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Evaluating the Feasibility of Ohmic Cooking for Home Meal Replacement Curry: Analysis of Energy Efficacy and Textural Qualities

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Abstract:
The feasibility of ohmic heating was tested for cooking instant home meal replacement (HMR) curry mixture. A curry mixture (curry powder, spam, carrot, potato, and water) was ohmically heated to 100 °C using different electric fields (9, 12, 15, and 18 V/cm). Temperature come-up time to 100 °C of curry soup were 5.27 ± 0.63, 3.15 ± 0.39, 2.28 ± 0.19, and 1.67 ± 0.24 min at the electric fields of 9, 12, 15, and 18 V/cm, respectively. The come-up time was decreased as a function of enhanced electric fields ($P < 0.05$). In terms of energy efficacy, the highest electric field (18 V/cm) resulted in the most efficient system performance coefficient (*SPC*), with a score of 0.62. In terms of textural qualities, cooking at 15 V/cm of carrot and potato the hardness was 3.41 ± 0.69 N and 1.04 ± 0.18 N, respectively, that resulted in the ideal level of hardness. Our study proposed the positive feasibility of ohmic heating to cook HMR curry soup.

Keywords: Ohmic heating, curry, home meal replacement, system performance coefficient, texture

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1 Introduction

Home meal replacements (HMRs) are rapidly growing in the food industry as a result of consumers increasingly lacking time, where an active population has little time to eat, let alone shop and cook [1]. Curry is a popular HMR food and is normally served with rice, vegetables, and meat products. Curry leaf plants (*Murraya koenegii*) are grown in South East Asia and the leaves are widely used for enhancing flavor [2]. Commercial curry products are generally sold in powder type, which is then mixed with various ingredients (vegetables, meat, and fish) and water. The curry mixture should be boiled using a gas stove or electrical cooker. However, these conventional heating systems are slow to transfer heat to the products due to poor conduction and convection. Alternative cooking techniques for curry mixtures are required in order to save time, labor, and energy. Ohmic heating could provide a solution for rapid cooking of HMR products.

Ohmic heating, also called electrical resistance heating, is a process where an alternating current is passed through food materials resulting in internal heat generation [3–6]. Ohmic heating has the advantages of rapid temperature rise, uniform heating, high energy efficacy, and minimized thermal damage since volumetric heating can infiltrate the entire product [7–12]. Ohmic heating yields better products which are superior in quality than those processed by conventional heating [13–16]. Heat dissipation during ohmic heating depends on the applied electric field and the electrical conductivity of the products or of individual product fractions, as determined by Ohm's law [17–19].

Although the ohmic heating technique has an advantage in uniform heating, there is still chance of partial non-uniform heating for solid-liquid mixtures. If the solid and liquid ingredients had different electrical conductivities, voltage gradient will not be uniform along the ohmic heater and subsequently induce non-uniform heating [20–22]. These authors suggested several mathematical models to analyze the non-uniform heating in solid-liquid mixtures including series, parallel, two forms of Maxwell–Eucken models and effective medium theory. Even though ohmic heating has a limitation in uniformity related to the electric conductivity of food [23], it has been found to be more uniform than other eletroheating techniques [24].

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Ohmic heating has shown its efficacy in the cooking of various food products in the past, including rice, meat patties, surimi, and instant noodles [18, 25, 26]. In our study, the potential of ohmic cooking was evaluated in cooking a commercial HMR curry mixture, which included its common ingredients (spam, carrot, potato). The analysis focused on: (a) the relationship between electric field strengths and temperature come-up, (b) the heating characteristics of different ingredients (spam, carrot, potato), (c) the system performance coefficient (*SPC*) as a function of electric field, and (d) the textural qualities of ohmic cooked ingredients.

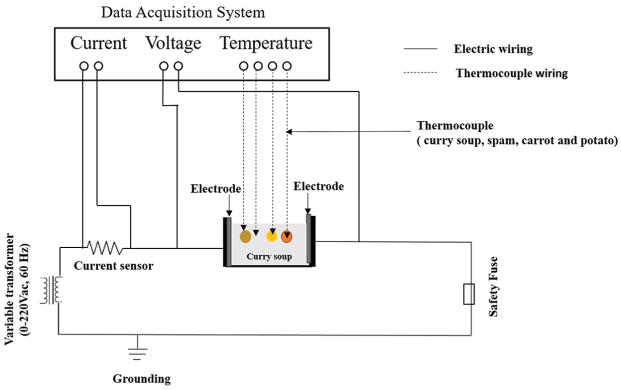
2 Materials and methods

2.1 Sample preparation

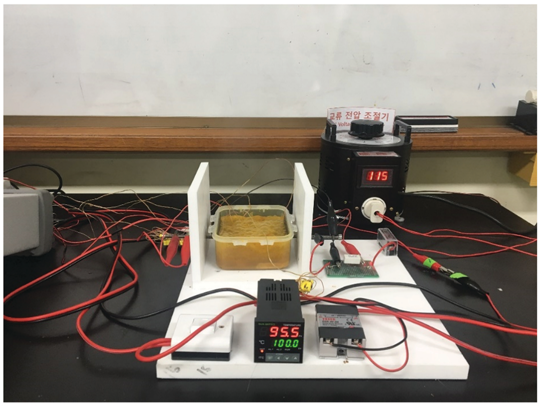
Curry powder (Ottogi mild curry powder), spam (The authentic quality brand), carrot (*Daucus carota* L.), and potato (*Solanum tuberosum* L.) were purchased at a local market (Homeplus, Korea). Spam, carrot, and potato were selected since they are the common ingredients in curry. Spam is shelf stable canned cooked meat which is popularly used ingredients for convenient foods. Carrots are one of the most commonly consumed vegetables in the world, one-fourth of which are consumed in processed form in the market foods [27, 28]. Potato is the third most important food product and its processing property is great food industry since it has a special place in the diet of people of developing countries [29]. They were cut into cylindrical pieces (diameter: 10 mm, length: 10 mm) using a cork borer (H9663, Fisher Scientific). Ten grams of each ingredient (spam, carrot, and potato) were mixed into deionized water (140 mL) and curry powder (20 g). This curry mixture was used for the ohmic heating experiment.

2.2 Ohmic heating system

Figure 1 shows the schematic ohmic heating systems used previous to our study [18]. A rectangular shape airtight food container (76 mm × 46 mm × 97 mm, Lock & Lock Seoul, Korea) was used as the ohmic container. Two square-type titanium electrodes (75 mm × 25 mm, thickness: 1 mm) were placed at the left and right ends of ohmic cell maintaining a distance of 95 mm. An AC power supplier applied different electric fields (9–18 V/cm) for the ohmic heating of the curry mixture. To measure the heating and energy efficacy, temperature, voltage, and current were measured and recorded every 3 s using an equipped Data Acquisition System (DAQ, 34970A, Agilent Technologies, Santa Clara, CA, USA).



(a)



(b)

Figure 1: (a) A schematic diagram and (b) photo image of an ohmic heating system for curry mixture (reproduced and modified with permission from our previous work [18] and Elsevier copyright clearance, License #: 4591811426843).

