



Ohmic heating application in food processing: Recent achievements and perspectives

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Received 30.09.2021; Revised 19.10.2021; Accepted 14.04.2022; Published online 23.06.2022

Abstract:

Food processing is an important operation in the food industry that converts fresh foods into final products with desirable characteristics for consumption and storage. Ohmic heating is an emerging technique for food processing that seems to be a suitable alternative to conventional heat treatment. Recently, there has been a lot of research into ohmic heating applications in processing various foods.

This review highlights the findings of studies conducted in 2018–2022 on the impact of ohmic heating on the physical, chemical, and sensory properties of foodstuffs during processing. We found that this technology provides more reliable process control compared to the traditional technique, namely conventional heating. Although ohmic heating has a positive effect on the quality of foods, its efficiency is limited by certain food components, including acid and fat, that markedly affect the electrochemical attributes of foods.

Therefore, to achieve optimal results, ohmic heating conditions should be set in accordance with the properties of food materials. There is a need for further in-depth studies on the performance of ohmic heating in food processing on a large, rather than a lab scale.

Keywords: Heat treatment, ohmic heating, food processing, novel technology, food quality, alternative method

Please cite this article in press as: Jafarpour D, Hashemi SMB. Ohmic heating application in food processing: Recent achievements and perspectives. *Foods and Raw Materials*. 2022;10(2):216–226. <https://doi.org/10.21603/2308-4057-2022-2-531>

INTRODUCTION

Fresh foods have a limited shelf life and spoil very quickly due to a high water content and easy availability of nutrients for microorganisms. Mechanical, physical, chemical, and microbial processes are the main causes of food spoilage. Therefore, processing of foods is very important in order to maintain their health benefits and quality.

Conventional thermal processing is widely used for microbiological safety and food preservation [1]. This technique effectively inactivates pathogens and spoilage microorganisms. However, the application of high temperatures has a negative effect on the food quality, namely color, texture, flavor, as well as nutritional and bioactive compounds [2, 3]. Heat transfer in traditional thermal processing includes three mechanisms, namely convection, conduction, and radiation [4]. The

heterogeneous distribution of heat in different parts of food, which occurs because of internal resistance, adds to the negative impact on the food quality.

Therefore, alternative technologies should be used to solve these problems. Ohmic heating, or Joule heating, is an emerging technique for food processing that seems to be a suitable alternative to conventional heat treatment. It generates heat by the passage of alternating current through food and the resistance of food particles to electrical current. In fact, food forms part of an electrical circuit in ohmic heating [5, 6].

Since ohmic heating converts electrical energy to thermal energy, the temperature inside the food rises uniformly and rapidly [7, 8]. As a result, there are fewer sensory changes, less off-flavor, fewer nutritional losses, and less bioactive degradation.

In addition, this new technology ensures the microbiological safety of the final product [9]. Other advantages of ohmic heating include shorter processing time, higher efficiency, and lower maintenance cost. Ohmic heating has a variety of uses in food processing, namely in pasteurization, peeling, blanching, drying, and concentration [4]. Thus, we aimed to review the latest studies on the application of ohmic heating in food processing.

OHMIC HEATING IN THE FOOD INDUSTRY

Ohmic heating application in dairy industry.

Ohmic heating technology appeared at the end of the 19th century. Although it was first utilized to pasteurize milk, ohmic heating was not commercialized due to the process control problems, high cost of electricity, and the lack of suitable materials for electrode production. Today, it is applied in dairy processing to produce safe, healthy, and high quality dairy products [10]. Particularly, it is used to pasteurize lactose-free milk since this product has good electrical conductivity. The material of electrodes used in ohmic heating is an important issue in dairy production [11]. Less fouling has been observed in titanium electrodes than in stainless steel electrodes. This phenomenon can be explained by the lower chemical reactivity of titanium compared to stainless steel. Also, milk pasteurized by ohmic heating with titanium electrodes had a safe content of chromium and no iron, while milk pasteurized by ohmic heating with stainless steel electrodes had more iron and chromium [12]. This is an important hygienic aspect for designers of food industry equipment.

The conditions of ohmic heating (variations of frequencies and voltages) are another factor which affects the final product. Costa *et al.* used ohmic heating with different voltages (2, 4, 5, 7, and 9 V/cm at 60 Hz) to process sweet whey and compared the results with conventional heating [9]. The authors reported that a higher electric field intensity resulted in lower luminosity (L^*) and lower color variation (ΔE^*). However, a lower electric field intensity led to better retention of bioactive compounds. This might be due to the relationship between the duration of heat exposure, whey protein denaturation, and the production of bioactive peptides. Besides, the authors recommended the 4 and 5 V ohmic heating for sweet whey, since these conditions ensured suitable sensory and rheological properties with higher bioactive compounds.

