LWT - Food Science and Technology 160 (2022) 113271

Contents lists available at ScienceDirect

LWT

journal homepage: www.elsevier.com/locate/lwt

Application of ohmic cooking to produce a soy protein-based meat analogue

Ah Hyun Jung [a], Jeong Hyeon Hwang [a], Soojin Jun [b], Sung Hee Park [a,*]

[a] Department of Food Science and Technology, Seoul National University of Science and Technology, Seoul, 01811, South Korea
[b] Department of Human Nutrition, Food, and Animal Sciences, University of Hawaii at Manoa, Honolulu, HI, 96822, USA

ARTICLE INFO

Keywords:
Ohmic cooking
Meat analogue
Soy protein
Texture
Energy

ABSTRACT

The potential of ohmic cooking for the production of a soy protein-based meat analogue was investigated. The ohmic cooking system subjected the meat analogue to a 30 V/cm electric field, enabling rapid heating within 0.66–0.87 min, depending on the cooking temperature. The sample was ohmically cooked using different combinations of temperature (70, 80, 90, and 100 °C) and holding time (1, 3, 5, and 7 min). A cooking temperature of 100 °C yielded the highest system performance coefficient (*SPC*) of 0.75. The electrical energy consumption was analyzed in terms of total energy consumption and holding energy consumption, which was minimal compared to the former. Hardness and gumminess increased as a function of cooking temperature and holding time. Cooking at 100 °C for 3 min yielded the appropriate meat analogue textural quality (hardness = 104 N), similar to that of commercial chicken nuggets and restructured beef steaks. The pH of ohmically cooked meat analogue ranged from 7.27 to 7.53, but was not influenced by cooking temperature and holding time. Increased cooking temperatures and longer holding times resulted in enhanced yellowness of the internal color. This study showed the potential of ohmic cooking to rapidly produce meat analogues with good quality attributes.

1. Introduction

The consumption of meat analogues has recently been increasing owing to several factors, such as its health advantages and its reduced environmental burden as well as the animal welfare issues surrounding meat consumption (Dekkers, Boom, & van der Goot, 2018). Meat analogues can be classified into two major types, namely plant-based meat analogues and cultured meat. Plant-based meat products are mainly composed of proteins of plant origin that have similar nutritional and sensorial properties to animal meat (Sun, Ge, He, Gan, & Fang, 2021). The most widely used ingredient in plant-based meat analogues is soy protein, which is rich in nutrients and possesses excellent gelling properties (Banerjee & Bhattacharya, 2012; Day & Swanson, 2013). Various processing techniques have been studied to reproduce the fibrous structure of meat, such as extrusion, freeze structuring, electrospinning, and shear cell technology (Yuliarti, Kiat Kovis, & Yi, 2021).

Consumer demand for plant-based meat analogues as a replacement for animal meat is increasing because it represents a sustainable protein source and avoids the ethical issues of slaughtering livestock animals (Kyriakopoulou, Dekkers, & van der Goot, 2019; Zhou, Hu, Tan, Zhang, & McClements, 2021). Therefore, inexpensive and less energy-intensive processing techniques are required to satisfy the growing market size (Mattice & Marangoni, 2020). Ohmic heating is a potential technique for producing meat analogues. It enables a rapid and uniform increase in the temperature of food through internal heat energy generation via alternating current (AC) (Varghese, Pandey, Radhakrishna, & Bawa, 2014; Vicente, de Castro, Teixeira, & Pereira, 2016), resulting in highly efficient direct conversion of electric energy into heat (Ghnimic, Flach-Malaspina, Dresch, Delaplace, & Maingonnat, 2008; Jan, Khan, Bashir, & Jan 2021). This technique is widely used in food processing, such as in sterilization, pasteurization, thawing, and cooking processes (Gally et al., 2017; Pereira, Martins, & Vicente, 2008). When ohmic heating is applied to the cooking of food, its textural, nutritional, and organoleptic qualities can change depending on the cooking temperature and holding time (Jo & Park, 2019; Soisungwan, Khampakool, You, & Park, 2020; Soisungwan, Khampakool, You, Park, & Park, 2019). To

Abbreviations: σ, electrical conductivity; E_{vd}, total volumetric ohmic internal energy; HEC, holding energy consumption; k, cell constant; $\dot{Q}_{ie}$, ohmic internal energy generation rate per volume; Q_{loss}, heat energy loss; Q_{taken}, heat energy uptake; *SPC*, system performance coefficient; TEC, total energy consumption.

* Corresponding author.
E-mail address: sunghpark@seoultech.ac.kr (S.H. Park).

https://doi.org/10.1016/j.lwt.2022.113271
Received 10 August 2021; Received in revised form 10 January 2022; Accepted 17 February 2022
Available online 25 February 2022

the best of our knowledge, ohmic heating techniques have not been studied for the production of meat analogues. The potential of ohmic cooking to produce a soy protein-based meat analogue was evaluated. The aim of this study was to investigate the effect of ohmic cooking temperature and holding time on the energy efficiency, textural qualities, and physicochemical properties of soy-based ohmically cooked meat analogue (OCMA).

2. Materials and methods

2.1. Raw ingredients

Meat analogue dough (100 g) contained soy protein isolate (25.9%), wheat gluten (13.0%), corn starch (1.9%), methyl cellulose (0.9%), red beet powder (1.3%), soybean oil (0.9%), salt (0.5%), and distilled water (55.6%). An optimal moisture content of 55.6% for reasonable textural quality was determined through preliminary experiments. The evenly blended dry ingredients (soy protein isolate, wheat gluten, corn starch, and red beet) were mixed with the soybean oil and distilled water that contained the dissolved salt. After thorough mixing, the samples were stored at 4 °C until further processing.

2.2. Ohmic cooking system

A schematic diagram of the ohmic cooking system used in this study is shown in Fig. 1. A customized Teflon plate (20 mm thickness) ohmic container (111 mm × 88 mm × 60 mm) was used as a mold to form a rectangular shape of meat analogue dough during ohmic cooking. Square-type titanium electrodes, positioned at both ends of the ohmic container, were maintained at a distance of 2.5 cm. Titanium electrodes minimize electrochemical reactions during the ohmic heating of food (Jo & Park, 2019; Samaranayake & Sastry, 2005). A teflon cast (110 mm × 20 mm × 95 mm) was designed to pressurize the meat analogue inside the ohmic container. Thus, the cooked meat analogues will have an appropriate structural form and texture. A variable transformer provided AC voltage of 60 Hz across the sample. A K-type thermocouple was used to monitor the temperature increase and holding during ohmic cooking. Temperature, voltage, and current data were monitored and