2.3 Ohmic heating treatment

In this study, the procedure of ohmic heating treatment followed up our previous work [18]. The prepared curry mixture was poured into the ohmic cell. In this study, four K-type thermocouples (0.25 mm diameter, TFIR-003–50, Omega Engineering, Stamford, CT, USA) were used to measure the temperatures of spam, carrot, potato, and curry soup. Each thermocouple was installed into the central position of each product. Moreover, one thermocouple was mounted into the curry soup. The power supplier applied four different alternating electric fields of 9, 12, 15, and 18 V/cm at 60 Hz across the curry mixture during a target temperature come-up time to 100 °C. Target soup temperature of 100 °C was maintained for 5 min under constant electric fields at 5 V/cm.

2.4 *SPC* calculation

The *SPC* was calculated to the ratio of total volumetric ohmic internal energy dose (E_{vd}, J) conversion into heat quantity (Q_{taken}, J) as proposed by a previous study of ours [18]. In this study, all the mathematical formulas and calculations followed the abovementioned study. Energy efficacy was calculated as the time the curry soup took to reach a temperature of 100 °C as the greatest electrical energy is spent during the temperature come-up time in ohmic heating [18].

Heat required (Q_{taken}, J) to raise the temperature of the curry soup to the target temperature (100 °C) was calculated taken into consideration the temperature increase of all ingredients, including the curry soup, spam, carrot, and potato [30] as shown in eq. (1). Q_{taken} was defined as the amount of energy in the form of heat (J):

$$Q_{taken} = m_c \cdot C_{p,c} \cdot (T_{ic} - T_{fc}) + m_s \cdot C_{p,s} \cdot (T_{is} - T_{fs}) + m_{ca} \cdot C_{p,ca} \cdot (T_{ica} - T_{fca}) + m_p \cdot C_{p,p} \cdot (T_{ip} - T_{fp}) \qquad (1)$$

where Q_{taken} is the amount of energy in the form of heat (J), m_c is the mass of curry soup (kg), m_s is the mass of spam (kg), m_{ca} is the mass of carrot (kg), m_p is the mass of potato (kg), $C_{p,c}$ is the specific heat of curry soup (J·kg^{-1}·K^{-1}), $C_{p,s}$ is the specific heat of spam (J·kg^{-1}·K^{-1}), $C_{p,ca}$ is the specific heat of carrot (J·kg^{-1}·K^{-1}), $C_{p,p}$ is the specific heat of potato (J·kg^{-1}·K^{-1}), T_{ic} is the initial temperature of curry soup (°C), T_{fc} is the final target temperature of curry soup as 100 °C, T_{is} is the initial temperature of spam (°C), T_{fs} is the final temperature of spam when soup temperature reached to 100 °C, T_{ica} is the initial temperature of carrot (°C), T_{fca} is the final temperature of carrot when soup temperature reached to 100 °C, T_{ip} is the initial temperature of potato (°C), and T_{fp} is the final temperature of potato when soup temperature reached to 100 °C.

In our study, the specific heat of curry soup ($C_{p,c}$) was 3659 J. The specific heat of curry soup was calculated from a ratio of water (4182 J) and curry powder (0.875:0.125). The specific heat of spam ($C_{p,s}$) was 3466 J, obtained from the published value of ham [31]. The specific heat of carrot ($C_{p,ca}$) was 3810 J [24]. The specific heat of potato ($C_{p,p}$) was 3430 J [32]. In our study, the specific heat of $C_{p,c}$, $C_{p,s}$, $C_{p,ca}$, and $C_{p,p}$ were assumed to be independent of temperature as suggested by previous researchers [18, 30].

In our study, heat loss to the surrounding environment (Q_{loss}) during temperature come-up was considered and calculated as suggested by our previous work [18] and Geankoplis (1993) [33], as shown in eq. (2). It is essential to quantify heat losses to ensure a completely safe ohmically cooked product [26]:

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

where Q_{loss} is the heat loss from each wall (top, bottom, side) of the ohmic cell (76 mm × 46 mm × 97 mm; Lock & Lock Seoul, Korea) to surrounding by natural convection; $\bar{h}_{tw}$ is the convective heat transfer coefficient (W/m^2·K) of the top wall of the ohmic cell; $\bar{h}_{bw}$ is the convective heat transfer coefficient (W/m^2·K) of the bottom wall of the ohmic cell; $\bar{h}_{sw}$ is the convective heat transfer coefficient (W/m^2·K) of the side wall of the ohmic cell; $\bar{h}_{sew}$ is the convective heat transfer coefficient (W/m^2·K) of the electrode side wall of the ohmic cell; A_{tw} is the area of the top wall of the ohmic cell; A_{bw} is the area of the bottom wall of the ohmic cell; A_{sw} is the area of the side wall of the ohmic cell; A_{sew} is the area of the electrode side wall of the ohmic cell; ΔT_{avtw} is the average temperature driving force of the top wall estimated from initial wall temperature, final wall temperature, and ambient air temperature; ΔT_{avbw} is the average temperature driving force of the bottom wall estimated from initial wall temperature, final wall temperature, and ambient air temperature; ΔT_{avsw} is the average temperature driving force of the side wall estimated from initial wall temperature, final wall temperature, and ambient air temperature; ΔT_{avsew} is the average temperature driving force of the electrode side wall estimated from initial wall temperature, final wall temperature, and ambient air temperature. A K-type thermocouple was attached to the surface of the top wall, bottom wall, and side wall of the ohmic cell with electrodes to measure the temperature changes and subsequent heat loss during ohmic come-up time as suggested by Marra et al. (2009) [34]. These data were utilized to estimate the average temperature driving force (ΔT), which is the average of the initial wall temperature, final wall temperature, and ambient air temperature [15, 18, 30]. The natural convective heat transfer coefficients ($\bar{h}$) of each wall were calculated through simplified equations for natural convection as shown in eq. (2) [30, 33]. Table 1 presents the convective heat transfer coefficient (h, W/m^2·K) and average temperature driving force (ΔT_{av}) of each top ($_{tw}$), bottom ($_{bw}$), side ($_{sw}$) and electrode side wall ($_{sew}$). The highest heat transfer coefficient was observed at the electrode side wall ($_{sew}$) which ranged from 10.87 to 10.99 W/m^2·K followed by side wall ($_{sw}$), top wall ($_{tw}$) and bottom wall ($_{bw}$). The existence of the overshoot of the electric field strength near the electrode edges allows for increased heating and thus a temperature rise [35]. The average temperature driving force showed the highest value at the top wall ($_{tw}$) followed by bottom wall ($_{bw}$), electrode side wall ($_{sew}$) and side wall ($_{sw}$). This trend would attribute to the heat transfer area of each wall.

Table 1: Parameters for heat loss estimation.

