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Ohmic cooking of instant rice cake soup: energy efficiency and textural qualities

Salinee Soisungwan[1] · Apinya Khampakool[1] · SangGuan You[1] · Sung Hee Park[2]

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Abstract The potential of ohmic heating was investigated to cook instant rice cakes according to electric field strengths (9, 12, 15, 18 V/cm) and cooking times (60, 80, 100, 120 s). Customized ohmic heating system was equipped with ohmic cell, electrodes, thermocouple, proportional–integral–differential controller and data acquisition system. Heating rate significantly increased when electric field strengths increased. Heating rate was 12.1 °C/min at 9 V/cm, and was increased to 38.8 °C/min at 18 V/cm. The energy efficiency was evaluated in terms of system performance coefficient (SPC) energy efficiency. The best SPC energy efficiency was 0.65 at an electrical field strength of 18 V/cm. An electric field strength of 15 V/cm and an 80 s cooking time resulted in the most preferable hardness (7.73 N). Ohmic heating would be applicable to cook instant rice cakes, resulting in good energy efficiency and textural qualities.

✉ Sung Hee Park
sunghpark@seoultech.ac.kr

Salinee Soisungwan
on_salinee@hotmail.com

Apinya Khampakool
apinya.nanattapin@gmail.com

SangGuan You
umyousg@gwnu.ac.kr

[1] Department of Marine Food Science and Technology, Gangneung-Wonju National University, Gangneung-si, Gangwon-do 25457, Republic of Korea

[2] Department of Food Science and Technology, Seoul National University of Science and Technology, Seoul 01811, Republic of Korea

Keywords Ohmic heating · Cooking · Rice cake · Energy efficiency · Texture

Introduction

Rice cake soup is a popular home meal replacement (HMR) food which could be conveniently served. Slices of dried rice cake are boiled until a dense and viscous soup is formed. Rice cakes have the nutritional value of a single meal as a highly valuable convenient food (Ku et al., 2018; Yoon and Oh, 2014). Recently, dried instant rice cake soups were launched in the global instant food markets. They can be conveniently consumed after pouring boiling water into the rice cake mixture. Generally, boiling water is poured into the instant rice cake mixture and then it is soaked for 2–3 min before consumption. However, undercooked rice cakes are frequently found in instant rice cake cooking because cooking dried rice cakes requires water absorption and subsequent starch gelatinization. Starch gelatinization is the disruption of its granular structure, resulting in starch molecules to dissolve in water (Ratnayake and Jackson, 2006). The driving energy for water sorption of dried starchy foods is high, and the sorption rate increased according to temperatures rise than that of gelatinization (Jang et al., 2016; Hasegawa et al., 2012). Consequently, more advanced cooking methods are required to improve the quality of dried rice cakes.

Ohmic heating will be one of the potential methods to cook dried rice cakes. Ohmic heating enables the homogenous temperature distribution during heating (Gavahian et al., 2016; Icier and Ilicali, 2004; Sabanci and Icier, 2017). This method is based on the passage of an electrical current through foodstuff by conversion of electrical energy into heat energy inside the food, depending on its resistance (Icier et al., 2017; Jha et al., 2011; Reznick, 1996; Sastry and Salengke, 1998; Shirsat et al., 2004). In the previous study, the potential of ohmic cooking for instant noodle and home meal replacement curry were demonstrated with rapid temperature rise, good energy efficiency and textural qualities (Jo and Park, 2019; Soisungwan et al., 2019).

The aim of this study was (a) to investigate the applicability of ohmic cooking for dried instant rice cakes, (b) to estimate the energy efficiency of cooking ohmic rice cakes, and (c) to evaluate the textural quality of ohmically-cooked rice cake soup.

Materials and methods

Instant rice cake mixture

Instant rice cake product was purchased from a local market. One package contained elliptical rice cakes (diameter: 25 mm, length: 45 mm, thickness: 2.5 mm, ≈ 77 cakes, 150 g), soy sauce (30 g), and vegetable flakes (1.6 g). For one batch experiment, half of a package (rice cakes: 75 g, soy sauce: 15 g, vegetable flakes: 0.8 g, powder: 2.5 g) was mixed to 150 ml of distilled water.

Ohmic heater

Figure 1 shows the schematic diagram of the experimental ohmic heating system for instant rice cake cooking that was used in our previous studies (Jo and Park, 2019; Soisungwan et al., 2019). The ohmic heater was equipped with a rectangular ohmic container which is made of airtight plastic (Lock & Lock Seoul, Korea). The width, length and height of ohmic container were 76, 97 and 46 mm, respectively. Two rectangular titanium electrodes (thickness: 1 mm) were fit into both ends of the ohmic container with distance of 95 mm. A variable power supplier (HCS-2SD50; HC TRASNFORMER, Busan, Korea) was used to provide the AC electric field (60 Hz) to ohmic heater. Proportional–integral–differential controller (ITC-100, INKBIRD, China) was installed to keep the constant target temperature during cooking time. Temperature changes were monitored and recorded every 3 s through a K-type thermocouple and data acquisition system (DAQ, 34970A; Agilent Technologies, Santa Clara, CA, USA). The voltages and currents applied to samples were also measured and recoded using the DAQ system. These measurements were used to estimate the temperature changes and system performance coefficient (SPC) energy efficiency.