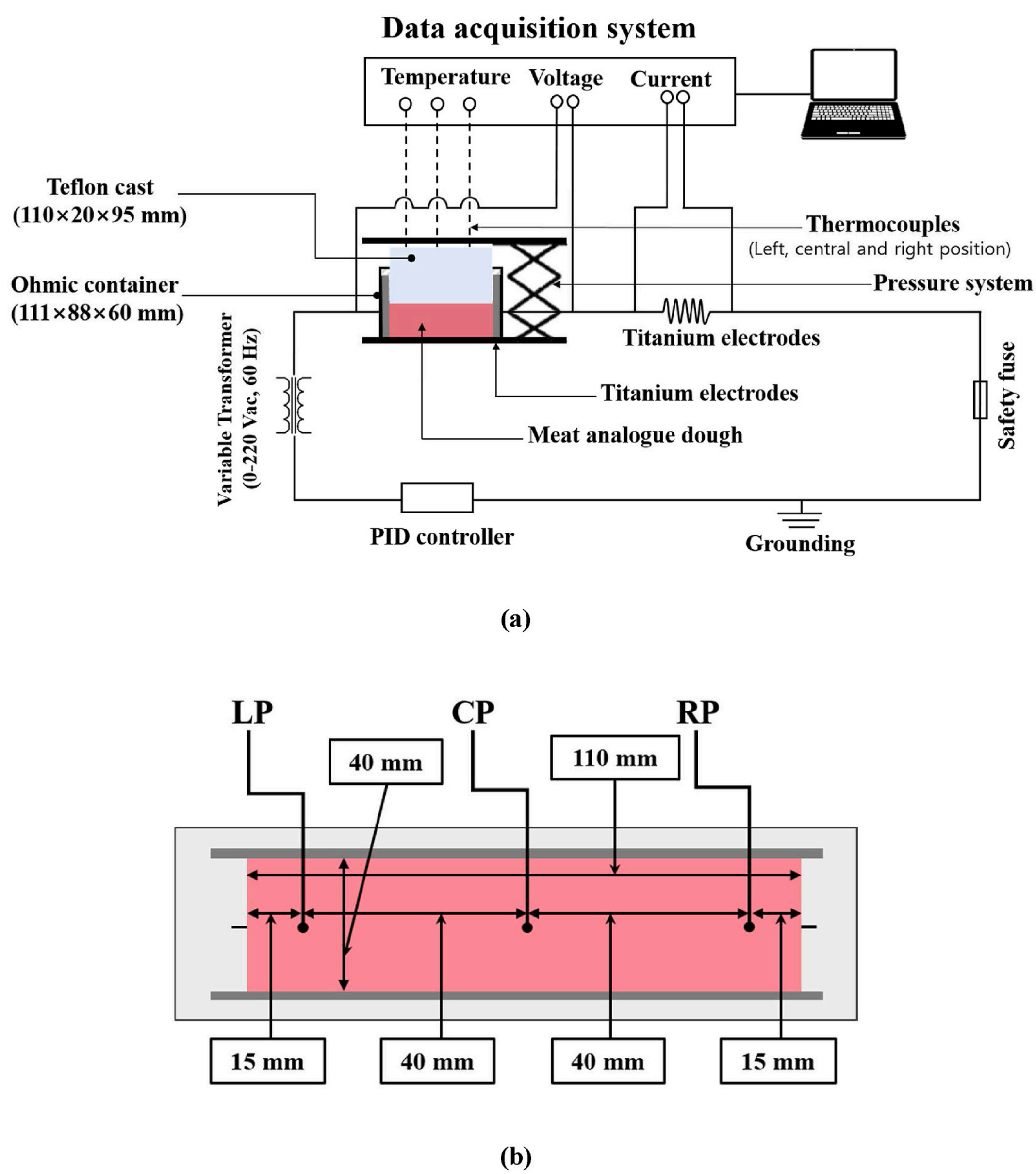

Fig. 1. (a) Schematic diagram of customized ohmic cooking system (b) installation of thermocouple into different geometry of meat analogue (LP: left position, CP: central position, RP: right position).

recorded using a 34970A Data Acquisition system (Keysight, Santa Rosa, CA, USA). These data were used to determine the process uniformity and the system performance coefficient (*SPC*) of the ohmic cooking system.

2.3. Ohmic cooking treatment

The prepared meat analogue dough (100 g) was transferred to the customized ohmic container. The temperature of the meat analogue during ohmic cooking was measured by three K-type thermocouples at the left (LP), central (CP), and right (RP) positions, as described in Fig. 1. An electric field of 30 V/cm at 60 Hz was supplied via a variable AC power supply (SV-5022; Daekwang Tech, Seoul, Korea) during the temperature come-up time, that is, the time to reach the specified target temperature. After reaching the target temperature, the electric field was lowered to 15 V/cm to prevent excessive heating during the temperature holding time. The target temperatures (70, 80, 90, and 100 °C) were controlled by a proportional-integral-derivative (PID) controller (ITC-100; Inkbird, Shenzhen, China) with an on/off function; holding times were maintained for 1, 3, 5, and 7 min. The 34970A Data Acquisition system (Keysight, Santa Clara, CA, USA) was used to monitor the temperature, voltage, and current of the meat analogue sample during ohmic heating. The OCMA was sealed using a vacuum packaging machine (FM5460-071; Simtech, Seoul, Korea) and cured at 4 °C for 24 h before analysis.

2.4. Energy efficiency analysis of SPC

The energy efficiency of ohmic cooking was analyzed in terms of the *SPC*. In studies of ohmic heating and cooking, *SPC* analysis has been widely used to estimate the internal energy generation dose and its conversion to heat (Darvishi, Khostaghaza, & Najafi, 2013; Icier & Bozkurt, 2011; Jo & Park, 2019; Park, Ha, & Kang, 2017; Soisungwan et al., 2019, 2020). In the calculation of *SPC*, the conversion ratio of total volumetric ohmic internal energy (E_{vd}, J) generation to temperature increases as the target temperature is approached (Jo & Park, 2019; Soisungwan et al., 2019, 2020) as described in the following steps.

Electric field ($|\nabla V|$, V/m) application resulted in an ohmic internal energy generation rate per volume ($\dot{Q}_{ie}$, W/m^3), taking into account the squared electric field and electrical conductivity (σ, S/m) changes of the sample, as shown in Eq. (1).

$$\dot{Q}_{ie} = \sigma \cdot |\nabla V|^2 \tag{1}$$

Electrical conductivity (σ, S/m) is the ability of a sample to conduct the electric current. It has a significant influence on ohmic heating, in that higher electrical conductivity of foods is associated with more rapid heating (Park, Balasubramaniam, & Sastry, 2014). The electrical conductivity of food was calculated using the cell constant (k, m^{-1}), applied voltage (V), and electric current (A) (Park, Balasubramaniam, Sastry, & Lee, 2013; Rieger, 1994) as shown in Eq. (2).

$$\sigma = k \cdot \frac{I}{V} \tag{2}$$

The ohmic internal energy generation rate per volume ($\dot{Q}_{ie}$, W/m^3) can be calculated via combination of Eqs. (1) and (2).