In the study of Silva *et al.*, ohmic heating was used for Dulce de leche treatment for the first time [13]. Dulce de leche is a dairy product which is made by evaporation and sugar addition. The authors indicated that the low and intermediate electric field strength gave the product weaker aroma, more bitter taste, and a higher sandiness score. At higher intensity, Dulce de leche was heated for a shorter time, which resulted in a weaker Maillard reaction and fewer Maillard reaction products (such as lactones and furans). Lactones and

furans are compounds which affect the aroma and flavor of sterilized products and may also have a negative impact on the quality of Dulce de leche. Furthermore, the ohmic-heated Dulce de leche had a homogeneous accumulation of whey proteins on a smaller scale. This prevented the contact of lactose molecules, as well as inhibited the growth of lactose crystals in size and sandiness in the final product [14].

Ferreira *et al.* processed raspberry-flavored whey beverage under different voltages and frequencies of ohmic heating [15]. The authors reported that certain parameters of this process (10, 100, 1000 Hz at 25 V and 45, 60, 80 V at 60 Hz) had a notable effect on the particle size, rheological properties, and the color of the whey beverage. Overall, ohmic-treated beverages showed higher viscosity than conventionally treated samples. Among ohmic-heated samples, 10 and 1000 Hz exhibited the highest viscosity due to the larger particle size and cell aggregation, while voltage-treated beverages had lower viscosity. In addition, 10 Hz-treated samples exhibited more color changes because of the electrochemical reaction. The authors proposed 10 and 1000 Hz at 25 V as an optimal treatment to achieve the desired color, physical, and rheological attributes.

In another study, Ferreira *et al.* revealed that under extreme conditions of ohmic heating (80 V at 60 Hz and 1000 Hz at 25 V), raspberry-flavored whey beverage had the lowest antioxidant activity, compared to mild and intermediate conditions (45 and 60 V at 60 Hz and 10 and 100 Hz at 25 V) [16]. Furthermore, the ohmic-heated samples showed higher α -glucosidase and α -amylase inhibition in comparison with the conventionally treated beverages. This could be related to the tendency of bioactive compounds in whey proteins to bind to the active sites of enzymes. Reducing the activity of these enzymes can result in lower hydrolysis of disaccharides and polysaccharides, as well as glucose uptake, with blood sugar levels maintained [17].

In a study of whey acerola-flavored beverage, Cappato *et al.* stated that ohmic heating decreased the relaxation period leading to small changes in fatty acid profiles, as well as preserving the nutritional properties of processed drink, compared to conventional heating [18].

Rocha *et al.* examined the quality parameters of Minas Frescal cheese produced from milk pasteurized by using ohmic heating [7]. This technique enhanced protein hydrolysis, resulting in a lower content of protein and a higher content of small peptides, compared to the cheeses made from conventionally treated milk. Cheeses manufactured from milk subjected to ohmic heating at the highest voltage showed the lowest proteolytic activity and the highest protein levels, similarly to the conventional method. Generally, ohmic heating notably decreased the hardness, elasticity, and firmness of the cheeses, yet improving their general acceptability. Low and intermediate electric field intensity (4 and 8 V/cm) increased the production of bioactive compounds and

antioxidant activity. Yet, these voltages altered the fatty acid profile and produced more saturated fatty acids. Therefore, ohmic heating at 8 V/cm was suggested for Minas Frescal cheese due to the shorter period of processing.

It was evidenced that ohmic heating resulted in lower hydroxymethylfurfural production and higher overall acceptability of whey dairy drinks, compared to conventional heating at the same temperatures. This was due to the shorter time to reach the process temperature, uniform heat, and lack of hot spots formation [19]. Thus, ohmic heating could be an innovative method for processing whey dairy drinks with improved sensory properties [20]. Table 1 summarizes recent applications of ohmic heating in food processing.

Ohmic heating application in fruit and vegetable processing. Fresh fruits and vegetables spoil rapidly after harvesting due to their nature (A_w , nutrients, etc.). Thus, it is essential to process and convert them into products which have a longer shelf life [42]. The traditional way is to concentrate fruit juices by conventional heating. However, this method impairs the quality of food due to a low coefficient of heat transfer and a long processing time [4]. An alternative method for concentrating fruit juices is ohmic heating [43].

