters within the row per foodborne pathogen are not significantly different ($P > 0.05$).
SMAC: Sorbitol MacConkey agar, SPRAB: Phenol Red Agar Base with 1% sorbitol, XLD: Xylose Lysine Deoxycholate agar, OAB: Oxford Agar Base with antimicrobial supplement, TSA: Tryptic Soy Agar.

store, transmit, and reflect electromagnetic energy when it is exposed to microwave energy (Sosa-Morales, Valerio-Junco, López-Malo, & García, 2010). Whereas, dielectric loss factor describes the dissipation of electric energy, which indicates the amount of heat generated by microwave energy (Datta & Davidson, 2000; Ramaswamy & Tang, 2008). Our results showed that adding more sugar slightly decreased the dielectric constant and sharply reduced the dielectric loss factor, and this had direct correlation with water activity. The study conducted by Roth et al., also showed that soil of higher moisture content had a higher dielectric constant (Roth, Malicki, & Plagge, 1992). This is due to the relation between water activity and dielectric properties of food materials. The water molecule has a high dipolar property, and it aligns its molecular orientation following the direction of microwave radiation. Microwave frequencies are very high, thus the rapid oscillation and realignment of water molecules causes friction inside the food matrix, resulting in volumetric heating. Therefore, water activity or moisture content has an important impact on dielectric properties of foods and is one of the main factors influencing microwave heating (Tanaka & Sato, 2007). Therefore, understanding dielectric properties of food relevant to water content and water activity is important for characterizing microwave heating effectiveness.

Our results showed that there was a direct correlation between the rate of temperature increase and dielectric loss factor. The effect of dielectric properties on the rate of temperature increase can be explained by the equation $P = 2\pi f V\varepsilon_0\varepsilon''$, where P is the electrical power which is transferred to the food matrix in the form of heat, V is the electrical field strength, ε_0 is

Table 3c
Comparison of pathogen populations between surviving cells and cells including heat-injured cells in 40% chili sauce following 915 MHz microwave heating at 3.0 kW.

Time (s)	*E. coli* O157:H7		*S.* Typhimurium		*L. monocytogenes*	
	SMAC	SPRAB	XLD	TSA-XLD	OAB	TSA-OAB
	Population (log CFU/ml)[a]					
0	7.69 ± 0.22a	7.58 ± 0.15a	8.26 ± 0.14a	8.24 ± 0.06a	7.42 ± 0.00a	7.57 ± 0.07b
10	6.03 ± 0.18a	7.53 ± 0.64b	7.44 ± 0.85a	7.50 ± 0.36a	6.92 ± 0.16a	7.10 ± 0.16a
15	5.02 ± 0.47a	6.39 ± 0.19b	6.07 ± 0.08a	6.44 ± 0.10b	6.48 ± 0.23a	6.86 ± 0.11b
20	5.22 ± 0.38a	6.24 ± 0.14b	5.81 ± 0.28a	6.35 ± 0.52a	6.15 ± 0.12a	6.28 ± 0.25a
25	4.32 ± 1.47a	5.47 ± 1.42a	4.13 ± 1.91a	5.49 ± 0.94a	5.45 ± 0.13a	5.45 ± 0.89a
30	2.39 ± 0.98a	2.71 ± 1.34a	2.60 ± 0.38a	2.88 ± 1.30a	4.11 ± 0.17a	4.44 ± 0 02b
40	ND	ND	ND	ND	ND	ND

a Means ± standard deviation from three replications. Values followed by the same letters within the row per foodborne pathogen are not significantly different ($P > 0.05$).
SMAC: Sorbitol MacConkey agar, SPRAB: Phenol Red Agar Base with 1% sorbitol, XLD: Xylose Lysine Deoxycholate agar, OAB: Oxford Agar Base with antimicrobial supplement, TSA: Tryptic Soy Agar.

Table 4
Color values and water activity of chili sauce of varying sugar content after conventional heating and 915 MHz microwave heating at 1.5 kW and 3.0 kW.

Sugar contents	Time (s)	Color[ab]			Water activity[a]
		L*	a*	b*	
10%	0^{A}	29.50 ± 0.23^{ab}	8.52 ± 0.34^{a}	10.33 ± 0.33^{ab}	0.919 ± 0.003^{a}
	20^{B}	28.59 ± 0.42^{abcd}	8.77 ± 1.33^{a}	10.89 ± 1.16^{a}	0.911 ± 0.001^{ab}
	50^{C}	30.02 ± 0.33^{a}	7.35 ± 0.22^{b}	7.82 ± 0.24^{c}	0.908 ± 0.000^{b}
	470^{D}	29.48 ± 1.72^{abc}	8.74 ± 0.37^{a}	9.92 ± 0.94^{b}	0.913 ± 0.004^{ab}
25%	0^{A}	28.02 ± 0.73^{cde}	4.43 ± 0.15^{c}	6.89 ± 0.06^{cd}	0.894 ± 0.003^{c}
	25^{B}	26.63 ± 0.88^{e}	3.89 ± 0.25^{c}	6.28 ± 0.25^{d}	0.879 ± 0.003^{d}
	60^{C}	28.33 ± 1.52^{bcd}	4.35 ± 0.24^{c}	5.99 ± 0.78^{de}	0.881 ± 0.005^{d}
40%	0^{A}	27.95 ± 0.16^{de}	2.02 ± 0.27^{d}	5.02 ± 0.04^{f}	$0.863 \pm 0.0.6^{e}$
	40^{B}	27.49 ± 0.13^{de}	1.53 ± 0.07^{d}	3.84 ± 0.06^{g}	0.832 ± 0.001^{g}
	70^{C}	27.14 ± 0.67^{de}	2.03 ± 0.19^{d}	5.05 ± 0.09^{ef}	0.840 ± 0.011^{f}