Ohmic cooking

Majority of ohmic cooking procedure followed our previous study (Jo and Park, 2019; Soisungwan et al., 2019) excepting the tested electric field strength and cooking times. Two K-type thermocouples (Ø 0.25 mm, TFIR-003-50; Omega Engineering, Stamford, CT, USA) were positioned into the geometric center of the rice cakes (T_{rc}) of the prepared rice mixture in the ohmic container. A 18 gauge syringe (SN1820, LK Korea, Gyeonggi-do, Korea) was used to insert the thermocouple into dried cake and then it was removed before ohmic cooking. Another thermocouple was placed into the geometric center of the mixture to measure the temperature rise of the soup (T_s). Four selected electric field strengths of 9, 12, 15, and 18 V/cm were provided to ohmic container using a variable power supplier (HCS-2SD50; HC TRASNFORMER, Busan, Korea). The rice cake soup was ohmically cooked to the temperature of 100 °C. Rice cakes were cooked at 100 °C for ohmic cooking times of 60, 80, 90, and 120 s. The electric field strength was kept constant at 7.5 V/cm with PID controller to prevent over-heating during the cooking time at 100 °C. Heating rate (H_{rt}) of ohmic

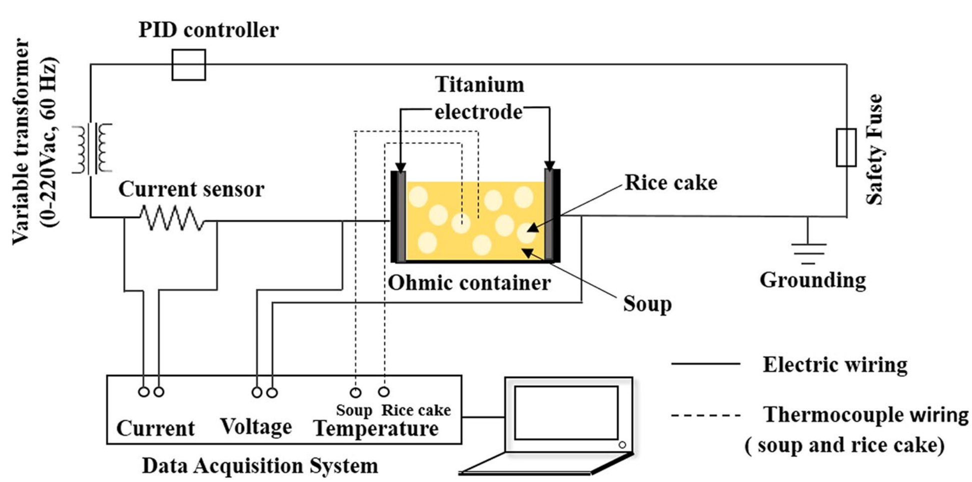


Fig. 1 A schematic diagram of ohmic heating system for instant rice cake cooking (reproduced and modified with permission from Jo and Park 2019: Elsevier and Copyright Clearance Center License Number: 4630791241042)

cooking was calculated through temperature increase from initial temperature (t_i) to final temperature (t_f) divided by temperature come-up time (t_{cu}) as shown in Eq. 1.

$$H_{rt} = \frac{T_f - T_i}{t_{cu}} \quad (1)$$

System performance coefficient (SPC) energy efficiency

Energy efficiency of ohmic heating was estimated in terms of system performance coefficient (SPC). An SPC is the efficiency parameter of ohmic heating system for increasing temperature (Darvishi et al., 2013; Icier and Bozkurt, 2011; Icier and Ilicali, 2004, 2005; Jo and Park, 2019; Park et al., 2017; Soisungwan et al., 2019). SPC energy efficiency is the ratio of the total volumetric ohmic internal energy dose (E_{vd}, J) to the amount of electrical energy in the form of heat (J) required to bring the temperature of the soup up to 100 °C (Fig. 2A ↔ B) as successfully demonstrated the energy efficiency of ohmic cooking in our previous study (Jo and Park, 2019; Soisungwan et al., 2019). In the present work, mathematical calculations of SPC energy efficiency were followed our previous work abovementioned. The required energy in the form of heat to increase the temperature of sample to the desired temperature (Q_{taken}, J) was calculated using the temperature elevation of both the soup and the rice cake itself, as suggested by previous researchers (Icier and Ilicali, 2005; Jo and Park, 2019; Soisungwan et al., 2019) since temperature come-up time is the period when it spends the most electrical energy, as previously used in our study in Eq. 2 (Jo and Park, 2019; Soisungwan et al., 2019):

$$Q_{taken} = m_s \cdot C_{p,s} \cdot (T_{is} - T_{fs}) + m_{rc} \cdot C_{p,rc} \cdot (T_{irc} - T_{frc}) \quad (2)$$

where Q_{taken} is the amount of energy in the form of heat (J), m_s is the soup mass in rice cake mixture (kg), m_{rc} is the rice cake mass in rice cake mixture (kg), $C_{p,s}$ is the specific heat of the soup (J/kg K), $C_{p,rc}$ is the specific heat of the rice cake (J/kg K), T_{is} is the initial temperature of the soup (°C), T_{fs} is the final target temperature (100 °C) of the soup, T_{irc} is the initial temperature of the rice cake (°C), and T_{frc} is the final temperature of the rice cake when the soup temperature reached 100 °C.