Fruit juices have high electrical conductivity, which makes them suitable for the ohmic heating technology. Darvishi *et al.* reported that the content of total phenols in ohmic-treated black mulberry juice was 3.0–4.5 times higher than in the samples treated conventionally [3]. The performance of concentration in ohmic heating was by about 38–46% greater than in conventional heating. In addition, the authors stated that as the voltage increased, the process time decreased, resulting in fewer changes in total phenols and pH.

Similarly, high voltages (45 and 50 V) were suggested by Norouzi *et al.* for concentration of sour cherry juice [30]. Although ohmic heating increased the turbidity of sour cherry juice compared to the conventional method, it was still less than the initial turbidity. This might be due to an increase in total phenols with enhanced voltage gradient [44]. The authors also stated that the application of different voltages did not have a significant effect on color changes (ΔE) and color parameters such as *L* (lightness) and *b* (blueness/yellowness).

Minimal alterations in terms of color have also been detected in ohmic-treated sugarcane juice [25, 45]. Fadavi *et al.* evaluated the impact of ohmic heating and conventional heating on tomato juice [4]. They found that ohmic heating caused little changes in the properties of tomato juice (acidity, turbidity, and lycopene) and that these changes would be even less significant in ohmic heating under vacuum.

Conventional and ohmic dewatering of grapefruit and orange pulps were investigated by Stojceska *et al.* [21]. The authors indicated that the moisture content decreased markedly during conventional and ohmic drying, while the amount of vitamin C and pH did not differ significantly.

Another study found that the application of ohmic heating for concentration of orange juice under vacuum significantly reduced the concentration time and led to the production of fruit juice with higher viscosity, better color retention, and less decomposition of vitamin C, compared to processing under atmospheric conditions [46].

Sabanci and Icier added that the changes in the temperature of evaporation during the concentration of orange juice had a notable impact on the time to reach

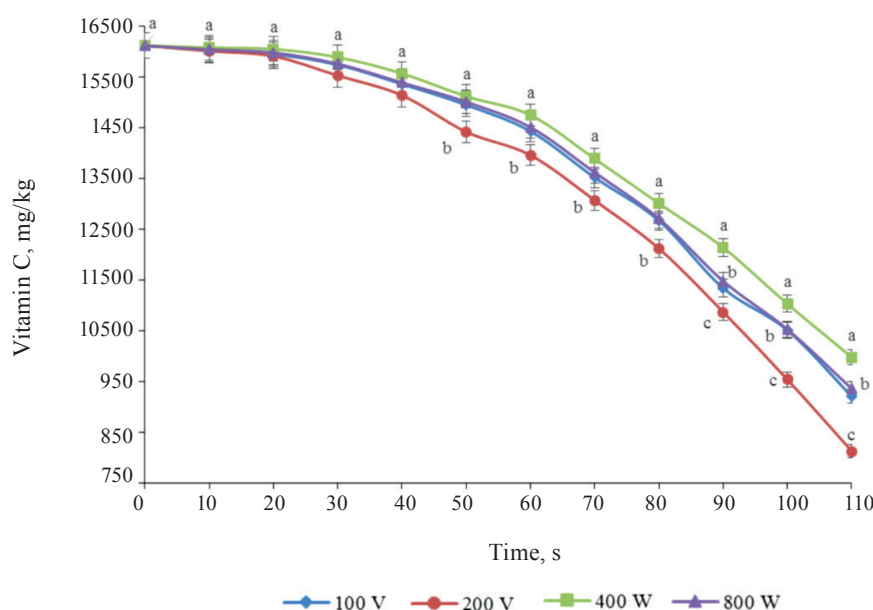


Figure 1 The effects of ohmic and microwave treatments on vitamin C content in cantaloupe juice. With the permission of the publisher, Hashemi *et al.* [22]