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

The total amount of volumetric internal energy generation (E_{vd}, J) is calculated through the integration of ohmic cooking time (s) versus ohmic internal energy generation rate per volume ($\dot{Q}_{ie}$, W/m^3).

$$\begin{aligned} E_{vd} &= \int_{t_i}^{t_f} \dot{Q}_{ie} dt \\ &= \int_{t_i}^{t_f} k \cdot \frac{I}{V} \cdot |\nabla V|^2 dt \\ &= \frac{k}{2} \cdot \left[\begin{array}{l} \left(\frac{I_0}{V_0} \cdot |\nabla V_0|^2 + \frac{I_1}{V_1} \cdot |\nabla V_1|^2 \right) \Delta t_{0\sim1} + \left(\frac{I_1}{V_1} \cdot |\nabla V_1|^2 + \frac{I_2}{V_2} \cdot |\nabla V_2|^2 \right) \cdot \Delta t_{1\sim2} \\ + \left(\frac{I_2}{V_2} \cdot |\nabla V_2|^2 + \frac{I_3}{V_3} \cdot |\nabla V_3|^2 \right) \cdot \Delta t_{2\sim3} \cdots + \left(\frac{I_{n-1}}{V_{n-1}} \cdot |\nabla V_{n-1}|^2 + \frac{I_n}{V_n} \cdot |\nabla V_n|^2 \right) \cdot \Delta t_{n-1\sim n} \end{array} \right] v \end{aligned} \tag{4}$$

Numerical integration for E_{vd} (J) was conducted using the trapezoidal rule coding function of MATLAB (Version 7.9.0.529; Mathworks Inc., Natick, MA, USA) software as suggested in our previous studies (Jo & Park, 2019; Park et al., 2017; Soisungwan et al., 2019, 2020).

The energy uptake in the form of heat (Q_{taken}) was calculated, taking into account the temperature increase, mass (m), and specific heat of the sample, as suggested by previous researchers (Icier & Ilicali, 2005; Jo & Park, 2019; Park et al., 2017; Soisungwan et al., 2019, 2020).

$$Q_{taken} = m \cdot C_p \cdot (T_i - T_f) \tag{5}$$

The energy efficiency of *SPC* was estimated via Q_{taken}, E_{vd}, and Q_{taken}, as shown in Eq. (6).

$$SPC = \frac{Q_{taken}}{E_{vd} + Q_{loss}} \tag{6}$$

Q_{loss} represents the heat loss from each wall of the ohmic container. It was calculated using Newton's cooling law through the installation of a K-type thermocouple on each wall.

2.5. Energy consumption analysis

The energy consumption of ohmic cooking, taking into account the applied voltage (V) and current (I), was calculated using Ohm's law as shown in Eq. (7).

$$P = I \times V \tag{7}$$

where P is the electrical power usage, I is the current passage through the sample, and V is the applied voltage.

In this study, the energy consumption was quite low during the temperature holding time compared with the total cooking time. Therefore, energy consumption was separately calculated during the temperature holding time and expressed as the holding energy consumption (HEC), whereas the total energy consumption (TEC) represents the energy consumption calculated for the total ohmic cooking time. The ratio between HEC and TEC was calculated by dividing HEC by TEC and expressed as a percentage value.

2.6. Texture profile analysis (TPA)

TPA of the OCMA was conducted using a two-bite test with a 16-TA-XT2i texture analyzer (Stable Micro Systems, Surrey, UK) fitted with a cylindrical probe (P/36, 36 mm diameter), as described by Chiang et al. (2021). The OCMA was stored overnight at 4 °C to stabilize its structure, and thawed at room temperature before TPA to ensure a uniform temperature. Rectangular-shaped samples (15 mm × 15 mm × 10 mm) were prepared and placed under the probe. The sample was twice compressed to 40% of the original height at a constant speed (pre-test: 1.0 mm/s; test: 1.0 mm/s; post-test: 1.0 mm/s) and pressure. The TPA parameters are classified into primary parameters (hardness, springiness, adhesiveness, and cohesiveness) and secondary parameters (gumminess, chewiness, and resilience) (Novakovi & Tomăsevi, 2017). Analysis and interpretation of all the TPA parameters are practically difficult; hence, representative primary (hardness) and secondary (gumminess and chewiness) parameters were selected based on previous studies on plant-based meat analogues (Chiang et al., 2021; Yuliarti, Kiat Kovis, & Yi, 2021). TPA measurements included hardness (N), gumminess (N), and chewiness (N), as previously described (Jo & Park, 2019; Klinmalai, Hagiwara, Sakiyama, & Ratanasumawong, 2017).

2.7. pH measurement

The pH of OCMA was measured using a glass electrode pH meter (Orion Star A211; Thermo Fisher Scientific, Chelmsford, MA, USA). It was calibrated using buffer solutions (pH 4, pH 7, and pH 10) before analysis. The OCMA sample (5 g) was homogenized in 20 mL of distilled water (1:4 dilution) using a homogenizer (SR-30; Misung Scientific Co. Ltd, Seoul, Korea). The pH values were recorded once stable readings were established.

2.8. Color measurement

The color of OCMA was determined using a calibrated colorimeter (CR-10; Konica Minolta Sensing Inc., Sakai, Osaka, Japan). The color coordinates L^*, a^*, and b^* refer to brightness, redness, and yellowness, respectively. Three random internal and external locations of each sample were selected for the color measurement. The total color difference (ΔE) was calculated to describe the changes in color of the meat analogue dough and of the OCMA at different time and temperature (Wang, Zhang, & Adhikari, 2015) using equation (8).

$$\Delta E = \sqrt{(L^* - L^*_0)^2 + (a^* - a^*_0)^2 + (b^* - b^*_0)^2} \quad (8)$$

2.9. Statistical analysis

Statistical analysis was conducted using SAS software (version 9.1.3; SAS Institute, Cary, NC, USA). Data were subjected to analysis of variance, including Fisher's least significant difference testing for multiple comparisons at a 95% confidence interval. Statistical significance was set at $p < 0.05$. All the experiments were conducted in three replicates.

3. Results and discussion

3.1. Temperature profiles and electric field-internal energy generation

Fig. 2 shows the representative temperature evolution and temperature-electric field profiles of the meat analogue during ohmic cooking with a 3 min holding time. The meat analogue dough was ohmically cooked at four different target temperatures (70, 80, 90, and 100 °C). Temperature come-up times for 70, 80, 90 and 100 °C were 0.66 ± 0.03 min, 0.73 ± 0.03 min, 0.83 ± 0.03 min, and 0.87 ± 0.03 min, respectively (Table 1). Although the temperature come-up time was not compared to conventional cooking in this study, the results show that ohmic cooking resulted in rapid temperature increases. Ohmic heating achieves this via the direct application of AC to food, thereby generating internal energy (Ding, Liu, Xiong, Wang, & Li, 2021; Hradecky, Kludska, Belkova, Wagner, & Hajslova, 2017; Wattanayon, Udompijitkul, & Kamonpatana, 2021). Fig. 2b presents the

Table 1
System performance coefficient (SPC) at different cooking temperatures.

Temperature (°C)	Temperature come-up time (min)	Heat quantity (Q_{taken}, J)	Heat loss (Q_{loss}, J)	Total volumetric internal energy generation (E_{vd}, J)	*SPC*
70	0.66 ± 0.03[d]	15,350	4429 ± 138[d]	17,521 ± 533[d]	0.70 ± 0.02[b]
80	0.73 ± 0.03[c]	18,420	4711 ± 190[c]	21,113 ± 1,090[c]	0.71 ± 0.03[ab]
90	0.83 ± 0.03[b]	21,490	4954 ± 241[b]	24,172 ± 2,212[b]	0.74 ± 0.06[ab]
100	0.87 ± 0.03[a]	24,560	5163 ± 236[a]	27,409 ± 478[a]	0.75 ± 0.02[a]

[a-d]Means(±Standard deviation) with a different letter in the same column are significantly different at $P < 0.05$.
SPC: System performance coefficient.