Superscript letter in time column indicates treatment applied to chili sauce.
A: Control, B: 915 Microwave heating at 3.0 kW, C: 915 MHz microwave heating at 1.5 kW, D: conventional heating.
a Means ± standard deviation from three replications. Values followed by the same letters within the column per sugar contents are not significant different ($P > 0.05$).
b Color parameters are L*(Lightness), a*(Redness), b*(Yellowness).

the dielectric constant of a vacuum (8.85 × 10–12 F/m), and ε'' is the dielectric loss factor of the sample (Marra, Lyng, Romano, & McKenna, 2007). We can calculate how much heat is generated inside of a food matrix based on this equation. As the microwave power was fixed at 3.0 kW and 1.5 kW, it is easily assumed that electric field strength was also fixed. Also, we conducted our study at 915 MHz. Thus, we consider only dielectric loss factor as determining the rate of temperature increase. Our results showed agreement with the above equations. The higher the loss factor the sample possessed due to higher water activity, the faster the rate of temperature increase.

Also, we investigated the inactivation efficiency of foodborne pathogens. Our results revealed higher inactivation efficiency of 915 MHz microwave heating treatment both at 1.5 kW and 3.0 kW compared to conventional heating. The population of *E. coli* O157:H7 dropped to below the detection limit after 5 min treatment when treated with conventional heating, whereas it took only 20 s and 40 s when exposed to 915 MHz at 3.0 kW and 1.5 kW, respectively. *S.* Typhimurium and L. *monocytogenes* also showed similar inactivation trends. This means that a more rapid temperature increase induces better inactivation of foodborne pathogens. Also, as power level of the microwave system increased, it took less time to reduce populations of foodborne pathogens to under the detection limit. The study conducted by Sung and Kang (2014) showed similar results. The population of *E. coli* O157:H7 was reduced by 5.17 log CFU/g after treatment with 915 MHz microwave heating at 1.8 kW, while the microbial population was inactivated to under the detection limit when 915 MHz microwave heating was applied at 4.8 kW (Sung & Kang, 2014). Additionally, sugar content of chili sauce also affected foodborne pathogen inactivation. Our results revealed that chili sauce of 10% sugar content had higher inactivation efficiency than chili sauce of 25% and 40% sugar content. This is because the rate of temperature increase for chili sauce of 10% sugar content was higher than that of chili sauce of 25% or 40% sugar content due to a higher dielectric loss factor.

We also investigated populations of sub-lethally injured cells after heating treatment. After certain treatments, sub-lethally injured bacterial cells can remain inside a food matrix and under suitable conditions resuscitate and produce colonies even on selective agar (Bozoglu, Alpas, & Kaletunç, 2004). Thus, it is an important issue to the food industry, as well as a serious food safety concern. Our results showed overall that populations of injured cells were slightly higher than non-injured cells on selective agar, though no significant difference was observed. However, 915 MHz microwave heating at 3.0 kW reduced levels of injured cells as effectively as populations on selective agar, as it took the same time to inactivate both groups to under the detection limit. Microwave heating of 915 MHz at 1.5 kW showed a different trend, except for *S.* Typhimurium, because the time required to reduce injured cells to under the detection limit took 10 s longer. However, conventional heating showed less effectiveness, since it took 6 min to reduce all injured bacterial cells under the detection limit. Our results suggest that microwave heating can be a very useful tool for inactivating bacterial cells to below the detection limit without generating a significant population of injured cells that can be a food safety concern.

Also, we investigated quality changes after conventional heating treatment and 915 MHz heating treatment at 1.5 kW and 3.0 KW. We focused our investigation on color values (L*, a*, b*) and water activity after treatment, since they can change after heating treatment. Heating treatment inevitably results in quality loss of food product due to destruction of heat sensitive food components. Chemat and Khan (2011) reported that conventional heating can cause quality deterioration in food ingredients (Chemat & Khan, 2011). However, Song and Kang (2016a,b) reported that peanut butter treated with 915 MHz microwave heating treatment showed no quality change (Song & Kang, 2016a). Our results showed that when comparing quality change, chili sauce of 10% sugar content after conventional heating or 915 Microwave heating at 1.5 kW or 3.0 kW showed no significant differences in color attributes, but water activity slightly decreased. When chili sauce had a lower sugar content, there was also less quality loss. These results indicate that microwave heating did not induce worse quality changes in comparison to conventional heating and chili sauce of high dielectric constant and dielectric loss factor contents could show better quality after microwave heating treatment.

In conclusion, this study demonstrated that microwave heating can not only reduce foodborne pathogens effectively but also does not induce quality loss as seen in conventional heating. In light of our results, microwave processing can be considered an alternative to conventional heating. Moreover, we investigated the effect of dielectric constants on microwave heating trends. As sugar content affects water activity, chili sauce of lower sugar content had a higher dielectric constant and dielectric loss factor resulting in a higher rate of temperature increase. Thus, chili sauce containing a small amount of sugar facilitates better inactivation of foodborne pathogens. The results of this study can be used for understating the relationships among sugar content, dielectric properties, and microwave heating treatment for pasteurization of chili sauce and for further practical application by the food industry.

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