Table 1 Ohmic heating applications in food processing

Product	Process purpose	Ohmic heating conditions	Main findings	References
Whey dairy beverages	Thermal processing	6, 9, 12, and 15 V/cm – 500, 1000, 1500, and 2000 Hz	Samples processed by increased voltage gradient and frequencies presented higher overall liking	[20]
Dulce de leche	Thermal processing	0, 2, 4, 6, 8, and 10 V/cm – 60 Hz	Low and intermediate electric field strength resulted in more bitter taste, weaker aroma, and higher sandiness; higher intensity reduced the heating time and weakened the Maillard reaction	[13]
Whey dairy beverage	Thermal processing	6 V/cm – 60 Hz	Ohmic heating led to less hydroxymethylfurfural production and increased overall liking, compared to conventional heating at the same temperatures	[19]
Sweet whey	Thermal processing	2, 4, 5, 7, and 9 V/cm – 60 Hz	Higher electric field intensity resulted in lower luminosity and lower color variation; lower intensity led to better retention of bioactive compounds	[9]
Whey-raspberry flavored beverage	Thermal processing	10, 100, and 1000 Hz – 25 V and 45, 60, and 80 V – 60 Hz	Extreme ohmic heating conditions led to the lowest antioxidant activity, compared to mild and intermediate conditions; ohmic heating-treated samples showed higher α -glucosidase and α -amylase inhibition, as well as higher viscosity, than the conventionally treated beverages; 10 Hz-treated samples exhibited more color changes	[15]
Whey acerola-flavored drink	Pasteurization	45, 60, and 80 V – 60 Hz and 10, 100, and 1000 Hz – 25 V	Ohmic heating led to small changes in fatty acids profiles or preservation of nutritional properties, compared to conventional heating; electric field effects caused small modifications of nutritional aspects, while frequency had a stronger influence on the quality of the product; high frequencies (1000 and 100 Hz) resulted in better bioactive compounds and antioxidant capacity	[18]
Lactose-free milk	Pasteurization	8.25 V/cm – 50 Hz	This product can be subjected to ohmic heating due to its good electrical conductivity; less fouling observed in titanium electrodes than in stainless steel electrodes	[11]
Minas Frescal cheese (MFC)	Pasteurization of milk intended for MFC manufacture	4, 8, and 12 V/cm	Cheeses manufactured from milk subjected to ohmic heating at the highest voltage showed the lowest proteolytic activity and highest protein levels, similar to conventional heating; ohmic heating decreased hardness, elasticity, and firmness, but improved general acceptance of cheeses; production of bioactive compounds and antioxidant activity increased at low and intermediate electric field intensity (4 and 8 V/cm)	[7]
Grapefruit and orange pulps	Drying	30 V/cm	Vitamin C and pH did not differ significantly between ohmic heating and thermal dehydration	[21]
Cantaloupe juice	Pasteurization	100 and 200 V	Higher voltage resulted in a reduced number of pathogens and lower contents of vitamin C, carotene, and phenolic compounds	[22]
Pulque	Pasteurization	60, 80, 100, and 120 V – 60 Hz	Ohmic heating improved the physicochemical and sensory properties, compared to conventional heating	[23]
Tomato juice	Concentration	10.5, 13.2, and 15.8 V/cm – 50 Hz	Ohmic heating caused slight changes in the properties of tomato juice (acidity, turbidity, and lycopene) which were even less pronounced when using vacuum	[4]
Orange juice	Concentration	13 V/cm – 50 Hz	Ohmic heating treatment under vacuum resulted in better retention of vitamin C and fewer color changes, compared to treatment under atmospheric conditions	[24]
Sugarcane juice	Pasteurization	60 Hz	Ohmic heating and ultrasound did not affect phenolic compounds, whose content was similar to fresh juice; only slight color changes were caused by ohmic heating	[25]
Pineapple cubes	Thermal processing	Electrical power was calculated based on the electrical conductivity of pineapple cubes	Lightness and antioxidant properties of the pineapples did not differ significantly between ohmic heating and conventional heating; ohmic heating increased the hardness of the pineapples compared to the conventional method	[26]
	Blanching	25, 30, and 35 V/cm	The highest textural degradation was observed at all electric field strengths at 90 s process time; higher strength (35 V/cm) resulted in a higher drying rate	[27]