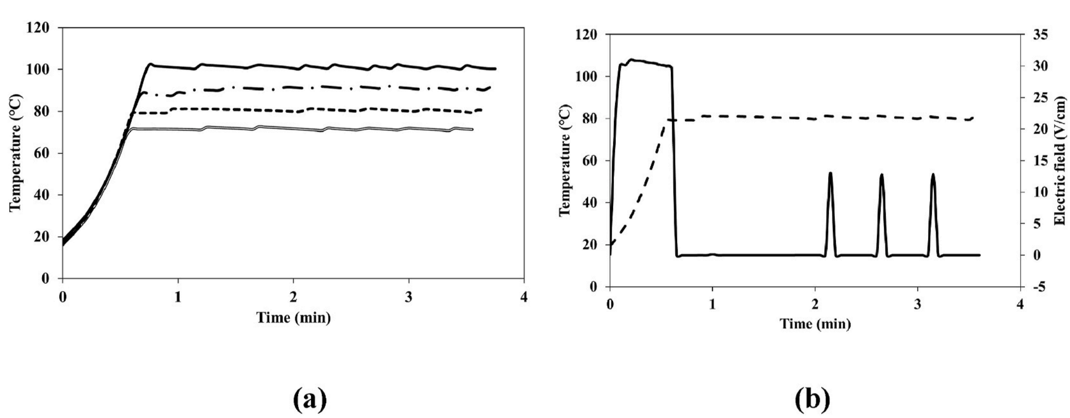

Fig. 2. (a) Temperature evolutions (═══: 70 °C, ▬▬▬: 80 °C, ▬ • •: 90 °C, ▬▬▬: 100 °C) and (b) temperature-electric field profiles during ohmic cooking of 3 min holding time (▬▬▬: Temperature, ▬▬▬: Electric field).

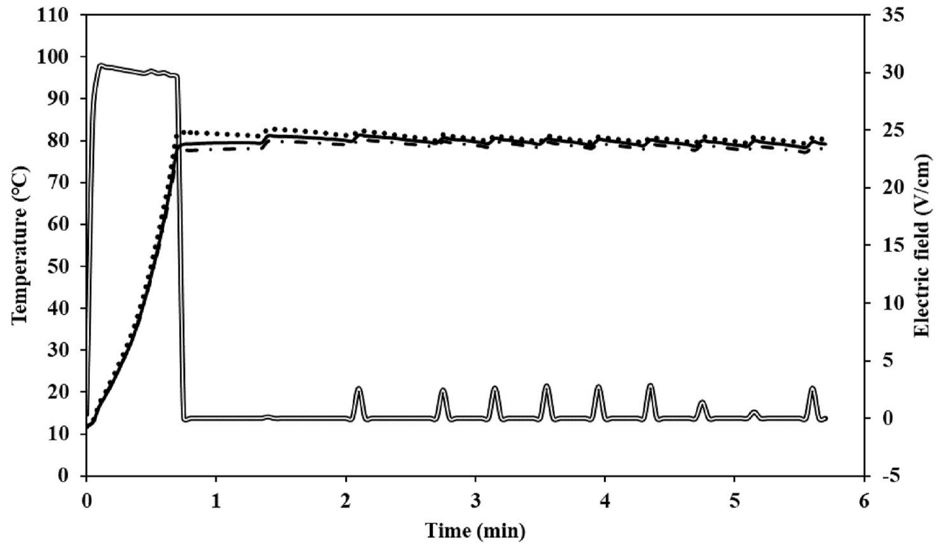

Fig. 3. Temperature distribution of different geometry (left, middle, right) at 80 °C and 5 min holding time (——: left position (LP), ········: central position (CP), ‒ · ‒: right position (RP), ═══: Electric field).

temperature-electric field profiles during ohmic cooking with a 3 min holding time at 80 °C. The meat analogue was subjected to an electric field of 30 V/cm until 80 °C was reached, after which the PID controller regulated the electric field via its automated on/off function. The electric field was intermittently applied to the samples during the holding time, which required less electric field application as compared with the temperature come-up time. This implies that energy consumption would be lower during the temperature holding time as compared with the temperature come-up time. This aspect will be discussed in section 3.2 on electrical power consumption.

Fig. 3 shows the representative temperature distribution in different geometries of meat analogue samples during ohmic cooking at 80 °C with 5 min of holding time. A thermocouple was installed at the left, central, and right positions of the meat analogue (Fig. 1b). There was no difference in temperature evolution between the left, central, and right positions of the meat analogue sample under the different ohmic cooking conditions. Thus, temperature uniformity of ohmic cooking was observed in the production of the OCMA. Ohmic heating has the advantage of enabling uniform temperature increases through internal heat generation (Ángel-Rendón, Filomena-Ambrosio, Cordon-Díaz, Benítez-Sastoque, & Sotelo-Díaz, 2019; Cappato et al., 2017; Engchuan, Jittanit, & Garnjanagoonchorn, 2014).

3.2. SPC and electrical power consumption

Table 1 presents the *SPCs* of different cooking temperature used in ohmic cooking treatment of the meat analogue. The energy uptake was increased at higher cooking temperatures. For example, Q_{taken} at 70 °C was 15,350 J, which increased to 24,560 J when the ohmic cooking temperature was raised to 100 °C. Higher cooking temperatures were associated with greater energy loss in the form of heat. Q_{loss} at an ohmic cooking temperature of 70 °C was 4429 ± 138 J, which increased to 5163 ± 236 J at 100 °C. A higher target temperature required a longer temperature come-up time, which resulted in higher Q_{loss}. The efficiency of ohmic heating is significantly enhanced by minimizing heat loss; thus, the ohmic cell should be equipped with appropriate thermal insulation (Zell, Lyng, Morgan, & Cronin, 2011). In this study, an ohmic cell was made of a teflon plate with a thickness of 20 mm and thermal conductivity of 0.24 W/mK (Tomo et al., 2021), which is relatively low, and similar to that of popularly used thermal insulators, such as coir and mineral wool (Guna et al., 2021; Zell et al., 2011).

The *SPC* values ranged between 0.70 ± 0.02 and 0.75 ± 0.02 (Table 1), which is higher than previously reported values, which ranged from 0.46 to 0.65 (Jo & Park, 2019; Soisungwan et al., 2019, 2020). During ohmic heating of starch-based foods, some of the internal energy is utilized for starch gelatinization rather than an increase in temperature (Jo & Park, 2019; Soisungwan et al., 2020). Therefore, in the present study, it is postulated that a proportion of the internally generated energy was used for denaturation of the soy protein.

Previous studies investigated the *SPC* of ohmic cooking of solid-liquid mixtures, such as noodles, rice cakes, and curry. Solid-liquid mixtures have different electrical conductivity attributes than solid foods, soup, and sauces; discrepancies in the heating rates of the various ingredients lower the *SPC* values. In contrast, the present meat analogue is a solid product with a uniform composition; thus, it would result in a higher *SPC*. The highest ohmic cooking temperature of 100 °C resulted in the maximum *SPC* of 0.75 ± 0.02, which indicates that 75% of the electrical energy was converted to heat. *SPC* values are dependent on the electric field strength, heat loss, heating rate, and sample composition (Darvishi et al., 2013; Icier & Ilicali, 2005). Internal energy generation is proportional to the squared electric field strength and electrical conductivity (Sarang, Sastry, & Knipe, 2008). In our study, the electrical conductivity of the sample increased with increasing cooking temperature; σ values of ≈1.15, 1.20, 1.30, and 2.0 S/m were measured at 70, 80, 90, and 100 °C, respectively. Therefore, internal energy generation occurs efficiently at higher ohmic cooking temperatures, which results in a higher *SPC*.