Electric field		Position			
		Top wall ($_{tw}$)	**Bottom wall ($_{bw}$)**	**Side wall ($_{SW}$)**	**Electrode side wall ($_{SEW}$)**
	Area (m^2)	**0.007**	**0.007**	**0.004**	**0.003**
9 V/cm	h (W/m^2·K)	10.05 ± 0.02^f	4.47 ± 0.01^h	10.29 ± 0.03^d	10.99 ± 0.04^a

	ΔT_{av} (K)	320 ± 3^{A}	313 ± 4^{C}	303 ± 3^{GF}	311 ± 4^{CD}
12 V/cm	h (W/m²·K)	10.01 ± 0.06^{g}	4.47 ± 0.01^{h}	10.31 ± 0.03^{d}	10.94 ± 0.03^{b}
	ΔT_{av} (K)	314 ± 8^{BC}	312 ± 3^{C}	305 ± 3^{DEF}	305 ± 3^{DEF}
15 V/cm	h (W/m²·K)	10.05 ± 0.03^{f}	4.46 ± 0.01^{h}	10.31 ± 0.02^{d}	10.95 ± 0.03^{ab}
	ΔT_{av} (K)	320 ± 4^{A}	309 ± 2^{CDE}	304 ± 2^{EF}	306 ± 4^{DEF}
18 V/cm	h (W/m²·K)	10.05 ± 0.02^{fg}	4.44 ± 0.02^{h}	10.23 ± 0.04^{e}	10.87 ± 0.02^{c}
	ΔT_{av} (K)	319 ± 3^{AB}	304 ± 6^{EF}	295 ± 4^{H}	297 ± 3^{GH}

Note: [a-h] Means (± standard deviation) with a different letter of the convective heat transfer coefficient (h, W/m^2·K) are significantly different at $P < 0.05$.
[A-H]Means (± standard deviation) with a different letter of the average temperature driving force (ΔT_{av}, K) are significantly different at $P < 0.05$.

The ohmic internal energy generation rate per volume ($\dot{Q}_{ie}$, W·m^{-3}) was calculated as a function of the squared electric field (V/m) and electrical conductivity (S/m), according to the suggestions from previous researchers [18, 36, 37]:

$$\dot{Q}_{ie} = \sigma \cdot |\nabla V|^2 \tag{3}$$

The electrical conductivity (σ, S/m) of a material is determined from the cell constant (k, m^{-1}), voltage, and current data. The cell constant is a consideration of sample dimensions where sample length (L, m) is divided by a cross sectional area (A, m^2). In our study, sample length (L, m) was 0.0950 m, which is the distance between electrodes. The cross sectional area (A, m^2) was equal to the area of rectangular-type titanium electrodes (0.075 m × 0.025 m), calculated as 0.0019 m^2 and the k value is 50.67 m^{-1}. Electrical conductivity (σ, S/m) was determined as follows [18]:

$$\sigma = k \cdot \frac{I}{V} \tag{4}$$

Thus, the ohmic internal energy generation rate ($\dot{Q}_{ie}$, W/m^3) was expressed as a combination of eqs. (3) and (4), as shown follows [18]:

$$\dot{Q}_{ie} = k \cdot \frac{I}{V} \cdot |\nabla V|^2 \tag{5}$$

The total volumetric ohmic internal energy dose (E_{vd}, J) of all sample was estimated from the ohmic internal energy generation rate (W/m^3), sample volume (v, m^3), and integration versus time (s) [18]

$$\begin{aligned} E_{vd} &= \int_{t_i}^{t_f} \dot{Q}_{ie} dt \\ &= \int_{t_i}^{t_f} k \cdot \frac{I}{V} \cdot |\nabla V| \, dt \\ &= \frac{k}{2} \left[\begin{array}{l} \left(\frac{I_0}{V_0} \cdot |\nabla V_0| + \frac{I_1}{V_1} \cdot |\nabla V_1| \right) \Delta t_{0\sim 1} + \left(\frac{I_1}{V_1} \cdot |\nabla V_0| + \frac{I_2}{V_2} \cdot |\nabla V_2| \right) \Delta t_{1\sim 2} + \\ \left(\frac{I_2}{V_2} \cdot |\nabla V_2| + \frac{I_3}{V_3} \cdot |\nabla V_3| \right) \Delta t_{2\sim 3} \ldots + \left(\frac{I_{n-1}}{V_{n-1}} \cdot |\nabla V_{n-1}| + \frac{I_n}{V_n} \cdot |\nabla V_n| \right) \Delta t_{n-1\sim n} \end{array} \right] \end{aligned} \tag{6}$$

The above function was calculated using trapezoidal numerical integration versus time to internal energy generation rate in MATLAB (Version 7.9.0.529, Mathworks Inc., MA, USA) as suggested by our previous work [18]. This method enables to calculate the total amount of internal energy generation as suggested by previous studies [18, 38].

Finally, the *SPC* was calculated as shown in eq. 7. *SPC* has been used previously to estimate the efficacy of ohmic heating for temperature increase in food products [18, 30, 39]:

$$SPC = \frac{Q_{taken}}{E_{vd} + Q_{loss}} \tag{7}$$

When the ohmic internal energy is 100 % converted to a temperature increase (heat), $SPC = 1$ and then decreases with low energy conversion status.

2.5 Texture profile analysis (*TPA*)

The texture profile analysis (*TPA*) of ohmically heated curry ingredients (spam, carrot. and potato) was conducted using a TA-XT Plus Texture Analyzer (Texture Technology Corp., NY, USA). In this study, the *TPA* settings of spam, carrot, and potato were identical to minimize any further changes since *TPA* setting modification took a long time. Ohmically cooked spam, carrot, and potato in the curry soup were individually taken out of the ohmic cell immediately after treatment and placed onto the metal plate of the *TPA*. A cylindrical probe (P/3–3 mm diameter) punctured the sample with a constant *TPA* setting (Pretest speed: 3 mm/s, Test speed: 5 mm/s, Post-test speed: 1.00 mm/s, Target distance: 5 mm, Time: 5.0 s, Trigger Type: Auto) and was expressed as hardness (N).

2.6 Statistical analysis

The data were analyzed using Statistical Analysis System (SAS) software (version 9.1.3, SAS Inst. Inc., Cary, NC, USA). Statistical analysis was conducted by an analysis of variance (ANOVA) for a multiple comparison. Fisher's least-significant difference (LSD) procedures were used for a multiple comparison among treatments at the 95 % confidence interval ($P < 0.05$). All the ohmic treatments were replicated three times.