Product	Process purpose	Ohmic heating conditions	Main findings	References
Pear	Assisting in lye peeling	426, 479, 532, 585, and 638 V/m	Ohmic heating enhanced the product yield, efficacy of peeling, as well as the quality of the final product; peel quality was best at much lower concentrations of lye (2% NaOH at 532 V/m and 3% NaOH at 426 and 479 V/m)	[28]
Mulberry juice	Concentration	15, 20, 25, and 30 V/cm – 50 Hz	Ohmic heating provided greater concentration than the conventional method (about 38–46%); higher voltage reduced the process time, resulting in fewer changes in total phenols and pH	[3]
Pekmez	Evaporation	17.5, 20.0, 22.5, and 25.0 V/cm	Energy consumption was higher in conventional heating than ohmic heating for all voltage gradients; energy efficiency increased with higher voltage gradient	[29]
Sour cherry juice	Concentration	8.3, 9.7, 122.0, 11.1, 12.5, and 13.9 V/cm – 50 Hz	Although ohmic heating increased the turbidity of sour cherry juice compared to the conventional method, it was still lower than the initial turbidity; different voltages did not have a significant effect on color parameters such as “ <i>L</i> ” (lightness) and “ <i>b</i> ” (blueness/yellowness)	[30]
Coconut water	Pasteurization	10 and 20 V/cm – 50 Hz	Ohmic heating could completely inactivate peroxidase but not polyphenol oxidase; no pink color found in ohmic heating-treated samples during cold storage, unlike conventionally pasteurized samples	[31]
Short grain rice	Cooking	60 Hz	Ohmic heating adversely affected color parameters (color intensity and lightness), resulting in softer texture compared to the hotplate cooking system	[32]
Noodle	Cooking	10.0, 12.5, 15.0, and 17.5 V/cm – 60 Hz	Temperature come-up time decreased significantly with an increase in electric field; 15 V/cm electric field strength with the holding time of 90 s was suggested as the best treatment in terms of desirable texture and energy efficiency	[33]
Whole and decorticated pearl millet grain	Cooking	60 Hz	Grain pericarp considered the principal factor influencing the cooking process rather than the method of heating; no significant differences observed between conventional open-pan and ohmic heating methods in terms of texture and color	[34]
Pork	Cooking	21 ± 1 V/cm – 60 Hz	Shorter cooking time; such important factors as cooking loss, color, and water holding capacity were not significantly affected, compared to pan cooking	[35]
Vacuum packaged sausage	Post-pasteurization	230 V – 50 Hz	Ohmic heating only slightly changed the texture and color of vacuum packaged sausages, while having no notable impact on pH, water holding capacity, lipid oxidation, or cooking loss	[36]
Beef	Cooking	50 V – 20 kHz	Electrical conductivity is affected by the amount of fat in the muscle tissue; series electric current reduces electrical conductivity, compared to parallel current	[37]
Whole egg	Pasteurization	20 kHz	Ohmic heating improved the hardness and foaming capacity compared to conventional pasteurization and caused slight changes in color; although ohmic heating increased viscosity, its detrimental impact could be reduced by adjusting the process conditions; low temperature pasteurization was proposed due to its low impact on protein denaturation	[38]
Egg white	Pasteurization	20 kHz	Fewer proteins denatured during thermally-induced gelation of egg white protein under ohmic heating	[39]
Starch	Gelation	7 to 27 V/cm – 60 Hz	The stability of starch gels strongly depended on the type of starch and was not affected by the type of heat treatment	[40]
Surimi-canned corn mixed gels	Thermal processing	250 V – 10 kHz	Ohmic heating effectively reduced moisture loss in corn and preserved the texture of corn and surimi gel better than the water-bath heating method	[41]

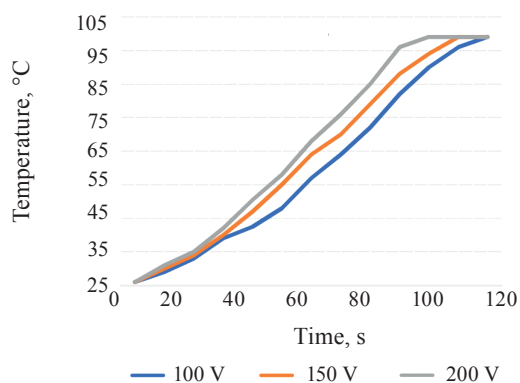


Figure 2 Temperature profile of sour orange juice during ohmic heating for 120 s and three different voltages (100, 150, and 200 V). With the permission of the publisher, Hashemi *et al.* [47]

the target values of total soluble solids, performance, and electrical conductivity [24]. They explained that various values of absolute pressure and, consequently, boiling temperatures applied in ohmic heating affected energy efficiency, according to the second law of thermodynamics. Higher boiling temperature decreased the process time and had a positive effect on energy efficiency.

In some studies, ohmic heating has been used to pasteurize fruit juices. Particularly, Hashemi *et al.* compared the efficiency of ohmic and microwave processes for treatment of cantaloupe juice [22]. They indicated that higher voltage of ohmic heating and microwave power markedly decreased phenolic compounds, vitamin C, and the number of pathogens. In fact, at high voltages compounds are produced that catalyze the decomposition pathways of ascorbic acid in the presence of oxygen due to thermal effects, electrode reactions, and the electrolysis of the solution. Hashemi *et al.* observed the highest degradation of vitamin C in the ohmic treatment at 200 V and the lowest in the microwave treatment at 400 W (Fig. 1) [22].