Table 2 presents the energy consumption of the sample during ohmic cooking at different temperatures and holding times. TEC represents the total energy consumption during the temperature come-up time and the holding time, whereas HEC considers only energy consumption during the holding time. TEC was more affected by the cooking temperature than by the holding time. For example, when comparing the group with a 5 min holding time, it was observed that the TEC was 19,726 ± 1355 J, 23,378 ± 1252 J, 26,264 ± 1754 J, and 30,548 ± 942 J at cooking temperature of 70, 80, 90, and 100 °C, respectively. The magnitude of the difference ranged between 2886 and 4284 J when the cooking temperature was increased by 10 °C. However, the contributing effect of the holding time resulted in holding time-dependent increases in TEC. For example, TEC of the 80 °C cooked samples amounted to 20,257 ± 1378 J, 21,326 ± 1089 J, 23,378 ± 1252 J, and 24,576 ± 1183 J at holding times of 1, 3, 5, and 7 min, respectively. The magnitude of the difference ranged between 1069 and 2052 J when the holding time was increased by 2 min. Once the sample reached the target temperature, the

Table 2
Energy consumption of meat analogue ohmic cooking.

Cooking temperature (°C)	Holding time (min)	TEC (J)	HEC (J)	HEC/TEC (%)
70	1	16,998 ± 1,345[i]	2 ± 3[e]	0.01 ± 0.02[e]
	3	17,833 ± 649[hi]	313 ± 118[de]	1.74 ± 0.61[de]
	5	19,726 ± 1,355[gh]	511 ± 293[de]	2.53 ± 1.30[cde]
	7	19,319 ± 667[gh]	772 ± 728[cd]	3.92 ± 3.58[bcd]
80	1	20,257 ± 1,378[g]	5 ± 3[e]	0.02 ± 0.02[e]
	3	21,326 ± 1,089[fg]	213 ± 12[de]	1.00 ± 0.08[e]
	5	23,378 ± 1,252[ef]	526 ± 244[de]	2.23 ± 0.95[cde]
	7	24,576 ± 1,183[de]	1172 ± 937[bc]	4.67 ± 3.51[bc]
90	1	25,274 ± 2,658[de]	4 ± 5[e]	0.01 ± 0.02[e]
	3	24,484 ± 2,344[de]	312 ± 175[de]	1.25 ± 0.63[e]
	5	26,264 ± 1,754[cd]	463 ± 40[de]	1.76 ± 0.04[de]
	7	25,907 ± 363[cd]	1578 ± 610[ab]	6.10 ± 2.35[ab]
100	1	28,996 ± 1,542[ab]	48 ± 82[e]	0.18 ± 0.30[e]
	3	27,899 ± 536[bc]	491 ± 94[de]	1.76 ± 0.32[de]
	5	30,548 ± 942[a]	706 ± 96[cd]	2.31 ± 0.27[cde]
	7	29,186 ± 1,411[ab]	2190 ± 341[a]	7.49 ± 0.94[a]

[a-i]Means(±Standard deviation) with a different letter in the same column are significantly different at $P < 0.05$.
TEC: Total energy consumption.
HEC: Holding energy consumption.
HEC/TEC: Percentage of HEC versus TEC.

Table 3
Texture profile analysis (TPA) of ohmically cooked meat analogue.

Ohmic cooking temperature (°C)	Holding time (min)	Texture properties		
		Hardness (N)	Gumminess (N)	Chewiness (N)
70	1	44 ± 1.0[j]	37 ± 1.1[j]	36 ± 1.6[hi]
	3	45 ± 1.5[j]	39 ± 1.9[j]	38 ± 2.4[hi]
	5	54 ± 2.3[h]	45 ± 0.8[i]	43 ± 1.9[g]
	7	52 ± 1.1[hi]	44 ± 1.1[i]	43 ± 1.4[g]
80	1	51 ± 0.7[i]	44 ± 1.4[i]	43 ± 2.1[g]
	3	53 ± 1.5[hi]	46 ± 1.8[i]	45 ± 2.1[g]
	5	58 ± 1.3[g]	51 ± 2.1[h]	50 ± 1.3[f]
	7	66 ± 1.3[f]	57 ± 0.7[g]	57 ± 0.7[e]
90	1	69 ± 0.5[f]	61 ± 1.2[f]	60 ± 0.8[de]
	3	72 ± 0.5[e]	64 ± 2.6[ef]	63 ± 1.8[d]
	5	73 ± 1.3[e]	64 ± 1.1[e]	64 ± 1.2[d]
	7	84 ± 1.5[d]	73 ± 3.7[d]	72 ± 4.3[c]
100	1	91 ± 0.7[c]	80 ± 2.4[c]	80 ± 2.5[b]
	3	104 ± 1.1[b]	92 ± 1.6[ab]	92 ± 1.7[a]
	5	104 ± 1.6[b]	89 ± 1.3[b]	89 ± 1.4[b]
	7	107 ± 2.3[a]	93 ± 2.0[a]	92 ± 3.4[a]

[a-j]Means(±Standard deviation) with a different letter in the same column are significantly different at $P < 0.05$.

PID controller intermittently provided an electric field whenever the sample temperature fell below the target temperature (Fig. 2b). Therefore, HEC was significantly lower than TEC. HEC/TEC represents the ratio of HEC to TEC, expressed as a percentage value, which ranged between 0.01 ± 0.02% and 7.49 ± 0.94%, suggesting that minimal energy is required to maintain the target ohmic cooking temperature after temperature come-up.

3.3. Texture attributes of OCMA

Higher ohmic cooking temperatures and longer holding times were associated with increased hardness of the OCMA (Table 3). Texture parameters of meat analogues are highly correlated with moisture content (Bakhsh, Lee, Lee, Hwang, & Joo, 2021). Although moisture contents were not measured in this study, it appeared that higher cooking temperatures resulted in more moisture loss, subsequently contributing to increased hardness. A cooking temperature-holding time combination of 70 °C and 1 min resulted in hardness of 44 ± 1.0 N, which increased to 52 ± 1.1 N at 7 min of holding time. The optimal hardness of the OCMA was determined by comparison with commercial chicken nuggets, as previously suggested in a study that used a commercial chicken nugget with hardness of 118 N as a reference standard for the hardness of plant-based meat analogues (Yuliarti, KiatKovis, & Yi, 2021). Florowski et al. (2019) reported the optimal hardness of restructured beef steak as 92 N. Herein, similar hardness could be obtained only at a cooking temperature of 100 °C, which resulted in OCMA hardness that increased with prolonged holding time. The hardness of the OCMA cooked at 100 °C with a 1-min holding time was 91 ± 0.7 N, which increased to 104 ± 1.1 N when the holding time was extended to 3 min. Moreover, at a fixed cooking temperature of 100 °C, the gumminess of the OCMA with a 1 min holding time amounted to 80 ± 2.4 N, which then increased to 92 ± 1.6 N at 3 min of holding time. The chewiness presented a similar trend to those of hardness and gumminess. Significant additional HEC was required for a 7 min holding time as compared with only 3 min (Table 2). Considering the energy consumption, we postulated that a 3 min holding time is sufficient to produce acceptable textural properties in the OCMA at a cooking temperature of 100 °C.

