Received: 3 December 2019 | Revised: 13 February 2020 | Accepted: 19 February 2020
DOI: 10.1111/jfs.12787

ORIGINAL ARTICLE

Journal of Food Safety
WILEY

Application of ohmic heating for the inactivation of microbiological hazards in food products

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Funding information
Dankook University, Grant/Award Number: The present research was conducted by the research

Abstract

Ohmic heating has long been used to inactivate pathogens in food products. Several research investigations on the use of ohmic heating technology in the inactivation of microbial hazards in food products are discussed in this review. These studies are discussed under the following sub-headings: (a) inactivation of microbiological hazards, (b) in combination treatments with other sanitizing technologies, and (c) mathematical modeling, all of which are of long-standing interest. In this review, we evaluate ohmic heating as a rapid and volumetric heating process that inactivates microbiological hazards in food products. We also examine ohmic heating-based combination treatments as promising methods to maximize microbial inactivation efficacy and minimize the quality deterioration of food products. We first highlight the fact that most researchers had an interest in the inactivation of vegetative pathogens, whereas only a few focused on the inactivation of bacterial spores. In general, significantly higher treatment conditions were needed to inactivate bacterial spores (>95°C) than vegetative pathogens (>50°C). Studies on the inactivation of viral pathogens by ohmic heating are limited, and further research is needed in this field. In the first part of this review, the nonthermal effects of ohmic heating are also discussed, which is a popular topic in the food industry. Cumulatively, research suggests that that these nonthermal effects are dependent on the treatment conditions and the electrical conductivity of different food samples. Therefore, we suggest that focus should be on the thermal rather than the nonthermal effects of ohmic heating when considering the application of this technology to inactivate pathogens. Finally, we introduced combination technology based on ohmic heating and mathematical modeling, which are of interest recently.

1 | INTRODUCTION

Food safety remains a major concern worldwide. The globalization and expansion of international trade increase the spread and risks of foodborne outbreaks (Fung, Wang, & Menon, 2018). Moreover, changes in technology, society, climate, and the pathogens themselves also contribute to the development and maintenance of foodborne illnesses (Cohen, 2000). According to the US Centers for Disease Control and Prevention (US CDC, 2010) ~3,000 Americans die from foodborne illness each year. Many hazardous agents can cause these illness, but pathogens are still the major causative agents. Foodborne pathogens can be classified into vegetative pathogenic bacteria such as *Escherichia coli* O157:H7, *Salmonella* Typhimurium, and *Listeria monocytogenes* (Min et al., 2016), spore-forming pathogens such as *Bacillus* and *Clostridium* spores (Jo et al., 2019), and viruses such as the Norovirus (NoV) that are associated with winter illnesses (Park et al., 2016). Resistance of these pathogens would change resulting from climate change, antibiotics usage, and natural mutations, which are of great concern to food safety (S.-S. Kim, Lee, et al., 2019; Lee, Kim, & Kang, 2019). Some spoilage microorganisms such as *Alicyclobacillus acidoterrestris* and *Lactobacillus brevis* are also the microbial food hazards.

Food processing technologies targeting microbiological hazards have progressively improved over time (Kim, Cho, et al., 2017). Nonthermal interventions such as high pressure, cold plasma, and gas treatment have been used to inactivate pathogens (Rosello-Soto et al., 2018). However, advanced thermal technologies such as microwave, radio-frequency, and ohmic heating are more widely used because they apply rapid and volumetric heating (Tola & Ramaswamy, 2018).

In particular, researchers and the food processing industry alike have a keen interest in ohmic heating technology as a means to process food. Ohmic heating is dependent on electrical currents produced by a function generator and a power amplifier, and is a technology that was adopted by the food industry very early (Varghese, Pandey, Radhakrishna, & Bawa, 2014). However, this process was plagued by significant obstacles such as electrode corrosion which producing toxic chemicals and process temperature control which results in over heating (Samaranayake & Sastry, 2005).

Several interventions have been suggested to prevent electrode corrosion during the ohmic heating process. Lee, Ryu, and Kang (2013) proposed the use of high frequency as a way to prevent electrode corrosion, and Samaranayake, Sastry, and Zhang (2005) reported that electrode corrosion was significantly reduced when high-frequency pulse waveforms were produced by platinum–titanium electrodes. Along this line of thought several researchers have reported on the applicability of ohmic heating for pathogen inactivation in food samples without causing electrode corrosion. In this regard, it is of interest to evaluate these research articles, but review articles on this topic have been limited.