In another study [47], they found electric current and temperature to be the major variables which affected the pasteurization of sour orange juice. The authors showed that heat transfer in orange juice was accelerated by the application of a higher electric field (Fig. 2).

Alcántara-Zavala *et al.* reported that ohmic heating improved the physicochemical and sensory properties of fermented beverage obtained from the agave plant (known as pulque) [23]. Pulque is an alcoholic beverage with acidic taste. Ohmic heating improved its flavor (alcoholic perception and acidity) and made it more palatable for consumption, compared to conventional heating. Due to its mineral content, pulque showed good electrical conductivity. Its pasteurization with 120 V at 65°C for 5 min was reported as the best treatment.

Rinaldi *et al.* evaluated the physical and chemical impacts of ohmic heating and conventional heating

on cubes of pineapple in syrup [26]. They observed insignificant differences in the lightness (L^*) and antioxidant properties between the two methods, while the hardness of the ohmic-treated pineapples was higher than that of those treated conventionally. In addition, Kumar *et al.* observed the highest textural degradation of pineapple cubes at all electric field strengths at 90 s process time [27]. They also found that higher electric field strength resulted in a higher drying rate.

Ohmic heating can be used as an alternative to conventional blanching prior to drying and storage of vegetables and fruits. Kanjanapongkul and Baibua applied ohmic heating to pasteurize coconut water and found that it could completely inactivate peroxidase, but not polyphenol oxidase [31]. In addition, no pink discoloration was reported in the ohmic-heated samples, while the conventionally pasteurized samples featured a pink color during cold storage.

Another application of ohmic heating is in the peeling process. Removing the skin of fruits and vegetables is one of the most common treatments in food processing. The conventional peeling methods (lye, steam, and mechanical method) have several drawbacks, including high peeling losses, high consumption of energy, and environmental issues. Therefore, there is a growing demand for alternative methods [48]. Gupta and Sastry employed ohmic heating to remove the skin of pear [28]. Furthermore, a combination of ohmic heating and CO₂ laser drilling has been used to remove tomato skins [49]. These studies have shown that ohmic heating enhances the product yield, efficacy of peeling, as well as the quality of the final product. However, some parameters should be considered to optimize the peeling process, such as temperature, composition of peeling medium, and electric field strength [28, 50].

Ohmic heating application in grain processing.

The boiling of food products, such as rice and noodles, is a time-consuming process. Today, as the people's lifestyles have altered, there is a growing demand for rapid cooking methods and alternatives to traditional methods. Gavahian *et al.* investigated the impact of ohmic heating and traditional cooking on the textural and physical attributes of short grain rice [32]. They reported that although ohmic heating adversely affected the color parameters (color intensity and lightness), it resulted in softer texture in comparison with the hotplate cooking system. In this regard, the corrosion of electrodes and electrochemical reactions have been expressed as factors affecting the color of ohmic-heated foods [32].

Ohmic heating has also been found to markedly reduce the cooking time, fouling, and consumption of energy, compared to the traditional method [51]. Similarly, Jo and Park utilized different electric fields (10.0, 12.5, 15.0, and 17.5 V/cm) for cooking instant noodles [33]. They observed that heat transfer between noodles and soup was expedited at higher electric fields. Therefore, the authors suggested 15 V/cm with the