3.4. pH

pH of the OCMA ranged between 7.27 and 7.53 (Table 4). A cooking temperature of 70 °C produced an OCMA with lower pH; however, there were no significant differences between the pH values of the OCMA cooked at 80, 90, and 100 °C. Initial pH value of the meat analogue dough was 7.3 ± 0.2. The cooked OCMA, at 70 °C, showed a similar pH value and then it increased with higher cooking temperature. It would

Table 4
pH value of ohmic cooked meat analogue.

Cooking temperature (°C)	Holding time (min)	pH value
70	1	7.27 ± 0.06[c]
	3	7.27 ± 0.04[c]
	5	7.27 ± 0.07[c]
	7	7.33 ± 0.01[bc]
80	1	7.46 ± 0.03[a]
	3	7.50 ± 0.07[a]
	5	7.51 ± 0.04[a]
	7	7.53 ± 0.02[a]
90	1	7.47 ± 0.04[a]
	3	7.44 ± 0.04[a]
	5	7.52 ± 0.00[a]
	7	7.52 ± 0.07[a]
100	1	7.46 ± 0.04[a]
	3	7.45 ± 0.07[a]
	5	7.42 ± 0.02[ab]
	7	7.44 ± 0.04[a]

[a-c]Means(±Standard deviation) with a different letter in the same column are significantly different at $P < 0.05$.

Table 5
External and internal colour of ohmically cooked meat analogue.

Temperature (°C)	Holding time (min)	External colour				Internal colour			
		L*	a*	b*	ΔE	L*	a*	b*	ΔE
70	1	27.2 ± 0.3^{fgh}	28.4 ± 0.4^{a}	17.0 ± 0.4^{g}	7.2 ± 0.4^{de}	29.1 ± 1.1^{f}	27.3 ± 0.8^{a}	18.3 ± 0.5^{i}	6.6 ± 11.1^{kl}
	3	27.2 ± 0.5^{fgh}	28.7 ± 0.4^{a}	17.3 ± 0.5^{fg}	7.0 ± 0.7^{e}	29.1 ± 0.5^{f}	27.4 ± 0.3^{a}	18.4 ± 0.6^{i}	6.6 ± 0.3^{l}
	5	27.4 ± 0.1^{fgh}	28.3 ± 0.2^{ab}	17.4 ± 0.6^{fg}	7.1 ± 0.2^{e}	29.5 ± 0.4^{f}	26.7 ± 0.3^{ab}	19.4 ± 0.9^{hi}	7.1 ± 0.1^{jkl}
	7	27.3 ± 0.2^{fgh}	28.2 ± 0.4^{abc}	17.5 ± 0.6^{fg}	7.2 ± 0.3^{de}	29.6 ± 0.2^{f}	25.9 ± 0.4^{bc}	20.4 ± 1.3^{gh}	7.9 ± 0.6^{jk}
80	1	26.7 ± 0.6^{h}	27.4 ± 0.6^{bcd}	17.3 ± 0.9^{fg}	8.2 ± 0.5^{cde}	29.6 ± 1.1^{f}	25.7 ± 1.0^{cd}	19.8 ± 1.2^{ghi}	8.1 ± 0.4^{ij}
	3	27.1 ± 0.4^{gh}	27.3 ± 0.6^{cde}	17.4 ± 1.1^{fg}	8.0 ± 0.5^{cde}	29.9 ± 1.0^{ef}	24.7 ± 0.7^{de}	21.4 ± 2.1^{g}	9.3 ± 1.4^{hi}
	5	27.3 ± 0.4^{fgh}	27.3 ± 0.2^{cde}	17.9 ± 0.9^{efg}	7.8 ± 0.4^{cde}	31.3 ± 1.2^{de}	24.1 ± 0.5^{e}	23.7 ± 0.7^{f}	10.4 ± 0.4^{gh}
	7	27.1 ± 0.2^{gh}	26.7 ± 0.8^{de}	18.7 ± 0.1^{def}	8.4 ± 0.7^{cd}	31.4 ± 0.2^{de}	23.1 ± 0.9^{f}	25.5 ± 0.7^{e}	12.2 ± 0.7^{f}
90	1	27.7 ± 0.6^{efg}	27.4 ± 0.7^{bcd}	18.4 ± 0.2^{efg}	7.4 ± 0.9^{de}	32.0 ± 0.6^{ab}	24.3 ± 0.8^{e}	24.8 ± 1.7^{ef}	10.9 ± 1.7^{g}
	3	28.1 ± 0.7^{def}	26.9 ± 0.5^{de}	19.3 ± 0.1^{de}	7.6 ± 0.7^{cde}	33.2 ± 0.1^{bc}	22.1 ± 0.7^{f}	27.9 ± 0.9^{d}	14.4 ± 1.1^{e}
	5	28.7 ± 0.2^{cde}	26.7 ± 0.4^{de}	18.6 ± 1.2^{def}	7.4 ± 0.3^{de}	34.6 ± 0.1^{b}	20.7 ± 0.3^{g}	28.5 ± 1.5^{d}	16.1 ± 1.0^{d}
	7	29.2 ± 0.2^{bc}	26.4 ± 0.4^{e}	19.4 ± 1.6^{de}	7.5 ± 0.3^{de}	36.2 ± 0.9^{a}	19.6 ± 0.8^{h}	30.8 ± 2.5^{c}	18.6 ± 2.0^{c}
100	1	28.9 ± 1.1^{bcd}	25.3 ± 0.4^{f}	19.9 ± 1.3^{cd}	8.7 ± 1.0^{bc}	33.5 ± 1.9^{cd}	19.5 ± 1.0^{h}	28.5 ± 2.1^{d}	16.9 ± 2.0^{d}
	3	28.5 ± 1.2^{ecd}	24.6 ± 0.7^{f}	21.1 ± 1.6^{bc}	9.8 ± 1.0^{b}	34.4 ± 1.7^{b}	17.6 ± 0.7^{i}	30.7 ± 0.7^{c}	19.8 ± 0.6^{c}
	5	29.8 ± 0.9^{ab}	24.3 ± 0.7^{f}	21.7 ± 2.8^{b}	9.9 ± 1.5^{b}	36.8 ± 1.1^{a}	17.2 ± 0.5^{ij}	33.1 ± 1.7^{b}	21.9 ± 1.6^{b}
	7	30.2 ± 0.9^{a}	22.8 ± 1.1^{g}	23.3 ± 1.6^{a}	11.6 ± 1.5^{a}	37.4 ± 0.6^{a}	16.3 ± 0.2^{j}	34.7 ± 1.9^{a}	23.8 ± 1.4^{a}

[a-l]Means(±Standard deviation) with a different letter in the same column are significantly different at $P < 0.05$.

attribute to the loss of moisture in the OCMA at higher ohmic cooking temperatures.