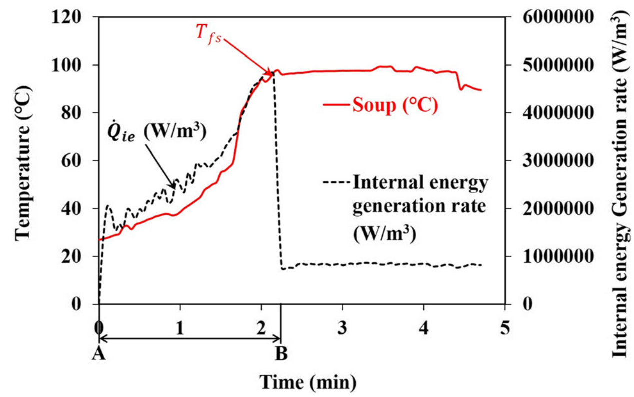


Fig. 2 Temperature histories of soup (T_s) and rice cake (T_{rc}) versus volumetric internal energy generation rate ($\dot{Q}_{ie}$, W/m^3) at 15 V/cm and 120 s holding time

In this study, $C_{p,s}$ was estimated as 4184 J/kg K similar to that of water. The moisture content of rice cake used in our study was 40.4% which was measured using dry oven. Threfore,$C_{p,rc}$ was estimated as 2543 J/kg K, which is similar values for waxy starch at 40.4% moisture content (Tan et al., 2004), the same composition as the rice cakes in this study. In our study, the specific heat values $C_{p,s}$ and $C_{p,rc}$ were considered to be independent of temperature increase, as suggested by previous researchers (Icier and Ilicali, 2005; Jo and Park, 2019; Soisungwan et al., 2019).

Heat loss has a significant effect on the SPC energy efficiency during ohmic heating (Jo and Park, 2019; Soisungwan et al., 2019). Heat loss should be appropriately considered for a microbial safe ohmically-cooked food (Marra, 2009). In this study, heat loss to surrounding environment during temperature come-up time (Q_{loss}) was calculated as suggested by Geankoplis (1993) and our previous study (Jo and Park, 2019; Soisungwan et al., 2019), shown in Eq. 3.

$$\begin{aligned} Q_{loss} &= [\bar{h}_{tw} \cdot A_{tw} \cdot \Delta T_{avtw} + \bar{h}_{bw} \cdot A_{bw} \cdot \Delta T_{avbw} + 2 \cdot \bar{h}_{sw} \cdot A_{sw} \cdot \Delta T_{avsw} + 2 \cdot \bar{h}_{sew} \cdot A_{sew} \cdot \Delta T_{avsew}] \times t_{cu} \\ &= \begin{bmatrix} 1.32 \cdot \left(\frac{\Delta T_{avtw}}{L}\right)^{1/4} \cdot A_{tw} \cdot \Delta T_{avtw} + 0.59 \cdot \left(\frac{\Delta T_{avbw}}{L}\right)^{1/4} \cdot A_{bw} \cdot \Delta T_{avbw} \\ + 2 \times 1.37 \cdot \left(\frac{\Delta T_{avsw}}{L}\right)^{1/4} \cdot A_{sw} \cdot \Delta T_{avsw} + 2 \times 1.37 \cdot \left(\frac{\Delta T_{avsew}}{L}\right)^{1/4} \cdot A_{sew} \cdot \Delta T_{avsew} \end{bmatrix} \times t_{cu} \end{aligned} \quad (3)$$

where Q_{loss} is the total heat loss from all the heat transfer area (top, bottom, and sides) of the ohmic container to surrounding air through natural air convection as proposed by our previous study (Jo and Park, 2019; Soisungwan et al., 2019). $\bar{h}_{tw}$, $\bar{h}_{bw}$, $\bar{h}_{sw}$, and $\bar{h}_{sew}$ are the natural convective heat transfer coefficients (W/m^2·K) of the top wall, bottom wall, side wall and electrode side wall of the ohmic container, respectively; A_{tw}, A_{bw}, A_{sw}, and A_{sew} are the heat transfer areas of top wall, bottom wall, side wall, and electrode-side wall of the ohmic container, respectively; and ΔT_{avtw}, ΔT_{avbw}, ΔT_{avsw}, and ΔT_{avsew} are the average temperature driving forces of the top wall, bottom wall, side wall and electrode-side wall, respectively, estimated from initial wall temperature, final wall temperature, and ambient air temperature for each wall during temperature come-up time of ohmic cooking.

As suggested by previous works (Jo and Park, 2019; Marra, 2009; Soisungwan et al., 2019), four K-type thermocouples were attached on the heat transfer area of each wall surface in the ohmic container to record the temperature changes and their heat loss. The average temperature driving force (ΔT_{av}) was estimated using temperature data measured on each surface of the ohmic container including the average of the initial wall temperature, final wall temperature, and ambient air temperature (Darvishi et al., 2012; Icier and Ilicali, 2005; Jo and Park, 2019; Soisungwan et al., 2019). The simplified equations for natural convection was utilized to calculate the natural convective heat transfer coefficients ($\bar{h}$) for each heat transfer surface with an appropriate Gr × Pr value range (Geankoplis, 1993; Icier and Ilicali, 2005; Jo and Park, 2019; Soisungwan et al., 2019). Gr and Pr are Grashof and Prandtl numbers. $\bar{h}$ values ranged from 4.46 to 10.41 W/m^2 K. The electrode-side had the highest heat transfer coefficient (10.35–10.37 W/m^2 K).

Ohmic internal energy generation rate per volume ($\dot{Q}_{ie}$,W/m^3) was calculated as a multiplication of squared electric field strength (V/m) and electrical conductivity (S/m) as shown in Eq. 4 (Jo and Park, 2019; Li and Zhang, 2010; Soisungwan et al., 2019):

$$\dot{Q}_{ie} = \sigma \cdot |\nabla V|^2 \tag{4}$$

The electrical conductivity of tested sample (σ, S/m) was determined using recorded current (A) and voltage (V) data with consideration of the cell constant (k, m^{-1}). The cell constant (k, m^{-1}) was estimated using the sample volume (volume of ohmic container) in which the distance between electrodes (L, 0.095 m) was divided by cross-sectional area of the electrode (A, 0.0034 m^2) (Jo and Park, 2019; Park et al., 2013; Soisungwan et al., 2019). Equation 5 shows the formula to calculate electrical conductivity (σ, S/m) of sample during ohmic cooking (Ito et al., 2014; Jo and Park, 2019; Park et al., 2013; Soisungwan et al., 2019).