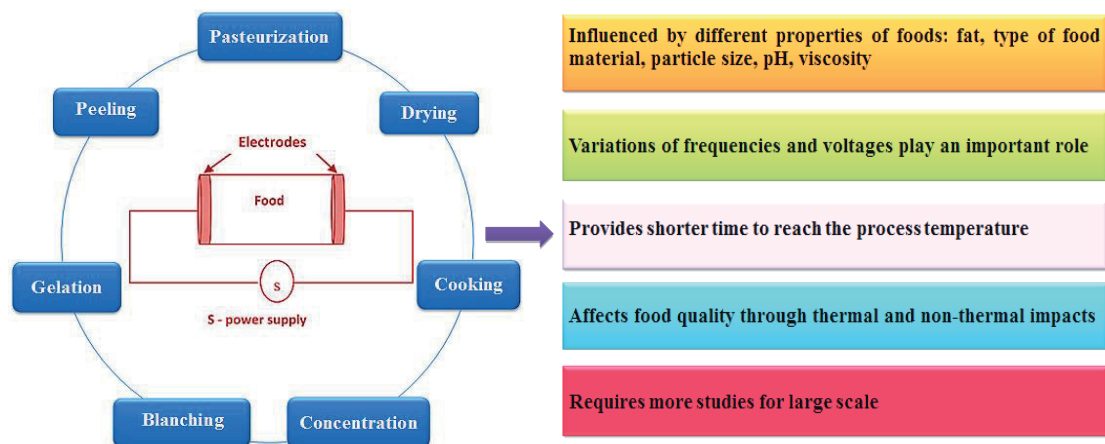


Figure 3 Various applications of ohmic heating in food processing

holding time of 90 s as the best treatment in terms of desirable texture and energy efficiency.

Dias-Martins *et al.* compared the impact of conventional open-pan and ohmic heating on whole and decorticated pearl millet grains [34]. They found the grain pericarp to be the principal factor influencing the cooking process, rather than the method of heating. Regarding pearl millet grain, no significant differences were observed between the two cooking methods in terms of texture and color. However, the ohmic-heated decorticated grains exhibited greater lightness and harder texture, compared to the conventionally cooked grains.

Waziroh *et al.* examined the basic aspects of using ohmic heating for baking gluten-free bread [52]. They stated that the changes in the physical properties of gluten-free bread during heating depended on the ingredients and their interaction in the dough. They believed that two major factors affected the porosity and viscosity of dough during baking by ohmic heating, namely dough ingredients and their properties (e.g., non-ionic and ionic compounds, particle size, surface hydrophobicity, emulsification ability, etc.) and dough structural properties (foam formation, protein denaturation, and starch gelatinization).

Ohmic heating application in meat industry.

It has been investigated that ohmic heating can be used for processing meat and meat products. Several factors affect the electrical conductivity and therefore the efficiency of the ohmic process, including meat structure (type of meat, amount of fat and moisture), lean-to-fat ratio, and electric current direction [35]. Llave *et al.* studied the impact of meat type (Japanese beef and Australian beef) and the direction of electric current (series and parallel) on the electrical conductivity during ohmic cooking [37]. They reported that Japanese meat had lower electrical conductivity than Australian meat due to its higher fat content. Having low electrical conductivity, fat prevents the passage of current by covering lean particles, which

reduces the electrical conductivity during ohmic heating, as well as uniform heating. The authors also found that series electric current reduced electrical conductivity, compared to parallel current. Reduction of shrinkage and drip loss were observed in both types of meat during ohmic cooking at 50 V and 20 kHz [37].

Additionally, ohmic heating can be applied to cook pork since it shortens the cooking time without having a significant impact on the water holding capacity, color, and cooking loss, compared to the traditional pan cooking [35]. Similarly, ohmic heating has no significant effect on the properties of scallops (texture, shrinkage, and water release) and reduces the denaturation of actin by shortening the heating time [53].

Inmanee *et al.* investigated the impacts of ohmic heating on *Listeria monocytogenes* contamination and the quality of sausages during post-pasteurization [36]. They showed that the ohmic process effectively inactivated *L. monocytogenes* (≥ 5 -log reduction). The authors compared the electrical conductivity of sausage, salt solution, and collagen casing. They found that the collagen casing had a higher electrical conductivity than the sausage and attributed it to the presence of fat, which made up to 20% of the sausage. The salt solution acted as a conductor, with lower conductivity than the sausage and casing.

The study also showed that the ohmic process only slightly changed the texture and color of the vacuum-packaged sausages. At the same time, it had no notable impact on pH, water holding capacity, lipid oxidation, and cooking loss. However, these slight changes in texture and color were not detectable by sensory evaluators. Therefore, ohmic heating has the potential to be applied in the meat and meat products industry with the least impact on their quality.

Other food products. Several studies have investigated the technological attributes of eggs under ohmic heating. Since fresh-laid eggs can be a cause of salmonella infection, manufacturers prefer pasteurized egg for both its safety and ease of handling [54].

Eggs are a rich source of protein and due to their sensitivity to high temperature, great care must be taken during egg pasteurization to prevent proteins denaturation and coagulation. Alamprese *et al.* reported that ohmic heating improved the hardness and foaming capacity of the whole egg, compared to conventional pasteurization, and caused slight changes in its color [38]. The authors stated that although ohmic heating increased viscosity, its detrimental impact could be reduced by adjusting the process conditions. In general, they proved that ohmic treatment could be used as a desirable method for whole egg treatment and proposed low temperature pasteurization due to its low impact on protein denaturation.