In this review, we evaluate and compare studies on the applicability of ohmic heating as a method to inactivate foodborne pathogens. Variables such as the types of pathogens (or surrogate), food samples, and treatment conditions of ohmic heating are considered when comparing each study. Where the study did not report variables such as waveform and target temperature, assumptions are made based on the standard approach (sine waveform) and temperature history for target temperature. This review evaluates the applicability of ohmic heating for the inactivation of microbiological hazards in food products and reveals the challenges and prospects of this technology with the following subjects; (a) inactivation of microbiological hazards, (b) in combination with other sanitizing technologies, and (c) mathematical modeling. The first section is further divided into (1) bacterial pathogen inactivation, (2) inactivation of bacterial spores or viruses, and (3) nonthermal inactivation effects.

2 | MATERIALS AND METHODS

Research articles were searched by combining several keywords (ohmic heating, pathogen inactivation, combination treatment, mathematical modeling). Recent articles (2010–2020) were selected to represent in Tables 1–4.

3 | INACTIVATION OF MICROBIOLOGICAL HAZARDS

3.1 | Bacterial pathogen (vegetative cell) inactivation

Ohmic heating applications for the inactivation of vegetative foodborne pathogens are widely reported (Table 1). Vegetative cells can be effectively inactivated by ohmic heating using shorter treatment times and lower target temperatures than those conditions to inactivate bacterial spores. The efficacy of ohmic heating depends on intrinsic and extrinsic factors, as well as the bacterial species and their growth stage. Intrinsic factors such as pH, moisture, and fat contents in the food sample affect the efficacy of ohmic heating by changing the electrical conductivity and heating rates (Kim & Kang, 2015a). Specifically, higher fat content in a food sample adversely affects its electrical conductivity, and accordingly, the heating rate in this sample is reduced (Kim & Kang, 2015c). On one hand, an increased total ion content has a positive effect on the electrical conductivity of food products (Kim & Kang, 2015b). Therefore, foodborne pathogens inoculated in food products with lower fat content or with higher total ion content are inactivated more rapidly by ohmic heating. Extrinsic

TABLE 1 Inactivation of foodborne bacterial pathogens (vegetative cells) by ohmic heating

		Ohmic heating					
Bacterial pathogen	Food sample	Applied voltage (V/cm)	Frequency (kHz)	Waveform	Maximum treatment time (target temperature)	Maximum reduction (log CFU)	References
Pathogen cocktails (*E. coli* O157:H7, *S.* Typhimurium, *L. monocytogenes*)	Tomato juice	9.43–12.14	1	Pulse	N. I.[a] (80°C)	>5	Kim, Park and Kang (2018)
	Apple juice	30 or 60	20	Sine	60 s (ca. 90°C)	>5	Park, Ha, and Kang (2017)
	Tomato paste	8.3–27.8	20	Sine	40 s (ca. 80°C)	>2.5	Kim et al. (2016)
	Orange juice	25.6	20	Sine	70 s (ca 70°C)	>4	Kim and Kang (2015b)
		16	20	Sine	60 s (50, 55, 60°C)	>5	Lee, Kim, and Kang (2015)
	Salsa	12.5	0.06–20	Sine, square, sawtooth	90 s (90°C)	>6	Lee et al. (2013)

[a] Not indicated.

TABLE 2 Inactivation of bacterial endospores or virus by ohmic heating

		Ohmic heating					
Type of spore or virus	Food sample	Applied voltage (V/cm)	Frequency (kHz)	Waveform	Treatment time after reaching target temperature (target temperature)	Maximum reduction (log CFU)	References
Bacillus cereus spore	Tsuyu sauce	26.7	25	Sine	30–90 s (95, 105, 115, 125°C)	>5.5	Ryang et al. (2016)
Alicyclobacillus acidoterrestris spores	Orange juice	30, 40, 50	50	Sine	0–30 min (70, 80, 90°C)	>5	Baysal and Icier (2010)
	Apple juice	26.7	25	Sine	30–90 s (85, 90, 95, 100°C)	Ca. 5	Kim, Ryang, et al. (2017)
Geobacillus stearothermophilus spores	Tomato soup	N. I.[a]	0.06, 10	Pulse	Max. 120, 90, 10 s (121, 125, 130°C)	Ca. 5	Somavat, Mohamed, Chung, Yousef, and Sastry (2012)
MS-2 bacteriophage (norovirus surrogate)	Tomato juice	47.7	0.06–1	Pulse	N. I.[a] (80°C)	5.13–5.80	Kim, Choi, et al. (2017)

[a] Not indicated.