3.5. Color

Table 5 presents the external and internal color attributes of the OCMA. The observed L*, *a**, and *b** values of external color ranged from 27.2 to 30.2, 22.8–28.7, and 17.0–23.3, respectively; the internal color *L**, *a**, and *b** value ranges were 29.1–37.4, 16.3–27.4, and 18.3–34.7, respectively. The OCMA was slightly darker than grilled beef ham, for which *L**, *a**, and *b** values of 48.4 ± 1.9, 22.3 ± 0.6, and 13.7 ± 1.6, respectively, were reported by Savadkoohi, Hoogenkamp, Shamsi, and Farahnaky (2014).

Regarding the external color, *L** increased with prolonged holding time at ohmic cooking temperature of 90 °C and 100 °C. An elevated cooking temperature was associated with lower *a**. For example, at a fixed 3 min holding time, 70 °C cooking resulted in *a** of 28.7 ± 0.4, which decreased to 24.6 ± 0.7 at 100 °C. Ohmic cooking temperature also had an effect on *b**, which decreased when the temperature was raised. In this study, red beet powder was used as the colorant for OCMA. Red beet is an excellent source of natural color. The colouring agent/constituent of red beet is betalain (Koul et al., 2002). Betalain, extracted from red beet, is water soluble with high tinctorial strength (Roy, Gullapalli, Chaudhuri, & Chakraborty, 2004). Betalain degrades at higher temperature; thus, it decreases *a** value and increases *b** value at higher cooking temperatures and longer processing time (Chandran, Nisha, Singhat, & Pandit, 2014). Therefore, in this study, discoloration of OCMA can be attributed to degradation of betalain at the evaluated ohmic cooking temperatures.

Ohmic cooking temperature and holding time had a more pronounced effect on internal color than external color. An increased ohmic cooking temperature produced a brighter internal color in the meat analogue. For example, at a fixed 3 min holding time, a cooking temperature of 70 °C resulted in *L** of 29.1 ± 0.5, which increased to 34.4 ± 1.7 at 100 °C. The ohmic cooking temperature also had a notable effect on *a**, which significantly decreased as a function of elevated cooking temperature. In contrast, increased cooking temperatures and longer holding times resulted in enhanced internal yellowness. The internal color change showed a similar trend to that described for roast beef by Goñi and Salvadori (2011) who reported that *a** decreased and *b** increased when the end-point cooking temperature was increased. In this study, moisture migration was observed from internal side to out side during ohmic cooking; thus, internal discoloration would attribute to moisture migration. The use of plant-based colorants is an important consideration for consumers' appeal of meat analogues.

4. Conclusions

This study investigated the potential of ohmic cooking to produce protein-based meat analogues by adjusting the effects of different cooking temperatures and holding times. Ohmic cooking enabled the rapid production of a soy-based meat analogue while achieving uniform cooking at all geometries. In terms of energy efficiency, the highest cooking temperature of 100 °C resulted in a maximum *SPC* of 0.75. Rapid high-temperature cooking efficiently converted electrical energy to heat. Ohmic cooking consumed minimal electrical energy during the holding time, once the temperature of the sample reached target temperature. With regard to energy efficiency and the textural quality of the OCMA, a cooking temperature-holding time combination of 100 °C and 3 min was optimal. The color of the OCMA was more dependent on cooking temperature than on holding time. Higher ohmic cooking temperature resulted in enhanced yellowness, in accordance with pr.

CRediT authorship contribution statement

Ah Hyun Jung: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. **Jeong Hyeon Hwang:** Methodology, Writing – review & editing, Visualization. **Soojin Jun:** Conceptualization, Methodology, Writing – review & editing. **Sung Hee Park:** Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This study was supported by the Advanced Research Project funded by the SeoulTech(Seoul National University of Science and Technology).

References

Ángel-Rendón, S. V., Filomena-Ambrosio, A., Cordon-Díaz, S., Benítez-Sastoque, E. R., & Sotelo-Díaz, L. I. (2019). Ohmic cooking: Application of a novel technology in pork and influences on water holding capacity, cooking loss and colour. *International Journal of Gastronomy and Food Science, 17*, 100164.

Bakhsh, A., Lee, S. J., Lee, E. Y., Hwang, Y. H., & Joo, S. T. (2021). Evaluation of rheological and sensory characteristics of plant-based meat analog with comparison to beef and pork. *Food Science of Animal Resources, 41*, 983–996.

Banerjee, S., & Bhattacharya, S. (2012). Food gels: Gelling process and new applications. *Critical Reviews in Food Science and Nutrition, 52*, 334–346.

Cappato, L. P., Ferreira, M. V. S., Guimaraes, J. T., Portela, J. B., Costa, A. L. R., Freitas, M. Q., et al. (2017). Ohmic heating in dairy processing: Relevant aspects for safety and quality. *Trends in Food Science & Technology, 62*, 104–112.

Chandran, P., Nisha, P., Singhal, R. S., & Pandit, A. B. (2014). Degradation of colour in beetroot (*Beta vulgaris L.*): A kinetics study. *Journal of Food Science & Technology, 51*, 2678–2684.

Chiang, J. H., Tay, W., Ong, D. S. M., Liebl, D., Ng, C. P., & Henry, C. J. (2021). Physicochemical, textural and structural characteristics of wheat gluten-soy protein composited meat analogues prepared with the mechanical elongation method. *Food Structure, 28*, 100183.

Darvishi, H., Khostaghaza, M. H., & Najafi, G. (2013). Ohmic heating of pomegranate juice: Electrical conductivity and pH change. *Journal of the Saudi Society of Agricultural Sciences, 12*, 101–108.

Day, L., & Swanson, B. G. (2013). Functionality of protein-fortified extrudates. *Comprehensive Reviews in Food Science and Food Safety, 12*, 546–564.

Dekkers, B. L., Boom, R. M., & van der Goot, A. J. (2018). Structuring processes for meat analogues. *Trends in Food Science & Technology, 81*, 25–36.

Ding, X., Liu, J., Xiong, X., Wang, S., & Li, X. (2021). Influence of ohmic heating on the electrical conductivity, volume, and rice quality of each component of the water–rice mixture. *Innovative Food Science & Emerging Technologies, 72*, 102757.

Engchuan, W., Jittanit, W., & Garnjanagoonchorn, W. (2014). The ohmic heating of meat ball: Modeling and quality determination. *Innovative Food Science & Emerging Technologies, 23*, 121–130.

Florowski, T., Florowska, A., Chmiel, M., Dasiewicz, K., Adamczak, L., & Pietrzak, D. (2019). The effect of nuts and oilseeds enriching on the quality of restructured beef steaks. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 104*, 128–133.

Gally, T., Rouaud, O., Jury, V., Havet, M., Ogé, A., & Le-Bail, A. (2017). Proofing of bread dough assisted by ohmic heating. *Innovative Food Science & Emerging Technologies, 39*, 55–62.

Ghnimic, S., Flach-Malaspina, N., Dresch, M., Delaplace, G., & Maingonnat, J. F. (2008). Design and performance evaluation of an ohmic heating unit for thermal processing of highly viscous liquids. *Chemical Engineering Research and Design, 86*, 626–632.