$$\sigma = k \cdot \frac{I}{V} \tag{5}$$

Ohmic internal energy generation rate per volume ($\dot{Q}_{ie}$, W/m^3) can be calculated with a combination of above equations as shown in Eq. 6 (Jo and Park, 2019; Soisungwan et al., 2019):

$$\dot{Q}_{ie} = k \cdot \frac{I}{V} \cdot |\nabla V|^2 \tag{6}$$

The total volumetric ohmic internal energy dose (E_{vd}, J) of ohmic apparatus is the sum of the energy generation in rice cakes and soup. It was computed using the ohmic internal energy generation rate ($\dot{Q}_{ie}$, W/m^3), the sample volume (v, m^3), and their integration versus temperature come-up time (s) as shown in Eq. 7 (Jo and Park, 2019; Soisungwan et al., 2019):

$$\begin{aligned} E_{vd} &= \int_{t_i}^{t_f} v \cdot \dot{Q}_{ie} dt \\ &= \int_{t_i}^{t_f} v \cdot k \cdot \frac{I}{V} \cdot |\nabla V|^2 dt \\ &= v \cdot \frac{k}{2} \cdot \left[\begin{array}{l} \left(\frac{I_0}{V_0} \cdot |\nabla V_0|^2 + \frac{I_1}{V_1} \cdot |\nabla V_1|^2 \right) \Delta t_{0\sim1} + \left(\frac{I_1}{V_1} \cdot |\nabla V_1|^2 + \frac{I_2}{V_2} \cdot |\nabla V_2|^2 \right) \cdot \Delta t_{1\sim2} \\ + \left(\frac{I_2}{V_2} \cdot |\nabla V_2|^2 + \frac{I_3}{V_3} \cdot |\nabla V_3|^2 \right) \cdot \Delta t_{2\sim3} \cdots + \left(\frac{I_{n-1}}{V_{n-1}} \cdot |\nabla V_{n-1}|^2 + \frac{I_n}{V_n} \cdot |\nabla V_n|^2 \right) \cdot \Delta t_{n-1\sim n} \end{array} \right] \cdot v \end{aligned} \tag{7}$$

The trapezoidal numerical integration function of MATLAB software (Version 7.9.0.529; Mathworks Inc., Natick, MA, USA) was used to solve Eq. 7 as utilized in our previous study (Jo and Park, 2019; Soisungwan et al., 2019).

Finally, the SPC energy efficiency was computed using Q_{taken}, E_{vd}, and Q_{loss} as shown in Eq. 8. The energy efficiency of the ohmic apparatus can be predicted using the magnitude of the SPC energy efficiency (Darvishi et al., 2012; 2013; Icier and Bozkurt, 2011; Icier and Ilicali, 2004; 2005; Jo and Park, 2019; Park et al., 2017; Soisungwan et al., 2019).

$$SPC = \frac{Q_{taken}}{E_{vd} + Q_{loss}} \tag{8}$$

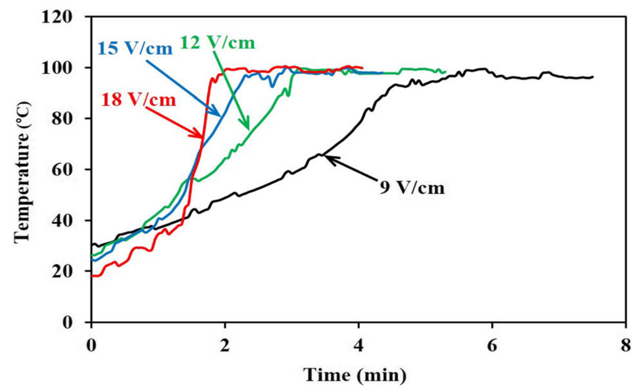
Total conversion of ohmic internal energy into heat is represented by an SPC energy efficiency value of 1, and values less than 1 indicate lower energy efficiency of the ohmic system.

Texture profile analysis

The textural qualities of ohmically-cooked rice cakes were analyzed using a Texture Analyzer (TA-XT Plus, Texture Technology Corp., Brewster, NY, USA). Hardness (N) and cohesiveness of ohmically-cooked rice cakes were estimated. After ohmic cooking, rice cakes were immediately picked-up using a mesh ladle, and soup was eliminated from the cooked rice cakes. Care was taken to minimize the textural changes during the time-lag for analysis. The rice cake was placed on the stainless-steel sample hold. Cutting test rice cakes was conducted using a pasta blade (TA-47, Texture Technology Corp., Brewster, NY, USA). The texture analyzer was set with appropriate test conditions: a pretest speed of 5.0 mm/s, test speed of 3.3 mm/s, post-test speed of 1.0 mm/s, target distance of 2.0 mm, time of 2.0 s, and an auto trigger type. The average thickness of cooked rice cakes was 2.5 mm. The cutting depth was 80% of the cooked rice cake, since the rice cakes had a thickness of 2.5 mm and the blade was able to cut 2.0 mm deep. Hardness and cohesiveness were measured and analyzed as follows (Mehta et al., 2012). The hardness of a cooked rice cake is the force to make a given deformation as maximum force. Cohesiveness represents the adhesion of the sample under compression or tensile.

Statistical analyses

Multiple comparisons of experimental data was conducted to evaluate the significance of differences in tested data using Analysis of variance (ANOVA) of the Statistical Analysis System (SAS) software (version 9.1.3, SAS Institute Inc.). Fisher's least-significant difference (LSD) procedure was selected for multiple comparisons among treatments at a 95% confidence interval ($P < 0.05$). All the ohmic trials were replicated three times.