TABLE 3 Nonthermal effect of ohmic heating for inactivation of foodborne pathogens in food samples

		Ohmic heating					
Type of pathogen	Food sample	Maximum treatment voltage (V/cm)	Frequency (kHz)	Waveform	Treatment time (target temperature)	Additional effect compared to conventional heating	References
E. coli O157:H7 *S.* Typhimurium *L. monocytogenes*	Skim milk and cream	9. 6–32	20	Sine	140 s (71.5 and 82°C)	No significant additional effect (partially observed at 60–65°C).	Kim and Kang (2015a)
	Apple juice	60	20	Sine	30 s (55, 58, 60°C)	Additional log reduction (<3 log reduction) and morphological change by TEM (electroporation effect)	Park and Kang (2013)
Bacillus cereus spore	Soy bean paste (doenjang)	26.7	25	Sine	30, 60, 90 s (95, 105, 115, 125°C)	>3 log reduction	Ryang, Kim, Lee, Kim, and Rhee (2016
Bacillus licheniformis spore	Carrot juice extract	1	4	Square	Max. 25 min (87, 92, 97°C)	Lower D-value by ohmic heating but no significant effect	Tola and Ramaswamy (2014)
Bacillus coagulans spores	Tomato juice	13	0.06, 10	Pulse	Max. 30 min (95°C)	Additional effect was remarkable with 60 Hz than 10 kHz ohmic heating	Somavat, Mohamed, and Sastry (2013)

factors such as applied voltage, frequency, and waveform, also influence the efficacy of this process (Baysal & Icier, 2010). The ohmic heating rate of food products is proportional to the applied voltage and frequency. It has been reported that pathogens are inactivated more rapidly when using a higher voltage (Kim et al., 2016) and a higher frequency (Lee et al., 2013). Therefore, when treating foods with ohmic heating, intrinsic and extrinsic factors that affect the heating rate and thus pathogen inactivation efficacy, should be considered when choosing treatment conditions.

Juice and particulate food products are suitable food to be ohmically heated because they have a high ion and moisture content. The electrical conductivity of these juice products is relatively high, which is key to the ohmic heating process. Many researchers have reported on the applicability of ohmic heating to inactivate foodborne pathogens in juice products as indicated in Table 1. A short ohmic heating treatment (60–90 s) can induce more than a four log reduction in foodborne pathogens such as *E. coli* O157:H7, *S.* Typhimurium, and *L. monocytogenes* inoculated in juice products. However, this treatment time must be increased to 300–540 s when the applied voltage is low (Lee, Sagong, Ryu, & Kang, 2012; Sagong, Park, Choi, Ryu, & Kang, 2011). Therefore, inactivation of vegetative foodborne pathogens can be easily achieved by high voltage ohmic heating. Spoilage bacteria such as *A. acidoterrestris* are also important microbiological hazards in juice products. Guaiacol, a product of *A. acidoterrestris*, is involved in the formation of off-flavors in juice products (Chang & Kang, 2004). Hence, it is important to inactivate not only pathogenic

TABLE 4 Combination of ohmic heating with other technology (hurdle technology) for inactivation of foodborne pathogens or surrogate

Foodborne pathogens or surrogate	Food sample	Ohmic heating	Combined technology or chemicals	Maximum reduction (log CFU) by ohmic heating	Maximum reduction (log CFU) by other technology	Maximum reduction (log CFU) by combined technology (additional effect)	References
MS-2 phage (norovirus surrogate)	Salsa (pH 3.7)	Pulsed 11.5 V/cm 500 Hz	Carvone Eugenol Citral Thymol	1.85	0.05–0.20	1.82–2.53 (max. 0.49)	Kim and Kang (2017a)
		Pulsed 12.1 V/cm 60 Hz	Cavacrol	4.2	0.16	6.2 (1.84)	Kim and Kang (2017b)
Bacillus amyloliquefaciens spore	Carrot puree (pH 5)	50 V/cm, 60 Hz	High-pressure (600 MPa)	N. I.[a]	N. I.[a]	2.82 (–)	Park et al. (2013)
E. coli O157:H7 *S.* Typhimurium *L. monocytogenes*	Tomato juice (pH 3.6)	Pulsed 13.4 V/cm 500 Hz	Ultraviolet (254 nm)	1.84	0.48	3.83 (1.51)	Kim, Park, et al. (2019)
	Apple juice (2.95)	Pulsed 33 V/cm 500 Hz	KrCl excilamp (222 nm)	Ca. 1.5	Ca. 1	>4.5 (>2)	Kim, Park, Park, Hong, and Kang (2020)

[a] Not indicated.

bacteria, but also non pathogens such as *A. acidoterrestris* (Lee, Dougherty, & Kang, 2002). Inactivation of *A. acidoterrestris* spores is discussed in the following section because this microorganism also exists in a spore form.