3 Results and discussion

3.1 Temperature histories of curry ingredients (spam, carrot, potato, and soup) at different electric fields

Figure 2 shows the temperature histories of curry soup, spam, carrot, and potato at different electric fields (9, 12, 15, 18 V/cm) and 5 min holding time. The temperature of the curry soup indicated the fastest come-up time compared to those of spam, carrot, and potato in all the tested electric fields. The temperature of curry soup reached 100 °C within 1.67 ± 0.24 min at 18 V/cm (Table 2). Other ingredients showed significantly slower temperature come-up times compared to that of soup ($P < 0.05$). The times were of 1.73 ± 0.18, 3.80 ± 0.25, and 4.97 ± 1.50 min for spam, carrot, and potato at 18 V/cm, respectively. In the present study, the temperature increase of the soup was attributed to the higher electrical conductivity of the soup compared to those of other ingredients (spam, carrot, and potato), since the soup contained various ions, including sodium and chloride, as well as seasonings. In general, liquid food contains more ions, such as those from solutes, spices, and herbs than solid products; thus, these liquids are rapidly heated during ohmic heating due to their high electrical conductivity [18, 31]. The amount of heat generation is directly determined by the square of the electric field and electrical conductivity [17, 19]. In the tested solid products (spam, carrot, potato), the temperature of spam increased quicker than carrot or potato. For example, spam took 2.62 ± 0.45 min to reach 100 °C at 15 V/cm, whereas carrot and potato took 5.03 ± 0.21 and 4.58 ± 0.42 min, respectively. In the present study, the initial electrical conductivities of spam, carrot, and potato were 2.565 ± 0.021, 0.027 ± 0.003, and 0.051 ± 0.007 S/m, respectively. The high electrical conductivity of spam allowed for a greater electric current passage and subsequently an enhanced heat generation. Carrot and potato had relatively slower temperature come-up rates since they have relatively lower electrical conductivities compared to spam.

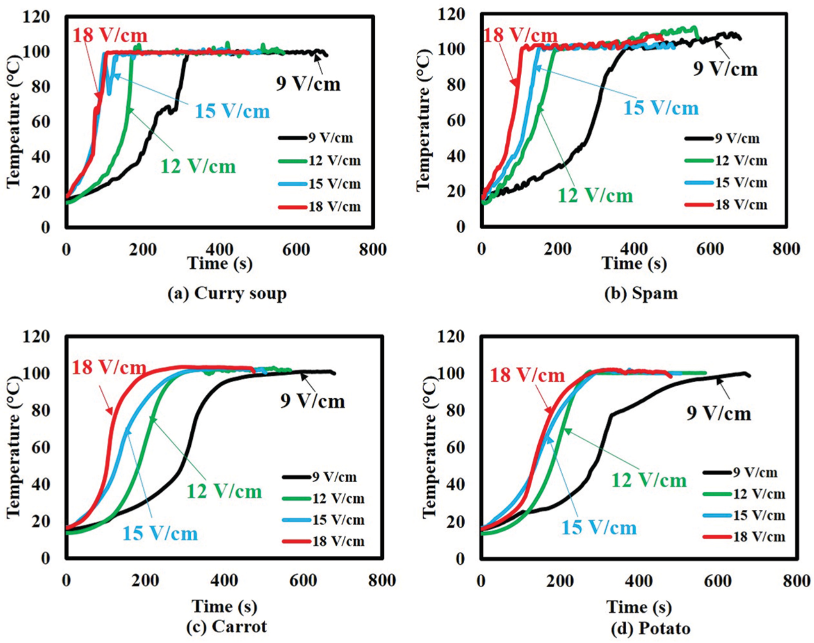


Figure 2: Ohmic heating curves of curry soup and ingredients (spam, carrot, and potato) at different electric fields (9, 12, 15, and 18 V/cm) and 5 min holding time.

Table 2: Comparison of temperature come-up time to 100 °C (min) of curry soup, spam, carrot, and potato at different electric fields (9, 12, 15, and 18 V/cm).

Electric field (V/cm)	Come-up time (min)			
	Curry soup	Spam	Carrot	Potato
9	5.27 ± 0.63^{aB}	6.08 ± 0.21^{aAB}	7.75 ± 1.09^{aA}	7.67 ± 2.00^{aA}
12	3.15 ± 0.39^{bC}	3.78 ± 1.30^{bCB}	5.38 ± 1.84^{bAB}	6.00 ± 0.15^{abA}
15	2.28 ± 0.19^{cB}	2.62 ± 0.45^{bcB}	5.03 ± 0.21^{bA}	4.58 ± 0.42^{bA}
18	1.67 ± 0.24^{cB}	1.73 ± 0.18^{cB}	3.80 ± 0.25^{bA}	4.97 ± 1.50^{bA}

Note: $^{a\text{-}c}$ Means (± standard deviation) with a different letter in the same column are significantly different at $P < 0.05$.
$^{A\text{-}C}$ Means (± standard deviation) with a different letter in the same row are significantly different at $P < 0.05$.

Concerning the relationship between the magnitude of the electric field and temperature rise, increasing the electric field expedited the temperature come-up rate. The temperature come-up time of the curry soup significantly decreased from 5.27 ± 0.63 min at 9 V/cm to 1.67 ± 0.24 min at 18 V/cm as a function of increasing electric fields ($P < 0.05$). Previous studies reported that elevated electric fields of ohmic heating generated greater internal energy and subsequently enhanced volumetric heating [9, 11, 12]. In the present study, the effect of the voltage gradient on the ohmic heating times of solid products (spam, carrot, potato) was found to be statistically significant ($P < 0.05$). For example, for spam, the temperature come-up times to 100 °C were 6.08 ± 0.21, 3.78 ± 1.30, 2.62 ± 0.45, and 1.73 ± 0.18 min at 9, 12, 15, and 18 V/cm as the voltage gradient increased, respectively. In ohmic heating, the rate of temperature increase is associated with an enhanced voltage gradient [18, 40, 41]. Since the electrical energy per treatment time that is converted to heat energy depends on the voltage gradient and the current passing through the sample, temperature rises at any instant are higher voltage gradients [15, 18].

3.2 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 *SPC*

Table 3 presents the initial and final electrical conductivity of tested spam, carrot, potato and curry/distilled water mixture and their mass ratio. These values are important consideration to estimate the total volumetric ohmic internal energy dose (E_{vd}, J). For an initial electrical conductivity at 20 °C, curry/distilled water mixture showed the highest electrical conductivity of 0.519 ± 0.016 S/m followed by spam (0.313 ± 0.008 S/m), carrot

(0.023 ± 0.003 S/m) and potato (0.016 ± 0.003 S/m). Mass ratio is the influential factor for internal energy generation of multi-phase foods during ohmic heating. The maximum ratio of 0.842 was found in curry/distilled water mixture. Final electrical conductivity showed the similar trends to initial electrical conductivity where curry/distilled water mixture showed the highest electrical conductivity of 3.230 ± 0.089 S/m followed by spam (3.017 ± 0.155 S/m), carrot (0.495 ± 0.017 S/m) and potato (0.398 ± 0.089 S/m). In our study, the curry/distilled water mixture showed the most mass ratio of 0.842 with significantly higher electrical conductivity as compared to other ingredients. Therefore, it is postulated the curry/distilled water mixture is mainly responsible for ohmic internal energy dose. Although there are few mathematical models of ohmic internal energy generation (series, parallel, two forms of Maxwell–Eucken models and effective medium theory), they are quite-difficult-to determine experimentally and assure the accuracy [22]. Our study aimed the feasibility test of ohmic cooking for curry; so, we hypothesized that electrical properties and mass ratio of curry mixture will be dominant in which we measured the changes in electric field, current and subsequent total volumetric internal energy dose.