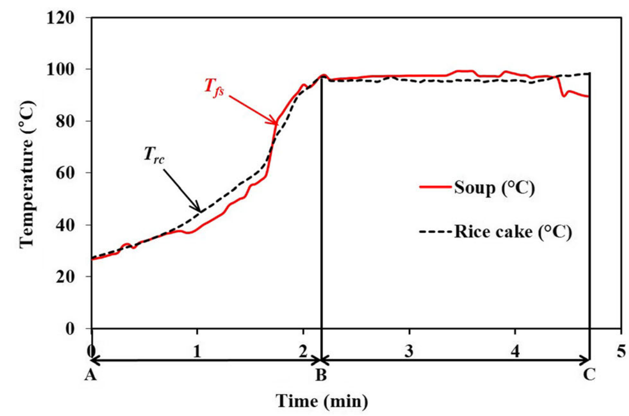


Fig. 3 (**A**) Temperature histories of soup during ohmic heating at different electric fields (9, 12, 15 and 18 V/cm) and (**B**) representative comparison of temperature histories between soup and rice cake at 15 V/cm electric field application

Results and discussion

Temperature evolution of soup and rice cakes during ohmic cooking

Figure 3(A) shows the temperature rise of rice cake soup at selected electric field applications (9, 12, 15, and 18 V/cm) and at a cooking time of 120 s at 100 °C during ohmic cooking, as a representative example. Heating rate to 100 °C was 12.1 ± 0.8, 21.3 ± 1.3, 27.7 ± 1.6, and 38.8 ± 1.6 °C/min at 9, 12, 15, and 18 V/cm electric field strengths, respectively (Table 1). Once temperature of the soup was elevated to 100 °C, it was held at 100 °C for cooking time of 60, 80, 90, and 120 s. Elevating the electric field strengths enabled rapid temperature increase. In ohmic heating, the rate of temperature increase is governed by the applied electric field strength and the material's electrical conductivity, as shown in Eq. 5 (Jo and Park, 2019; Soisungwan et al., 2019). Table 2 shows the electrical conductivities of rice cake soup at different electric field strengths and temperatures. The minimum

Table 1 Comparison of temperature come-up time to 100 °C (min), amount of energy in the form of heat (Q_{taken}, J), total volumetric ohmic internal energy dose (E_{vd}, J), and SPC energy efficiency during temperature come-up time to among different electric fields (9, 12, 15 and 18 V/cm)

Electric field (V/cm)	Heating rate (°C/min)	Amount of energy in the form of heat (Q_{taken}, J)	Heat loss (Q_{loss}, J)	Total volumetric ohmic internal energy dose (E_{vd}, J)	SPC energy efficiency
9	12.1 ± 0.8^{a}	60,947 ± 405^{ba}	22,411 ± 131^{a}	96,906 ± 7403^{a}	0.51 ± 0.03^{ca}
12	21.3 ± 1.3^{b}	60,882 ± 195^{b}	12,609 ± 72^{b}	90,690 ± 2604^{ab}	0.59 ± 0.02^{b}
15	27.7 ± 1.6^{c}	61,596 ± 112^{aa}	9707 ± 71^{c}	85,198 ± 1217^{b}	0.65 ± 0.01^{aaa}
18	38.8 ± 1.6^{d}	61,012 ± 297^{b}	6793 ± 42^{d}	87,016 ± 7682^{b}	0.65 ± 0.06^{a}

$^{a–d}$Means (± SD) with a different letter in the same column are significantly different at $P < 0.05$

Table 2 The electrical conductivity at different electric field

Temperature (°C)	Electrical conductivity (S/m)			
	9 V/cm	12 V/cm	15 V/cm	18 V/cm
20	0.43 ± 0.13^{aG}	0.11 ± 0.03^{aF}	0.22 ± 0.10^{aG}	0.30 ± 0.30^{aH}
30	0.69 ± 0.12^{cF}	0.98 ± 0.20^{aE}	0.82 ± 0.13^{bcF}	0.86 ± 0.09^{abG}
40	0.90 ± 0.14^{bE}	1.21 ± 0.08^{aD}	1.06 ± 0.20^{abEF}	1.09 ± 0.09^{abFG}
50	1.25 ± 0.27^{aD}	1.40 ± 0.07^{aD}	1.23 ± 0.34^{aDE}	1.25 ± 0.12^{aEF}
60	1.61 ± 0.35^{aC}	1.68 ± 0.14^{aC}	1.52 ± 0.38^{aCD}	1.48 ± 0.11^{aDE}
70	1.78 ± 0.27^{aC}	1.88 ± 0.15^{aC}	1.56 ± 0.47^{aCD}	1.63 ± 0.17^{aCD}
80	1.97 ± 0.29^{aB}	2.10 ± 0.20^{aB}	1.74 ± 0.50^{aBC}	1.86 ± 0.20^{aBC}
90	2.15 ± 0.29^{aAB}	2.13 ± 0.17^{aB}	1.98 ± 0.37^{aAB}	2.10 ± 0.11^{aAB}
100	2.32 ± 0.15^{aA}	2.37 ± 0.11^{aA}	2.20 ± 0.30^{aA}	2.32 ± 0.07^{aA}

$^{a–d}$Means (± SD) with a different letter in the same row are significantly different at $P < 0.05$

$^{A–H}$Means (± SD) with a different letter in the same column are significantly different at $P < 0.05$

electrical conductivity of soup was 0.11 ± 0.03 S/m at 12 V/cm and 20 °C, and increased up to 2.37 ± 0.11 S/m at 12 V/cm and 100 °C. The electrical conductivity of rice cake soup increased according to temperature elevation. However, no clear differences among the selected electric field strengths (9-18 V/cm) were found. In the ohmic heating, electrical conductivity is determined by mineral or ionic content (Srivastav and Roy, 2014). Previous researchers reported that the elevation in electrical conductivity values with temperature rise is explained by the lowered drag of ion movement (Darvishi et al., 2013; Icier and Ilicali, 2005; Srivastav and Roy, 2014).