Goñi, S. M., & Salvadori, V. O. (2011). Kinetic modelling of colour changes during beef roasting. *Procedia Food Science, 1*, 1039–1044.

Guna, V., Yadav, C., Maithri, B. R., Ilangovan, M., Touchaleaume, F., Saulnier, B., et al. (2021). Wool and coir fiber reinforced gypsum ceiling tiles with enhanced stability and acoustic and thermal resistance. *Journal of Building Engineering, 41*, 102433.

Hradecky, J., Kludska, E., Belkova, B., Wagner, M., & Hajslova, J. (2017). Ohmic heating: A promising technology to reduce furan formation in sterilized vegetable and vegetable/meat baby foods. *Innovative Food Science & Emerging Technologies, 43*, 1–6.

Icier, F., & Bozkurt, H. (2011). Ohmic heating of liquid whole egg: Rheological behaviour and fluid dynamics. *Food and Bioprocess Technology, 4*, 1253–1263.

Icier, F., & Ilicali, C. (2005). Temperature dependent electrical conductivities of fruit purees during ohmic heating. *Food Research International, 38*, 1135–1142.

Jan, S., Khan, A. L., Bashir, K., & Jan, K. (2021). Ohmic processing of plant-related food products. In K. Knoerzer, & K. Muthukumarappan (Eds.), *Innovative food processing technologies A comprehensive review* (pp. 699–705). Elsevier Inc.

Jo, Y. J., & Park, S. H. (2019). Evaluation of energy efficacy and texture of ohmically cooked noodles. *Journal of Food Engineering, 248*, 71–79.

Klinmalai, P., Hagiwara, T., Sakiyama, T., & Ratanasumawong, S. (2017). Chitosan effects on physical properties, texture, and microstructure of flat rice noodles. *Food Science and Technology, 76*, 117–123.

Koul, V. K., Jain, M. P., Koul, S., Sharma, V. K., Tikoo, C. L., & Jain, S. M. (2002). Spray drying of beet root juice using different carriers. *Indian Journal of Chemical Technology, 9*, 442–445.

Kyriakopoulou, K., Dekkers, B., & van der Goot, A. J. (2019). Chapter 6 - plant-based meat analogues. In C. M. Galanakis (Ed.), *Sustainable meat production and processing* (pp. 103–126). Academic Press.

Mattice, K. D., & Marangoni, A. G. (2020). Comparing methods to produce fibrous material from zein. *Food Research International, 128*, 108804.

Novakovi, S., & Tomaševi, I. (2017). A comparison between warner-bratzler shear force measurement and texture profile analysis of meat and meat products: A review. *IOP Conference Series: Earth and Environmental Science, 85*.

Park, S. H., Balasubramaniam, V. M., & Sastry, S. K. (2014). Quality of shelf-stable low-acid vegetables processed using pressure-ohmic-thermal sterilization. *Lebensmittel-Wissenschaft und -Technologie- Food Science and Technology, 57*, 243–252.

Park, S. H., Balasubramaniam, V. M., Sastry, S. K., & Lee, J. Y. (2013). Pressure–ohmic–thermal sterilization: A feasible approach for the inactivation of Bacillus amyloliquefaciens and *Geobacillus stearothermophilus* spores. *Innovative Food Science & Emerging Technologies, 19*, 115–123.

Park, I. K., Ha, J. W., & Kang, D. H. (2017). Investigation of optimum ohmic heating conditions for inactivation of *Escherichia coli* O157:H7, Salmonella enterica serovar Typhimurium, and Listeria monocytogenes in apple juice. *BMC Microbiology, 17*, 117.

Pereira, R. N., Martins, R. C., & Vicente, A. A. (2008). Goat milk free fatty acid characterization during conventional and ohmic heating pasteurization. *American Dairy Science Association, 91*, 2925–2937.

Rieger, P. H. (1994). *Electrochemistry* (2nd ed.). New York: Chapman and Hall (Chapter 3).

Roy, K., Gullapalli, S., Chaudhuri, U. R., & Chakraborty, R. (2004). The use of a natural colorant based on betalain in the manufacture of sweet products in India. *International Journal of Food Science and Technology, 39*, 1087–1091.

Samaranayake, C. P., & Sastry, S. K. (2005). Electrode and pH effects on electrochemical reactions during ohmic heating. *Journal of Electroanalytical Chemistry, 577*, 125–135.

Sarang, S., Sastry, S. K., & Knipe, L. (2008). Electrical conductivity of fruits and meats during ohmic heating. *Journal of Food Engineering, 87*, 351–356.

Savadkoohi, S., Hoogenkamp, H., Shamsi, K., & Farahnaky, A. (2014). Color, sensory and textural attributes of beef frankfurter, beef ham and meat-free sausage containing tomato pomace. *Meat Science, 97*, 410–418.

Soisungwan, S., Khampakool, A., You, S. G., & Park, S. H. (2020). Ohmic cooking of instant rice cake soup: Energy efficiency and textural qualities. *Food Science and Biotechnology, 29*, 641–649.

Soisungwan, S., Khampakool, A., You, S. G., Park, W. J., & Park, S. H. (2019). Evaluating the feasibility of ohmic cooking for home meal replacement curry: Analysis of energy efficacy and textural qualities. *International Journal of Food Engineering*, 20180380.

Sun, C., Ge, J., He, J., Gan, R., & Fang, Y. (2021). Processing, quality, safety, and acceptance of meat analogue products. *Engineering, 7*, 674–678.

Tomo, Y., Koga, H., Fukunaga, T., Kurata, K., Matsuno, H., Tanaka, K., et al. (2021). Thermal conductivity measurement of solid materials using an "ITX"method–A pilot study using DNA solid films. *International Journal of Heat and Mass Transfer, 176*, 121501.

Varghese, K. S., Pandey, M. C., Radhakrishna, K., & Bawa, A. S. (2014). Technology, applications and modelling of ohmic heating: A review. *Journal of Food Science & Technology, 51*, 2304–2317.

Vicente, A. A., de Castro, I., Teixeira, J. A., & Pereira, R. N. (2016). Ohmic heating for food processing. In D. W. Sun (Ed.), *Thermal food processing new technologies and quality issues* (2nd ed., pp. 459–499). CRC Press.

Wang, H., Zhang, M., & Adhikari, B. (2015). Drying of shiitake mushroom by combining freeze-drying and mid-infrared radiation. *Food and Bioproducts Processing, 94*, 507–517.

Wattanayon, W., Udompijitkul, P., & Kamonpatana, P. (2021). Ohmic heating of a solid-liquid food mixture in an electrically conductive package. *Journal of Food Engineering, 289*, 110180.

Yuliarti, O., Kiat Kovis, T. J., & Yi, N. J. (2021). Structuring the meat analogue by using plant-based derived composites. *Journal of Food Engineering, 288*, 110138.

Zell, M., Lyng, J. G., Morgan, D. J., & Cronin, D. A. (2011). Minimising heat losses during batch ohmic heating of solid food. *Food and Bioproducts Processing, 89*, 128–134.

Zhou, H., Hu, Y., Tan, Y., Zhang, Z., & McClements, D. J. (2021). Digestibility and gastrointestinal fate of meat versus plant-based meat analogs: An in vitro comparison. *Food Chemistry, 364*, 130439.