Table 3: Electrical conductivity, mass (g) and ratio of spam, carrot, potato and curry/DW mixture for ohmic cooking.

	Initial electrical conductivity, 20 °C	Final electrical conductivity, 100 °C	Mass (g)	Ratio
Spam	0.313 ± 0.008^{e}	3.017 ± 0.155^{b}	10	0.053
Carrot	0.023 ± 0.003^{f}	0.495 ± 0.017^{cd}	10	0.053
Potato	0.016 ± 0.003^{f}	0.398 ± 0.034^{de}	10	0.053
Curry/distilled water mixture	0.519 ± 0.016^{c}	3.230 ± 0.089^{a}	160	0.842

Note: $^{a\text{–}f}$ Means (± standard deviation) with a different letter in the table are significantly different at $P < 0.05$.

Table 4 summarizes the amount of energy in the form of heat (Q_{taken}, J), total volumetric ohmic internal energy dose (E_{vd}, J), heat loss (J), and *SPC* as a function of electric fields (9–18 V/cm). The highest Q_{taken} was obtained with an electric field of 9 V/cm; however, there was no significant difference with that of 12 V/cm. Increasing the electric fields to 15 and 18 V/cm slightly decreased the Q_{taken} down to 47,525 ± 405 J. Lower electric fields, at 9 and 12 V/cm, induced a longer temperature come-up time in the curry and vegetable samples than higher electric fields (15 and 18 V/cm); more heat was accumulated in the products.

Table 4: Comparison of 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 system performance coefficient (*SPC*) during temperature come-up time at different electric fields (9, 12, 15, and 18 V/cm).

Electric field (V/cm)	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)	System performance coefficient (*SPC*)
9	$49{,}352 \pm 764^{a}$	$76{,}950 \pm 6483^{a}$	$18{,}711 \pm 151^{a}$	0.52 ± 0.03^{c}
12	$49{,}334 \pm 695^{a}$	$73{,}547 \pm 3477^{ab}$	$11{,}161 \pm 118^{b}$	0.58 ± 0.03^{b}
15	$47{,}607 \pm 1106^{b}$	$72{,}519 \pm 7002^{ab}$	8056 ± 115^{c}	0.59 ± 0.05^{b}
18	$47{,}525 \pm 405^{b}$	$71{,}410 \pm 3700^{b}$	5822 ± 122^{d}	0.62 ± 0.03^{a}

Note: $^{a\text{–}c}$ Means (± standard deviation) with a different letter in the same column are significantly different at $P < 0.05$.

Figure 3 shows the representative temperature profiles at 12 V/cm and 5 min holding time of curry soup (T_c), spam (T_s), carrot (T_{ca}), and potato (T_{po}) versus the ohmic internal energy generation rate per volume ($\dot{Q}_e$, W/m^3). The initial temperature of the curry soup (T_{ic}) was raised from 17 °C to final target temperature of 100 °C (T_{fc}) within 180 s (A↔B). When the temperature of the curry soup reached up to 100 °C, the corresponding temperature of T_s, T_{ca}, and T_{po} was 70.8, 32.3, and 30.8 °C, respectively. The amount of dissipated heat is directly related to electric field strength and the electrical conductivity of the product or of the individual product fraction (Ohm's law) when solid-liquid mixtures are ohmically heated [11, 17, 19, 22]. As mentioned above, the electrical conductivity of curry soup was significantly higher than that of solid products (spam, carrot, potato); it showed the quickest heating. Ohmic internal energy generation rate per volume ($\dot{Q}_e$, W/m^3) continuously increased during the temperature come-up time of ohmic heating. $\dot{Q}_e$ was calculated with a combination of electrical conductivity (σ, S/m) and electric field (V/m) across the sample as shown in eq. (4). An increasing $\dot{Q}_e$ was responsible for increased electrical conductivity and subsequent heat dissipation increments according to temperature rise. Palaniappan and Sastry (1991) [42] reported that the electrical conductivities of tomato and orange juice increased linearly with temperature with reduced drag for the movement of ions.

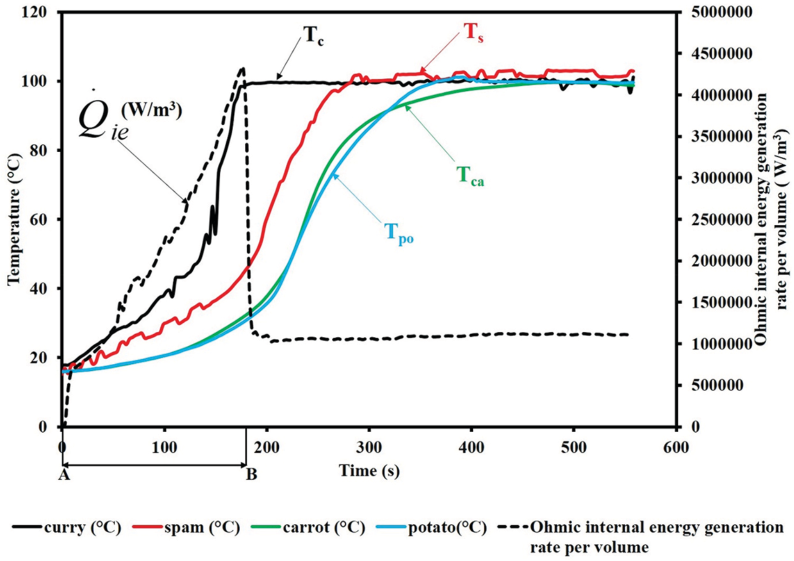


Figure 3: Temperature histories of curry soup, spam, carrot, and potato versus volumetric internal energy generation rate (W/m^3) at 12 V/cm and 5 min holding time.

Heat loss to the surrounding environment during the temperature come-up time was 18,711 ± 151, 11,161 ± 118, 8056 ± 115, and 5822 ± 122 J at 9, 12, 15, and 18 V/cm (Table 4), respectively. A lower electric field resulted in greater heat loss to the surrounding environment, whereas an elevated electric field minimized heat loss. The lowest electric field of 9 V/cm showed the longest temperature come-up time for soup, at 5.27 ± 0.63 min. A long temperature come-up time at a low electric field would result in a greater heat loss. Similar results had been found by Jo and Park (2019) [18], by studying ohmically cooked noodles that reported low electric field at 10 V/cm (13,937 ± 53 J) higher heat loss than electric field at 17.5 V/cm (4598 ± 20 J). Our results suggested that a rapid temperature come-up is desirable in order to minimize heat loss during ohmic heating. Heat loss could also be reduced by improving insulation, which would lower the overall heat transfer coefficient [34].