Figure 3(B) presents the results of a comparison of the temperature histories of soup and rice cakes at an electric field strength of 15 V/cm and a 120 s cooking time. In this study, the heating rate of soup and rice cake was quite similar at all selected electric field strength. Simultaneous temperature increase of soup and rice cake can be attributed to the advantages of ohmic cooking as a rapid and uniform temperature rise. It can therefore save cooking time and energy for rice cake soup preparation.

Calculation of the amount of energy in the form of heat (Q_{taken}, J), total volumetric ohmic internal energy dose (E_{vd}, J), heat loss (Q_{loss}, J), and the energy efficiency

Figure 2 shows the temperature profiles of soup and the volumetric internal energy generation rate ($\dot{Q}_{ie}$, W/m^3) at the electric field strength of 15 V/cm and a 120 s cooking time. The temperature and volumetric energy rate were utilized to calculate the SPC energy efficiency using heat generation (Q_{taken}, J) and heat loss (J). The volumetric internal energy generation rate ($\dot{Q}_{ie}$, W/m^3) increased as temperature increased, since a material's electrical conductivity rises with temperature elevation. In this graph, the initial temperature of the soup elevated from 25 °C to 100 °C during a 15 V/cm electric field strength application. During this period, the volumetric internal energy generation rate ($\dot{Q}_{ie}$, W/m^3) gradually increased from 0 W/m^3 to 4,799,642 W/m^3. The electric field was reduced down to 7.5 V/cm during the cooking time at 100 °C; subsequently, the volumetric internal energy generation rate ($\dot{Q}_{ie}$, W/m^3) went down to 815,446 W/m^3.

The amount of energy generation in the form of heat (Q_{taken}, J) ranged from 60,947 J to 61,596 J. Although the maximum Q_{taken} was observed at a 15 V/cm application, no clear difference or trend in Q_{taken} was found among different electric field applications.

Heat loss (Q_{loss}, J) decreased from 22,411 J at an electric field strength of 9 V/cm to 6793 J at an electric field strength of 18 V/cm. Elevating the electric field strength resulted in a more rapid temperature rise, minimizing heat loss. A faster heating rate can help to reduce heat loss in volumetric and internal heat generation techniques, such as microwave and ohmic heating (Jo and Park, 2019; Ramaswamy and Lin, 2011; Soisungwan et al., 2019). During ohmic heating, heat loss is attributed to the combination of vapor generation and heat transfer to the surrounding (Kong et al., 2008).

The total volumetric ohmic internal energy dose (E_{vd}, J) was estimated through a combination of the ohmic internal energy generation rate ($\dot{Q}_{ie}$, W/m^3), sample volume, and their integration versus time (Eq. 7). E_{vd} had a value of 96,906 J at a 9 V/cm application, and then continuously decreased to 85,198 J at an electric field of 15 V/cm. E_{vd} increased again to 87,106 J at 18 V/cm application; however, there was no clearance difference between the 15 and 18 V/cm applications ($P > 0.05$). Rapid temperature rise at higher electric fields would result in less electrical energy consumption, and subsequently, reduced E_{vd}.

The SPC energy efficiency can evaluate he efficiency of ohmic heating in terms of conversion of electrical energy into heat. If all the volumetric ohmic internal energy dose is converted to heat, SPC energy efficiency has a value of 1. Its value decreases with heat loss along with physical, chemical, and electrochemical reactions of foods during ohmic heating (Assiry et al., 2010; Darvishi et al., 2013; Icier and Ilicali, 2005; Jo and Park, 2019; Soisungwan et al., 2019). The lowest SPC energy efficiency, 0.51, was found at a 9 V/cm electric field application, and it significantly increased to 0.65 at a 15 V/cm application ($P < 0.05$). However, there was no significant difference between 15 and 18 V/cm ($P > 0.05$). The lowest SPC energy efficiency (at a 9 V/cm electric field) could be attributed to the excessive heat loss of 22,411 J during temperature rise. Increasing electric field strength reduced the heat loss to surroundings through a rapid heating rate; subsequently, it induced elevated SPC energy efficiency values. At high voltage gradients, the passing current through the product is excessive and may increase the heat generation rate (Aniesrani Delfiya and Thangavel 2016; Soisungwan et al. 2019). Furthermore, physical and chemical reactions of food matrices would have a minor influence on the SPC energy efficiency values. In our study, 75 g of rice cake was ohmically cooked. In general, starch is one of major components in rice cakes, taking up 51% of their total weight (Pottgen, 2016). Therefore, 38 g of starch would be gelatinized during one batch of ohmic heating. The enthalpy of starch gelatinization ranges from 0.807 to 1.591 J/g during the cooking process (Coral et al., 2009; Jo and Park, 2019; Li et al., 2004; Soisungwan et al., 2019). Subsequently, energy ranging from 30.7 to 60.5 J would be used to gelatinize the starch rather than increase the temperature, though this magnitude is minor compared to heat loss. Heat loss is an important consideration in the design of an ohmic heating system. Heat loss can be minimized by insulating the ohmic cell using a heat water jacket and the winding of heating tape (Zell et al., 2011). These measures were not tried in the present study, since our objectiev was a feasibility test to investigate the potential of ohmic heating for cooking rice cakes. Further studies are required to enhance the efficiency of the rice cake ohmic heating system by minimizing heat loss to surroundings.