3.2 | Inactivation of bacterial spores or viruses

It is well known that heat resistance of bacteria increased significantly by sporulation. Some researchers have used ohmic heating to inactivate bacterial spores in food samples because high temperatures can be achieved very rapidly this process (Table 2). While ohmic heating can effectively inactivate bacterial spores, a relatively high temperature (95–125°C) is needed as opposed to the target temperature required for vegetative cells (50–90°C; Ryang, Kim, Lee, Kim, Lee, et al., 2016). Kim, Ryang, et al. (2017) also reported that ohmic treatment at 100°C for 30 s resulted in >4.8–4.9 log reduction of *A. acidoterrestris* spores in apple juice without causing in degree°Bx, color, orpH. Moreover, *Geobacillus stearothermophilus* spores, which are known to be the most resistant to heat treatment, are effectively inactivated by ohmic heating (Somavat et al., 2012). Thus, ohmic heating can be used to inactivate even heat-resistant bacterial spores. In comparison to conventional heating, the time to reach the target temperature is significantly reduced with ohmic heating. Moreover, nonthermal effect which is defined as additional effects beyond conventional heating through the effect electricity (Park & Kang, 2013), is also a reason for the accelerated inactivation effect. This effect has been attributed to an increase in cell membrane permeability, which was verified by testing with the dipicolinic acid (Somavat et al., 2012). Research into the nonthermal effects will be discussed in detail in a later section.

Research on the application of ohmic heating to inactivate viruses is limited, and only studies on NOV surrogates have been reported. Kim, Choi, et al. (2017) reported that the MS-2 bacteriophage, NoV surrogate, could be inactivated effectively (>5 log reduction) by ohmic heating when 47.7 V/cm was applied to reach a target temperature of 80°C. The bacteriophage inactivation efficacy synergistically increase when ohmic heating is combined with some essential oil components such as carvacrol (Kim & Kang, 2017b), thymol or citral (Kim & Kang, 2017a). This research is of global interest as NoV is one of the most prevalent foodborne viruses and is the cause of outbreaks. However, there have yet to be any research publications on the application of ohmic heating to inactivate other hazardous foodborne viruses such as hepatitis A (HAV), rotavirus, astrovirus, and adenovirus (Li, Butot, Zuber, & Uyttendaele, 2018). It would be of interest to identify the nonthermal effects of ohmic heating for viral pathogen inactivation and their virucidal mechanism.

3.3 | Nonthermal inactivation effects

The nonthermal effects of ohmic heating for pathogen inactivation are still controversial. Some researchers have reported that nonthermal electrical effects contribute significantly to the effect of ohmic heating whereas others have indicated that there were little or no significant effects (Table 3). Both Park and Kang (2013) and Lee et al.

(2012) reported an additional effect by ohmic heating manifests as a morphological change in ohmic-treated pathogens in juice products. Cell membrane damage was identified as the primary target for nonthermal electrical effects when ohmic and conventional heating were compared using the same treatment time and temperature conditions (I. –K. Park & Kang, 2013). Some studies have indicated that there is an additional inactivation effect when targeting bacterial endospores. Ryang, Kim, Lee, Kim, and Rhee (2016) reported that *Bacillus cereus* spores were inactivated more effectively by ohmic heating in soybean paste (doenjang) than conventional heating, and the same trend was observed for *A. acidoterrestris* spores in apple juice (Kim, Ryang, et al., 2017). Somavat et al. (2013) reported that more *Bacillus coagulans* spores were reduced by ohmic heating than by conventional heating in tomato juice, and the additional effect was greater at 60 Hz than at 10 kHz. Similarly, Kim, Choi, et al. (2017) showed that low frequency pulsed ohmic heating was effective at inactivating pathogens in tomato juice. In contrast, *G. stearothermophilus* spores in tomato soup were reduced to a greater extent at 10 kHz than at 60 Hz with ohmic heating (Somavat et al., 2012). Many researchers, including those who have published the studies above, have proposed that the electrical effect on cell membranes were responsible for the additional nonthermal effects of ohmic heating methods.