Similarly, Llave *et al.* examined color alterations of egg yolk under ohmic treatment and evaluated the correlation between color changes and the degree of protein denaturation [54]. They found that increasing temperatures caused the egg yolk color to gradually turn from plain orange to vivid yellow, while the egg white gradually changed from transparent to cloudy.

In addition, the egg color changes were correlated with the non-denaturation ratio of the second peak temperature. In this regard, Joeres *et al.* indicated that egg white protein did not fully denature during ohmic heating [39]. They believed that this could be related to the oscillatory electric field which partially interfered with the complete denaturation and development of intermolecular beta-sheet structures during thermal gelation of ovalbumin. Also, according to the results of scanning electron microscopy, the ohmic-heated gels had a more open and porous network structure, compared to conventional treatment which exhibited denser gels.

In another study, da Silva *et al.* investigated the impact of ohmic heating on the rheological attributes and stability of gels produced from starch [40]. Particularly, they examined the effect of starch source (cassava and maize) and type of treatment. They found that the stability of starch gels strongly depended on the type of starch and was not affected by the type of heat treatment. The researchers revealed that ohmic heating had several advantages over conventional heating. In particular, it reduced energy and water consumption, as well as wastewater production, and did not affect the properties of the final product.

In a study by Jung *et al.*, ohmic heating was used to process surimi-corn mixture [41]. The authors reported that this technique effectively reduced the amount of moisture loss in corn and preserved the texture of corn and surimi gel better than the water-bath heating method.

Limitations and advantages. Ohmic heating has revealed its potential for processing various foods in industrial applications. Apart from heat treatment, it can also be used as an assisted treatment for other processes like peeling, concentration, and drying (Fig. 3). Although recent studies have indicated that

ohmic heating can improve the physical and chemical properties of foods, compared to conventional heating, there are some limitations regarding its application. Operator safety, high capital cost, and corrosion of electrodes are major concerns of food manufacturers to commercialize this novel technology.

Studies have shown that ohmic-treated foods have better texture, better aroma, lower color variation, higher bioactive compounds, and better sensory properties, compared to conventionally treated foods [3, 7, 9, 13, 16, 18, 20, 23, 26, 30, 33, 36, 49]. However, for some foods, there are no significant differences between the two methods in terms of quality [21, 26, 40].

In contrast, some studies have revealed that ohmic heating can adversely affect some physical properties of food such as color [32]. Electrode corrosion and some electrochemical reactions are among its limitations that can affect the food quality. Besides, ohmic heating is not a suitable method for processing foods with a high fat content since fat has low electrical conductivity. Therefore, the ohmic process conditions must be optimized according to the food properties in order to achieve the best result.

Other advantages of ohmic heating are a shorter time to reach the process temperature, lower consumption of energy, uniform distribution of heat, and a shorter total heating period [7, 10, 29, 40, 43]. Although this novel technology has some limitations and drawbacks, its advantages make it a suitable alternative to the traditional heating process.

CONCLUSION

Ohmic heating follows the Joule law to heat foods quickly and evenly, effectively and volumetrically. This method is markedly influenced by different properties of foods, including the amount of fat, type of food material, particle size, pH, viscosity, the content of charged ions, etc. In addition, variations of frequencies and voltages also play an important role in the performance of ohmic heating during food processing. Our review concludes that the processing of food materials by ohmic heating can be carried out in a shorter time, compared to conventional heating. In addition, the quality of foods can be effectively affected by ohmic treatment through both thermal and non-thermal impacts. While its thermal impacts on the food quality have been extensively studied, there is limited information on the non-thermal impacts of this technology on various food properties, such as texture, color, taste, etc. Therefore, a more detailed study is needed to fully realize the thermal and non-thermal impacts of ohmic heating for different foods and under various operating conditions. The ohmic process has many benefits for food industry, including process energy and time savings. Furthermore, this technology provides more reliable process control, compared to the traditional technique. These benefits suggest that ohmic heating can be a superior alternative

procedure for food processing in comparison with the traditional method. However, most studies have been performed on a lab-scale and very few on a pilot plant-scale. Therefore, more research is needed into ohmic heating application on a large-scale to evaluate the potential technical problems and economic issues.

CONTRIBUTION

The authors were equally involved in writing the manuscript and are equally responsible for plagiarism.

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

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