The total volumetric ohmic internal energy dose (E_{vd}, J) from the curry soup and ingredient (spam, carrot, and potato) samples was calculated by considering the ohmic internal energy generation rate ($\dot{Q}_e$, W·m^{-3}), sample volume (v, m^{-3}), and their integration versus time (s) as shown in eq. (5). The highest E_{vd} value was 76,950 ± 6483 J with an electric field of 9 V/cm. E_{vd} gradually decreased according to electric field increment; subsequently, the lowest E_{vd} of 71,410 ± 3700 J was found at an electric field of 18 V/cm. It is expected that a high electric field resulted in a rapid temperature come-up with enhanced heat dissipation; thus, it spent less electrical energy compared to those of low electric fields.

The *SPC* has been popularly used to estimate heating efficacy during ohmic heating [30, 39, 40]. *SPC* values range from 0.42 to 0.92 during ohmic heating [18, 30]. In our study, the *SPC* value was relatively low, ranging from 0.52 to 0.62. This may be explained by the fact that most of the electrical energy was utilized for cooking of the solid ingredients, i.e. the carrot and potato samples, and not only for heating the product. Notably, starch is a major component of potato (≈18 %), aside from moisture [43]. Once starch granules heat up, they lose their birefringence and crystallinity with gelatinization [44]. The electrical conductivity of starch-based foods decreases with gelatinization during ohmic heating and results in the conversion of electrical energy into heat [18, 45]. In the scope of present experiment, the most efficient *SPC* was found at 0.62 ± 0.03 when the highest electric field (18 V/cm) was applied to the curry mixture. *SPC* values of ohmic heating strongly depend on the voltage gradients applied [30, 40]. At high voltage gradients, the current passing through the sample is higher and might have increased the heat generation rate [46]. In the present study, a rapid temperature come-up during ohmic heating may enhance the efficacy of electrical energy conversion into a temperature increase and thus minimize heat loss. For ohmic cooking of a starch-based product, the appropriate adjustment of the electric field is required to ensure *SPC* efficacy.

3.3 Texture analysis

The tested texture parameters (hardness) of each ingredient are summarized in Figure 4. The hardness of spam ranged from 0.57 to 0.60 at different electric fields (9, 12, 15, and 18 V/cm); however, there was no significant difference among the tested electric fields ($P > 0.05$). Spam is a fully cooked shelf stable meat product which is sterilized in the can; as such, its texture might not be further modified during ohmic cooking.

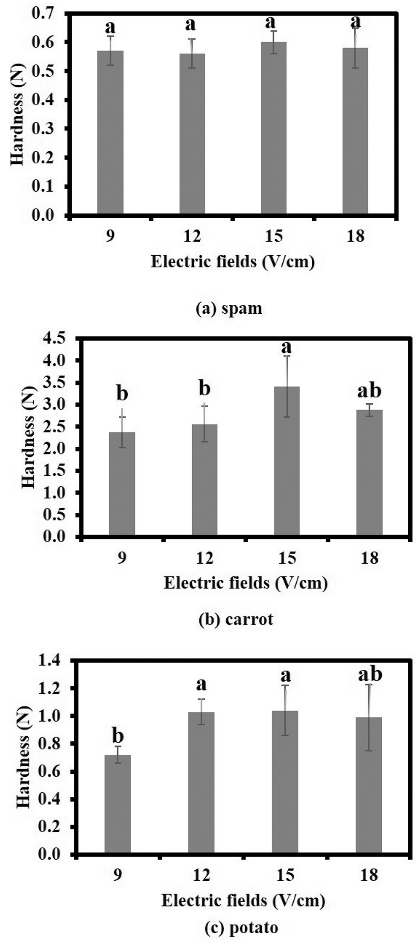


Figure 4: Hardness texture analyses of ohmically cooked spam, carrot, and potato in curry soup at different electric fields strengths (9, 12, 15, and 18 V/cm) at 5 min holding time. [a-b]Means (± standard deviation) with a different letter are significantly different at $P < 0.05$.

Raw carrot was calculated to have a hardness of 23.59 ± 1.06 N. Ohmic cooking at all the tested electric fields decreased the hardness of the carrot sample. The tissue structure of a carrot is divided into xylem (hard wall cells) and phloem (soft walled cells) [47]. Ohmic heating can cause dissolution of the cell wall components and protopectin, resulting in softening of the texture [47]. Cooking vegetables results in a softening of the texture due to a weakening of cell walls and a reduction in fracturability due to intercellular mucilage decomposition by thermal energy [29, 48, 49]. Farahnaky et al. [50]. reported the softening of various root vegetables after ohmic cooking. In the ohmic heating of vegetable products, electroporation is also an important consideration in terms of texture beyond thermal effects. Previous studies have reported that tissue damage in plant tissue occurs with electroporation during ohmic heating and is increased at low frequencies [51–55]. An electrical field of 9 V/cm resulted in the lowest hardness of the carrot sample at 2.37 ± 0.35 N, whereas an increased electric field at 15 V/cm resulted in a firmer texture with hardness of 3.41 ± 0.69 N. Excessive softening of vegetable tissue results in a rubbery texture which is undesirable. When vegetable products are exposed to excessive thermal treatment, they lose their cellular turgidity and become more deformable, producing a softer and rubbery texture [56, 57]. The total ohmic cooking time at 9 V/cm was 11.1 ± 0.1 min, whereas the application of 15 V/cm resulted in a cooking time of 8.4 ± 0.1 min. Excessive softening at 9 V/cm may be a result of a longer thermal treatment, which resulted in the loss of turgidity in carrot tissue. However, excessive high voltage gradient at ohmic heating induced more complete destruction of cellular structure and subsequent texture softening [50]. Vegetable tissues during heat treatment shows the pattern with a rapid rate of softening at the beginning, followed by slow rate of softening which starts at a cooking time of 10 min [50, 58, 59]. Overall, rapid cooking at the appropriate electric field is recommended to minimize the textural changes of vegetable tissue during ohmic heating.

The hardness values of the potato sample showed a very similar trend to carrot where they were influenced by the tested electric fields. The lowest hardness for the potato sample was 0.72 ± 0.06 N with an application of

9 V/cm, which increased to 1.04 ± 0.18 N at 15 V/cm. Potato exhibits a cellular structure that consists of smaller cells at the inner core and larger ones in the outer core; thus, the breakdown of the cell walls accelerates softening [47, 60]. After heat treatment of potato, calcium-pectic gel in the middle lamella and cell wall dissolves for potato texture softening [29, 61]. Dissolution of Overcooked potato absorbs excess water, leading to a sticky and soft texture [18, 62, 63]. Optimally cooked potato has a chewy and resilient bite without being sticky on the surface [64, 65]. The application of 15 V/cm for ohmic cooking resulted in a preferable hardness with a chewy and resilient bite. An application of 9 V/cm induced overcooking and long exposure to heat since temperature come-up is slow at low electric fields. Hardness of root vegetables decreases as a function of ohmic heating time [29, 61]. Although our study does not compare the textural qualities of ohmically heated vegetables to those of conventionally heated one, previous researchers reported that ohmic heating produced more comparable texture of the heated sample to original fresh sample when compared with the conventional heating method due to the heating process [66, 67]. Our study showed that the choice of electric field has a significant effect on the textural qualities of vegetables during ohmic cooking. Choosing the appropriate electric field is essential to retain the textural qualities of vegetables during ohmic heating.