Conversely, some researchers have reported little or no significant additional effects from that of conventional heating. Kim and Kang (2015a) reported that in skimmed milk and cream, the number of pathogens inactivated by ohmic heating did not significantly differ from the number inactivated by conventional water-bath heating. Tola and Ramaswamy (2014) reported that the decimal reduction time (*D*-values) of ohmic heating was lower than that of conventional heating for the inactivation of *B. licheniformis* spores in carrot juice extracts, but this difference was not significant. Therefore, the nonthermal electrical effect of ohmic heating is insignificant in food samples that have lower electrical conductivity such as skimmed milk and cream; and is strong in food samples that have high electrical conductivity such as juice and soy bean products. Cumulatively, these reports showed that additional nonthermal effect can only be observed under specific treatment conditions or in particular food samples. Moreover, this additional effect could be hidden by the thermal effect as the nonthermal effect is generally much smaller than its thermal counterpart. According to Somavat et al. (2012), the nonthermal effect of ohmic heating can only be precisely identified by comparing it to conventional heating. A person who applies ohmic heating to inactivate foodborne pathogens should focus on the thermal rather than the nonthermal effect. Finding a way to rapidly increase the sample temperature is of greater importance than identifying potential additional nonthermal effect.

4 | COMBINATION TREATMENTS BASED ON OHMIC HEATING

Combination treatment with other technologies, is known as hurdle technology, and has recently gained much interest. Several researchers have reported on ohmic heating-based hurdle technologies to inactivate foodborne pathogens (Table 4). The inactivation rate of these pathogens increased significantly when ohmic heating was combined with other chemical or physical treatments. It has been reported that a synergistic bactericidal and virucidal effect can be achieved by combining ohmic heating with carvacrol (Kim & Kang, 2017b), citral, thymol (Kim & Kang, 2017a), Hg UV-C lamp (Kim, Park, et al., 2019), or KrCl excilamp (Kim et al., 2020). Combination treatment of foodborne pathogens such as *E. coli* O157:H7, *S.* Typhimurium, *L. monocytogenes*, and the NoV surrogate MS-2 bacteriophage had synergistic effect when compared with the individual treatments. Additional nonthermal effects on the cell membrane were suggested to be the source bactericidal effect for these combination treatments.

Combination treatment based on ohmic heating is also effective at controlling bacterial endospores in food products. Park, Balasubramaniam, Sastry, and Lee (2013) reported that *B.amyloliquefaciens* and *G. stearothermophilus* spores, which are used to evaluate sterilization, were effectively inactivated by pressure-ohmic-thermal sterilization (POTS) treatment of low-acid foods such as green pea puree (pH 6.1), carrot puree (pH 5.0), and tomato juice (pH 4.1). The germination rate of spores was increased by POTS in comparison to ohmic heating, and this factor would affect the accelerated inactivation effect in this study. In this regard, combination technology based on ohmic heating would be effective for the inactivation of pathogens, damaging the same targets such as the cell membrane or damaging multiple targets simultaneously such as the cell membrane, nucleic acids, and proteins including some enzymes (Kim & Kang, 2017a, 2017b, Kim, Park, et al., 2019).

Other combination treatments such as microwave-ohmic and infrared-ohmic combination have also been attempted to improve the heating uniformity of this technology (Choi, Lee, Kim, & Jun, 2015; Choi, Nguyen, Lee, & Jun, 2011; Nguyen, Choi, Lee, & Jun, 2013), but an enhanced bactericidal effect was not identified with these combination. Many treatment combination with other technologies are possible, which can significantly reduce treatment time and target temperature of ohmic heating. For example, combination treatment of ohmic heating with cold plasma, superheated steam, or radio-frequency heating can be attempted. Additionally, food quality deterioration induced by ohmic heating would be minimized by using the combination treatment. Therefore, combining ohmic heating with other technologies is a promising way to improve food safety but also the quality of food after ohmic heating treatment In the future, verified new hurdle technology can be applied in the food industry.