Texture analysis

Figure 4 shows the results of the texture profiles (hardness and cohesiveness) of ohmically-cooked rice cakes at the electric field strengths of 9, 12, 15, and 18 V/cm and cooking times of 60, 80, 100, and 120 s. The hardness of ohmically-cooked rice cakes ranged from 4.55 to 9.35 N. A low electric field of 9 V/cm resulted in softness of texture, i.e. a lower hardness level (5.34–5.82 N). This could be attributed to overcooking due to a slow heating rate of 12.1 °C/min at 9 V/cm. In contrast, high electric fields and short cooking times caused undercooked rice cakes with a high magnitude of hardness. For example, an electrical field strength of 18 V/cm and a 60 s cooking produced the highest hardness, 9.35 N. An appropriate texture of cooked food can be achieved by the proper combination of electric field strength and cooking time (Jo and Park, 2019; Soisungwan et al., 2019). In our study, appropriate magnitude of hardness was estimated according to rice cakes cooked following the manufacturer's cooking guide. Boiling water at 100 °C was poured into the rice cake mixture and then it was soaked for 2 min. The hardness of these rice cakes was 7.56 N. Among ohmically-cooked rice cakes, an electrical field of 15 V/cm and an 80 s cooking time resulted in a hardness of 7.73 N, which is the most similar to that of rice cakes prepared according to the manufacture's cooking guide. Therefore, in the scope of our experimental conditions, it is postulated that 15 V/cm and 80 s would result in suitable hardness of an ohmically-cooked rice cake. Cohesiveness ranged from 0.48 to 0.71; however, there were no clear trends in cohesiveness influenced by electric field strength and cooking time.

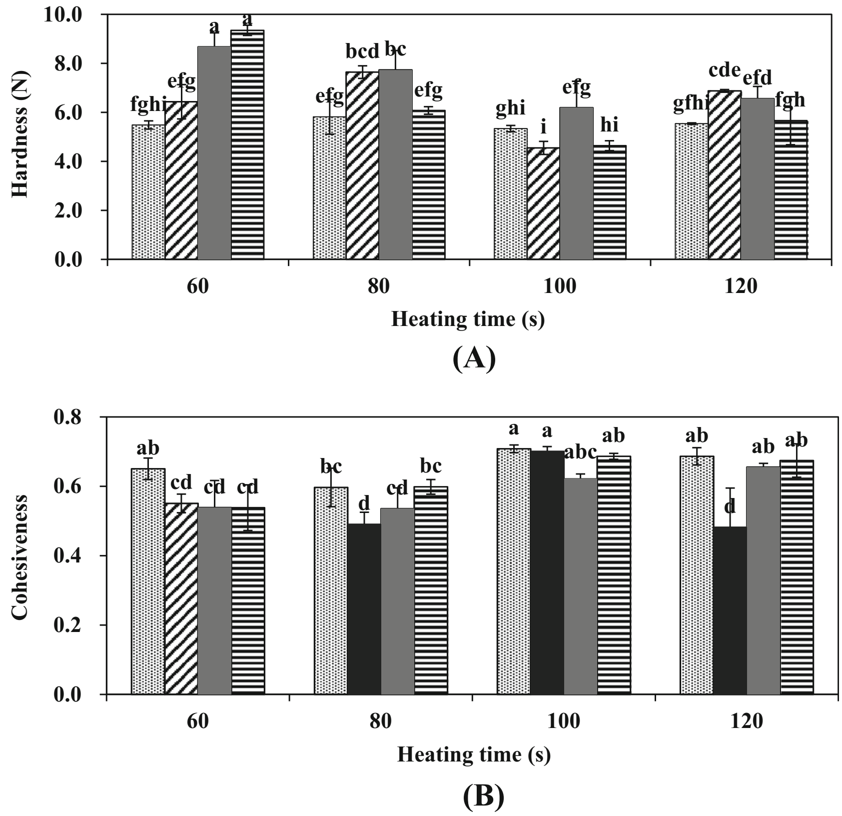


Fig. 4 (**A**) Hardness (N) and (**B**) Cohesiveness of ohmically cooked rice cakes as a function of electric field (V/cm) and holding time (s). 9 V/cm, 12 V/cm, 15 V/cm, 18 V/cm. [a–d]Means (± SD) with a different letter are significantly different at $P < 0.05$

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References

Aniesrani Delfiya DS, Thangavel K. Effect of ohmic heating on polyphenol oxidase activity, electrical and physicochemical properties of fresh tender coconut water. Int. J. Food Eng. 2: 691-700 (2016)

Assiry AM, Gaily MH, Alsamee M, Sarifudin A. Electrical conductivity of seawater during ohmic heating. Desalination. 260: 9-17 (2010)

Coral D, Pineda-Gómez P, Rosales-Rivera A, Rodriguez-Garcia M. Determination of the gelatinization temperature of starch presented in maize flours, J. Phys. Conf. Ser. 167: 012057 (2009)

Darvishi H, Hosainpour A, Nargesi F. Ohmic heating behaviour and electrical conductivity of tomato paste. J. Nutr. Food Sci. 2: 1-5 (2012)

Darvishi H, Khostaghaza MH, Najafi G. Ohmic heating of pomegranate juice: electrical conductivity and pH change. J. Saudi Soc. Agric. Sci. 12: 101-108 (2013)

Gavahian M, Farahnaky A, Sastry S. Ohmic-assisted hydrodistillation: A novel method for ethanol distillation. Food Bioprod. Process. 98: 44-49 (2016)

Geankoplis CJ. Transport processes and unit operations. NJ:PTR, Prentice Hall. p. 256 (1993)