4 Conclusions

Our study presented the potential of ohmic cooking for instant HMR curry soup and mixtures (spam carrot and potato). Electric field of 18 V/cm showed the best *SPC* in terms of energy efficacy, among the tested electric fields of 9, 12, 15 and 18 V/cm. Ohmic cooking enabled the rapid heating of curry soup to 100 °C within 1.67 min. Vegetable ingredients (carrot, potato) showed slower heating than soup since they have lower electrical conductivities. The preferable hardness for vegetable ingredients was found at an electrical field strength of 15 V/cm, which retained the appropriate chewiness and resilient bite of the vegetables. Potato showed the slowest heating since electrical energy was used to gelatinize the starch beyond temperature increase. When ohmic heating is used for starch based foods, gelatinization is one of important considerations for energy efficacy and quality attributes. Our study showed the significance of electric field adjustment for different food matrices, and its association with the composition and physicochemical characteristics of the foods. Further studies are required to test the efficacy of ohmic cooking for various HMR products.

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Nomenclature

A cross sectional area (m^2)

C_p specific heat (J/kg·K)

E total volumetric ohmic internal energy (E)

h convective heat transfer coefficients ($W \cdot m^{-2} \cdot K^{-1}$)

I current (A)

k cell constant (m^{-3})

L length (m) or electrode distance (m)

m mass (kg)

Q the amount of energy in the form of heat (J)

$\dot{Q}$ ohmic generation rate per volume ($W \cdot m^{-3}$)

SPC system performance coefficient

T temperature (°C)

TD thermal dose

TPA texture profile analysis

t time (s), time (min)

V voltage (V)

$|\nabla V|$ electric field (V/m or V/cm)

v volume (m^3)

σ electrical conductivity (S/m)

Subscript

av average

bw bottom wall

d dose

f final

fc final curry

fs final spam

fca final carrot

fp final potato

I initial

ie internal energy

ic initial curry

is initial spam

ica initial carrot

ip initial potato

loss loss to surroundings

sew side wall with electrode

sw side wall

taken heat taken

tw top wall

v volume

0, 1, 2, 3, …, n subinterval in trapezoidal numerical integration or parameters (intercept & slope) in the empirical model fitting

References

[1] Costa AI, Dekker M, Beumer RR, Rombouts FM, Jongen WM. A consumer-oriented classification system for home meal replacements. Food Qual Prefer. 2011;12:229–42.
[2] Singh AP, Wilson T, Luthria D, Freeman MR, Scott RM, Bilenker D, et al. LC-MS-MS characterisation of curry leaf flavonols and antioxidant activity. Food Chem. 2011;1:80–5.
[3] Fadavi A, Yousefi S, Darvishi H, Mirsaeedghazi H. Comparative study of ohmic vacuum, ohmic, and conventional-vacuum heating methods on the quality of tomato concentrate. Innov Food Sci Emerg Technol. 2018;47:225–30.
[4] Moreno J, Echeverria J, Silva A, Escudero A, Petzold G, Mella K, et al. Apple snack enriched with L-arginine using vacuum impregnation/ohmic heating technology. Food Sci Technol Int. 2017;23:448–56.
[5] Ramaswamy HS, Marcotte M, Sastry S, Abdelrahim K. Ohmic heating in food processing. Boca Raton, FL, USA: CRC Press, 2014.
[6] Torkian Boldaji M, Borghei AM, Beheshti B, Hosseini SE. The process of producing tomato paste by ohmic heating method. J Food Sci Technol. 2015;52:3598–606.
[7] 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. 2017;39:241–6.
[8] Jha SN, Narsaiah K, Basediya AL, Sharma R, Jaiswal P, Kumar R, et al. Measurement techniques and application of electrical properties for nondestructive quality evaluation of foods-a review. J Food Sci Technol. 2011;48:387–411.
[9] 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. 2013;19:115–23.