5 | MATHEMATICAL MODELING OF OHMIC HEATING

Mathematical modeling approaches have been applied to simulate the ohmic heating processing. Predicting the temperature distribution during ohmic heating is important not only in the field of food engineering but also in food safety because foodborne pathogens can survive in cold spots for a long time. De Alwis and Fryer (1990) developed a finite-element model to predict the ohmic heating system in 1990 and later expanded this model to include solid–liquid mixtures (Fryer, De Alwis, Koury, Stapley, & Zhang, 1993). Furthermore, various attempts have been reported to identify the worst-case heating scenario with static (Sastry & Palaniappan, 1992b) and flow-type continuous ohmic heaters (Sastry, 1992), and the effect of particle orientation (Sastry & Palaniappan, 1992a). These studies indicated that the type (static or continuous), the size of the heater, the sample flow rate, and the direction of the electrode in the chamber impact the worst-case heating scenario and should be considered before being used by the food industry. Mathematical modeling approaches can also be used to determine the cold-point, but these models should be validated before industry applications. Validation of mathematical modeling can be accomplished by comparing the simulated and actual temperature values at specific points, or the microbiological inactivation effect as reflected by *D*- and *z*-values. It is not easy to take measurements at specific point or to quantify the number of microorganisms at these points. In this regard, a Magnetic Resonance Imaging (MRI) mapping method was used to identify the temperature distribution during ohmic heating (Ye et al., 2003). Recently several studies have been published on combining mathematical modeling with microbiological validation (Choi, Kim, Park, Ahn, & Kang, 2020; Kamonpatana et al., 2013a, 2013b), which would be valuable for both the food industry and consumers. These attempts should further be applied to ohmic heating-based hurdle technologies discussed in this review or developed in the future.

6 | CONCLUSION AND RECOMMENDATIONS

Ohmic heating is widely used to inactivate vegetative pathogens in food samples and is a more rapid and uniform heating process in comparison to conventional heating. Intrinsic factors such as pH, moisture, and nutrient content, and extrinsic factors such as electric field strength, frequency, and waveform influence the electrical conductivity of food samples, and thus directly affect the heating rate. The electrical conductivity of food samples is proportional to its total ion and moisture contents and is inversely proportional to the fat content. Therefore, vegetative foodborne pathogens can be rapidly inactivated by ohmic heating under favorable conditions. However, significantly higher temperatures are needed to inactivate bacterial endospores in food products. Virucidal ohmic heating applications are limited, and further research is needed in this field. Many researchers have expressed interest in the nonthermal effects of ohmic heating to inactivate foodborne pathogens. However, the existence of electrical effects (a nonthermal contribution) is still controversial. Some researchers have reported that the efficacy of the ohmic heating process is significantly higher than that of conventional heating, whereas others insist that there is no additional electrical effect. Even though the magnitude of the nonthermal electrical effects differs in accordance to the type of pathogen, electrical voltage, frequency, or waveform, the contribution of this aspects of ohmic heating appears to be relatively insignificant compared to its thermal counterpart. Therefore, to guarantee food safety, we recommend to ensure heating uniformity rather than to expect any additional electrical effect by ohmic heating. Several studies have been reported on combining ohmic heating with other technologies to accelerate the pathogen inactivation effect. Synergistic bactericidal or virucidal effects have been observed when proper technologies were combined, and food quality deterioration was minimized by these combination treatments. The current research focus of ohmic heating-based hurdle technology is on its application in acidified food products such as salsa, puree, and tomato juice. An advantage of hurdle technology is that it can achieve maximum effect by combining two or more technologies, and combination treatment can be applied for more complex food products. In particular, some food products are harder to ensure safety. Applying various combination treatments to inactivate pathogens in these food products maybe a viable approach because when a verified hurdle technology can be applied to the food industry. Treatment conditions should be optimized before being taken up by the industry, with considerations for energy efficiency and product quality, and mathematical modeling would be helpful for the optimization.

Following recommendations would be considered for the application of ohmic heating. (a) Non-thermal effects of ohmic heating are still controversial, and were commend to ensure heating uniformity rather than identifying potential additional nonthermal effects. (b) Combining ohmic heating with other technologies is a promising way to improve food safety but also the quality of food after ohmic heating treatment. (c) Mathematical modeling can be used effectively before ohmic heating application in the food industry.

ACKNOWLEDGMENT

The present research was conducted by the research fund of Dankook University in 2020.

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How to cite this article: Shin M, Kim S-S, Kang D-H. Application of ohmic heating for the inactivation of microbiological hazards in food products. *J Food Saf*. 2020;40:e12787. https://doi.org/10.1111/jfs.12787