Hasegawa A, Ogawa T, Adachi S. Estimation of the gelatinization temperature of noodles from water sorption curves under temperature-programmed heating conditions. Biosci. Biotechnol. Biochem. 76: 2156-2158 (2012)

Icier F, Ilicali C. Electrical conductivity of apple and sourcherry juice concentrates during ohmic heating. J. Food Process Eng. 27: 159-180 (2004)

Icier F, Ilicali C. The effects of concentration on electrical conductivity of orange juice concentrates during ohmic heating. Eur. Food Res. Technol. 220: 406-414 (2005)

Icier F, Bozkurt H. Ohmic heating of liquid whole egg: rheological behaviour and fluid dynamics. Food Bioprocess Tech. 4: 1253-263 (2011)

Icier F, Yildiz H, Sabanci S, Cevik M, Cokgezme OF. Ohmic heating assisted vacuum evaporation of pomegranate juice: electrical conductivity changes. Innov. Food Sci. Emerg. Technol. 39: 241-246 (2017)

Ito R, Fukuoka M, Hamada-Sato N. Innovative food processing technology using ohmic heating and aseptic packaging for meat. Meat Sci. 96: 675-681 (2014)

Jang A, Kim JY, Lee S. Rheological, thermal conductivity, and microscopic studies on porous-structured noodles for shortened cooking time. LWT Food Sci. Technol. 74: 1-6 (2016)

Jha SN, Narsaiah K, Basediya AL, Sharma R, Jaiswal P, Kumar R. Measurement techniques and application of electrical properties for nondestructive quality evaluation of foods-a review. J. Food Sci. Technol. 48: 387-411 (2011)

Jo YJ, Park SH. Evaluation of energy efficacy and texture of ohmically cooked noodles. J. Food Eng. 248: 71-79 (2019)

Kong YQ, Li D, Wang LJ, Bhandari B, Chen XD, Mao ZH. Ohmic heating behavior of certain selected liquid food materials. Int. J. Food Eng. 4: 2. https://doi.org/10.2202/1556-3758.1378 (2008)

Ku SK, Hong JS, Choi HD, Park JD, Kim YB, Choi HW, Kim TK, Choi YS. A study of the quality characteristics of frozen Korean rice cake by using different thawing methods. Food Sci. Biotechnol. 27: 1343-1351 (2018)

Li F De, Li L Te, Li Z, Tatsumi E. Determination of starch gelatinization temperature by ohmic heating. J. Food Eng. 62: 113-120 (2004)

Li F, Zhang L. Ohmic heating in food processing. Taylor and Francis. London. pp. 661 (2010)

Marra F. Analysis of heat transfer during ohmic processing of a solid food. J. Food Eng. 91: 56-63 (2009)

Mehta, F, Rajagopalan, R, Trivedi P. Formulation and texture analysis of environment friendly Zein Gum. Int. J. Pharm. Tech. Res. 4: 1587-1598 (2012)

Park SH, Balasubramaniam VM, Sastry SK, Lee J. Pressure-ohmic-thermal sterilization: a feasible approach for the inactivation of *Bacillus amyloliquefaciens* and *Geobacillus stearothermophilus* spores. Innov. Food Sci. Emerg. Technol. 19: 115-123 (2013)

Park IK, Ha JW, Kang DH. Investigation of optimum ohmic heating conditions for inactivation of *Escherichia coli* O157:H7, *Salmonella enterica* serovar Typhimurium, and Listeria monocytogenes in apple juice. BMC Microbiol. 17: 117 (2017)

Pottgen EJ. Rice Consumption and effects of rice cake, Seolgitteok, on human health. MS thesis, University of Arkansas, Fayetteville, AR, USA (2016)

Ramaswamy HS, Lin M. Influence of system variables on the heating characteristics of water during continuous flow microwave heating. Int. J. Microw. Sci. Technol. 11: 10 https://doi.org/10.1155/2011/264249 (2011)

Ratnayake WS, Jackson DS. Gelatinization and solubility of corn starch during heating in excess water: new Insights. J. Agric. Food Chem. 54: 3712-3716 (2006)

Reznick D. Ohmic heating of fluid foods. Food Technol. 50: 250-51 (1996)

Sabanci S. Icier F. Applicability of ohmic heating assisted vacuum evaporation for concentration of sour cherry juice. J. Food Eng. 212: 262-270 (2017)

Sastry SK, Salengke S. Ohmic heating of solid-liquid mixtures: A comparison of mathematical models under worst-case heating conditions. J. Food Process Eng. 21: 441-58 (1998)

Shirsat N, Lyng JG, Brunton NP, McKenna B. Ohmic processing: Electrical conductivities of pork cuts. Meat Sci. 67: 507-514 (2004)

Soisungwan S, Khampakool A, You SG, Park WJ, Park SH. Evaluating the feasibility of ohmic cooking for home meal replacement curry: analysis of energy efficacy and textural qualities. Int. J. Food Eng. https://doi.org/10.1515/ijfe-2018-0380 (2019)

Srivastav S, Roy S. Changes in electrical conductivity of liquid foods during ohmic heating. Int. J. Agric. Biol. Eng. 7: 133-138 (2014)

Tan I, Wee CC, Sopade PA, Halley PJ. Estimating the specific heat capacity of starch-water-glycerol systems as a function of temperature and compositions. *Starch Stärke.* 56: 6-12 (2004)

Yoon SJ, Oh IS. Usage status of traditional rice cake as a meal substitute and analysis on the selection attributes affecting purchase. Culin. Sci. Hosp. Res. 20: 38-53 (2014)

Zell M, Lyng JG, Morgan DJ, Cronin, D. A. Minimising heat losses during batch ohmic heating of solid food. Food Bioprod, Process. 89: 128-134 (2011)