[10] Reznick D. Ohmic heating of fluid foods. Food Technol. 1996;50:250–1.
[11] Sastry SK, Salengke S. Ohmic heating of solid-liquid mixtures: A comparison of mathematical models under worst-case heating conditions. J Food Process Eng. 1998;21:441–58.
[12] Castro I, Teixeira JA, Salengke S, Sastry SK, Vicente AA. Ohmic heating of strawberry products: electrical conductivity measurements and ascorbic acid degradation kinetics. Innov Food Sci Emerg Technol. 2004;5:27–36.
[13] Allali H, Marchal L, Vorobiev E. Blanching of strawberries by ohmic heating: effects on the kinetics of mass transfer during osmotic dehydration. Food Bioprocess Technol. 2008;3:406–14.
[14] Chen C, Abdelrahim K, Beckerich I. Sensitivity analysis of continuous ohmic heating process for multiphase foods. J Food Eng. 2010;98:257–65.
[15] Darvishi H, Hosainpour A, Nargesi F. Ohmic heating behaviour and electrical conductivity of tomato Paste. J Nutr Food Sci. 2012;2:1–5.
[16] Icier F, Bozkurt H. Ohmic heating of liquid whole Egg: rheological behaviour and fluid dynamics. Food Bioprocess Tech. 2011;4:1253–63.
[17] Jaeger H, Roth A, Toepfl S, Holzhauser T, Engel KH, Knorr D, et al. Opinion on the use of ohmic heating for the treatment of foods. Trends Food Sci Technol. 2016;55:84–97.
[18] Jo YJ, Park SH. Evaluation of energy efficacy and texture of ohmically cooked noodles. J Food Eng. 2019;248:71–9.
[19] Varghese KS, Pandey MC, Radhakrishna K, Bawa AS. Technology, applications and modelling of ohmic heating: a review. J Food Sci Technol. 2012;51:2304–17.
[20] Salengke S, Sastry SK. Models for ohmic heating of solid-liquid mixtures under worst-case heating scenarios. J Food Process Eng. 2007;83:337–55.
[21] Sastry SK, Palaniappan S. Mathematical modeling and experimental studies on ohmic heating of liquid-particle mixtures in a static heater. J Food Process Eng. 1992;15:241–61.
[22] Zhu SM, Zareifard MR, Chen CR, Marcotte M, Grabowski S. Electrical conductivity of particle-fluid mixtures in ohmic heating: measurement and simulation. Food Res Int. 2010;43:1666–72.
[23] Knirsch MC, Dos Santos CA, de Oliveira Soares AA, Penna TC. Ohmic heating–a review. Trends Food Sci Technol. 2010;21:436–41.
[24] Morrissey MT, Almonacid S. Rethinking technology transfer. J Food Eng. 2005;67:135–45.
[25] Kanjanapongkul K. Rice cooking using ohmic heating: determination of electrical conductivity, water diffusion and cooking energy. J Food Eng. 2017;192:1–10.
[26] Wang R, Farid MM. Corrosion and health aspects in ohmic cooking of beef meat patties. J Food Eng. 2015;146:17–22.
[27] Lucier G, Lin BH Factors affecting carrot consumption in the United States USDA. Economic Research Service, 2007:1–21.
[28] Peng J, Tang J, Luan D, Liu F, Tang Z, Li F, et al. Microwave pasteurization of pre-packaged carrots. J Food Eng. 2017;202:56–64.
[29] Kamali E, Farahnaky A. Ohmic-assisted texture softening of cabbage, turnip, potato and radish in comparison with microwave and conventional heating. J Texture Stud. 2015;46:12–21.
[30] Icier F, Ilicali C. The effects of concentration on electrical conductivity of orange juice concentrates during ohmic heating. Eur Food Res Technol. 2005;220:406–14.
[31] Oliveira GS. Thermo-physical properties of cooked ham. Int J Food Prop. 2005;8:387–94.
[32] Srikiatden J, Roberts JS. Predicting moisture profiles in potato and carrot during convective hot air drying using isothermally measured effective diffusivity. J Food Eng. 2008;84:516–25.
[33] Geankoplis CJ. Transport processes and unit operations. NJ: PTR Prentice Hall, 1993:256.
[34] Marra F. Analysis of heat transfer during ohmic processing of a solid food. J Food Eng. 2009;91:56–63.
[35] Jun S, Sastry S. Modeling and optimization of ohmic heating of foods inside a flexible package. J Food Process Eng. 2005;28:417–36.
[36] Hosainpour A, Darvishi H, Nargesi F, Fadavi A. Ohmic pre-drying of tomato paste. Food Sci Technol Int. 2013;20:193–204.
[37] Li F, Zhang L. Ohmic heating in food processing. USA: Taylor and Francis, 2010:661.
[38] Park SH, Balasubramaniam VM, Sastry SK. Quality of shelf-stable low-acid vegetables processed using pressure-ohmic-thermal sterilization. LWT - Food Sci Technol. 2014;57:243–52.
[39] Darvishi H, Khostaghaza MH, Najafi G. Ohmic heating of pomegranate juice: electrical conductivity and pH change. J Saudi Soc Agric Sci. 2013;12:101–8.
[40] 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. 2017;17:117.
[41] Yoon SW, Lee CYJ, Kim KM, Lee CH. Leakage of cellular materials from Saccharomyces cerevisiae by ohmic heating. J Microbiol Biotechnol. 2002;12:183–8.
[42] Palaniappan S, Sastry SK. Electrical conductivity of selected juices: influences of temperature, solids content, applied voltage, and particle size. J Food Process Eng. 1991;14:247–60.
[43] Ngobese NZ, Workneh TS, Alimi BA, Tesfay S. Nutrient composition and starch characteristics of eight European potato cultivars cultivated in South Africa. J Food Compos Anal. 2017;55:1–11.
[44] Leach HW. Structure of starch granules. I. Swelling and solubility patterns of various starches. Cereal Chem. 1959;36:534–44.
[45] Li FD, Li LT, Li Z, Tatsumi E. Determination of starch gelatinization temperature by ohmic heating. J Food Eng. 2004;62:113–20.
[46] 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. 2016;2:691–700.
[47] Olivera DF, Salvadori VO, Marra F. Ohmic treatment of fresh foods: effect on textural properties. Int Food Res J. 2013;20:1617–21.
[48] Loh J, Breene WM. Between-species differences in fracturability loss: comparison of the thermal behavior of pectic and cell wall substances in potato and Chinese waterchesnut. J Texture Stud. 1982;13:381–96.
[49] Sterling C, Aldridge ML. Mealiness and sogginess in sweet potato. Food Chem. 1977;2:71–6.
[50] Farahnaky A, Azizi R, Gavahian M. Accelerated texture softening of some root vegetables by Ohmic heating. J Food Eng. 2012;113:275–80.
[51] de Vito F, Ferrari G, Lebovka NI, Shynkaryk NV, Vorobiev E. Pulse duration and efficiency of soft cellular tissue disintegration by pulsed electric fields. Food Bioprocess Technol. 2008;1:307–13.
[52] Kaur R, Gul K, Singh AK. Nutritional impact of ohmic heating on fruits and vegetables - A review. Cogent Food Agric. 2016;2:1–15.

[53] Kulshrestha SA, Sastry SK. Changes in permeability of moderate electric field (MEF) treated vegetable tissue over time. Innov Food Sci Emerg Technol. 2010;11:78–83.
[54] Lebovka N, Praporscic I. Does electroporation occur during the ohmic heating of food?. J Food Sci. 2005;70:308–11.
[55] Wang WC, Sastry SK. Effects of moderate electrothermal treatments on juice yield from cellular tissue. Innov Food Sci Emerg Technol. 2002;3:371–7.
[56] Loredo AB, Guerrero SN, Alzamora SM. Relationships Between Texture and Rheological Properties in Blanched Apple Slices (var. Granny Smith) Studied by Partial Least Squares Regression. Food Bioprocess Technol. 2014;7:2840–54.
[57] Xu C, Yu C, Li Y. Effect of blanching pretreatment on carrot texture attribute, rheological behavior, and cell structure during cooking process. LWT - Food Sci Technol. 2015;62:48–54.
[58] Huang YT, Bourne MC. Kinetics of thermal softening of vegetables. J Texture Stud. 1983;14:1–9.
[59] Bourne MC. Applications of chemical kinetic theory to the rate of thermal softening of vegetable tissue. In: Jen JJ, editor. Quality factors of fruits and vegetables. Chemistry and Technology. American Chemical Society Symposium Series No. 405. Washington DC, USA, 1989.
[60] Konstankiewicz K, Czachor H, Gancarz M, Król A, Pawlak K, Zdunek A. Cell structural parameters of potato tuber tissue. Int Agrophysics. 2002;16:119–28.
[61] Jarvis MC, Mackenzie E, Duncan HJ. The textural analysis of cooked potatoes. 2. Swelling pressure of starch during gelatinization. Potato Res. 1992;35:93–102.
[62] Ye X, Sui Z. Physicochemical properties and starch digestibility of Chinese noodles in relation to optimal cooking time. Int J Biol Macromol. 2016;84:428–33.
[63] Jin M, Wu J, Wu X A study on properties of starches used for starch noodle making. In Proceedings 1994 international symposium and exhibition on new approaches in the production of food stuffs and intermediate products from cereal grains and oil seeds, 1994:488–96.
[64] Miskelly DM, Moss HJ. Flour quality requirements for chinese noodle manufacture. J Cereal Sci. 1985;3:379–87.
[65] Sui Z, Lucas PW, Corke H. Optimal cooking time of noodles related to their notch sensitivity. J Texture Stud. 2006;37:428–41.
[66] Eliot SC, Goullieux A, Pain J. Processing of cauliflower by ohmic heating: influence of precooking on firmness. J Sci Food Agric. 1999;79:1406–12.
[67] Tumpanuvatr T, Jittanit W, Kaewchutong S, Jan-Ob O, Pham H, Sajjaanantakul T. Comparison between ohmic and conventional heating of pineapple longan in sucrose solution. Kasetsart J Nat Sci. 2015;49:615–25.