Chapter 1
Impact of Ohmic Processing on Food Quality and Composition

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1.1 Introduction

One of the novel promising technologies to pasteurize, sterilize, or cook a wide range of food products (e.g. fruits and vegetables, dairy products, and meat products) is ohmic heating, which usually helps to obtain a high product quality (Fig. 1.1). Ohmic heating is literally an electric resistance heating method, in which an alternating current (50 Hz to 100 kHz) is passed through the food material. In a flow through the unit, several electrode arrangements such as a parallel plate, colinear, parallel rod, and staggered rod electrodes are used depending on the required operation. However, alternative electrode arrangements could also be applied. Similar to other volumetric heating methods, the elimination of heating surfaces in contact with foodstuff in ohmic heating helps to reduce thermal degradation and consequently an enhancement in product quality.

Conventional heating methods provide heating from a hot surface via conductive and convective heat transfer (Damyeh, Niakousari, Saharkhiz, & Golmakani, 2016;

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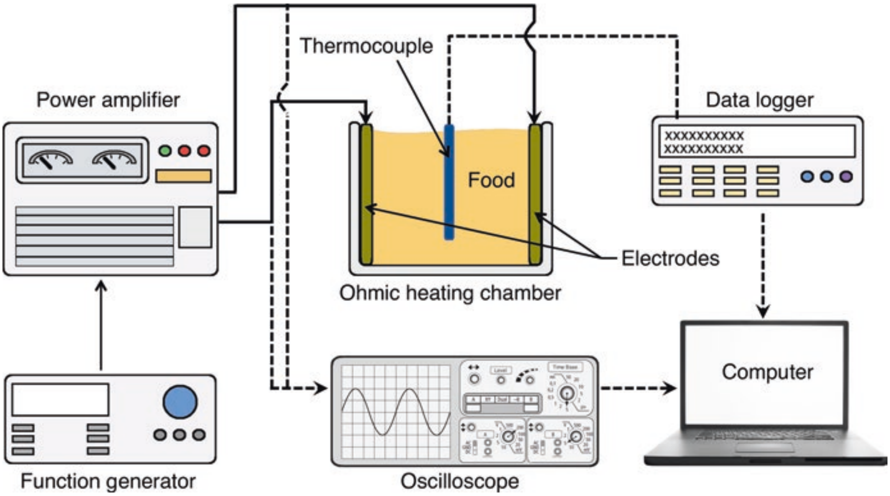

Fig. 1.1 Schematic representation of Ohmic heating equipment for food applications. (Reprinted with permission from Koubaa, Roselló-Soto, Barba-Orellana, and Barba (2016))

Seidi Damyeh & Niakousari, 2016). A hot medium (e.g. steam) in a heat exchanger (e.g. tube, shell, or plate type) or a vessel with a heated jacket can provide heat. These hot surfaces should be at a considerably higher temperature than the food material in order to reach the proper temperature gradient to transfer heat to the food material. As a consequence, thermally degradation or even burning effects could occur, which in turn leads to a reduction in product quality. Furthermore, limited heat transfer, when processing highly viscous fluids and fluids with particulates, causes a very slow process and non-uniform temperature profiles. However, with the aid of mechanical agitation, the required heat transfer and uniformity would be obtained, which may cause physical damages to the product (Niakousari, Hashemi Gahruie, Razmjooei, Roohinejad, & Greiner, 2018).

Application of ohmic heating overcomes the aforementioned downsides of conventional heating via direct heat generation inside the food material (Seidi Damyeh & Niakousari, 2017). Therefore, enhanced product quality (i.e. color, flavor, nutrient retention) is obtained owing to the absence of thermal degradation. Low flow rates or high viscosity fluids would not contribute to the performance decline in ohmic heating, which is because of not being dependent on turbulence effects. Ohmic heating also obviates the need for mechanical shear in particulate food material, which may cause damage to the product that is obviously due to its uniform heating.

In order to be successfully processed via ohmic heating, the food material should be pumpable with appropriate electrical conductivity (0.01–10 S/m). High process efficiency is obtained by ohmic heaters, in which over 95% of electrical energy is transformed to heat within the food material (in 50 Hz systems) (Damyeh, Niakousari, Golmakani, & Saharkhiz, 2016). This technique offers the ability to efficiently control the process and to have a rapid start-up due to its electrical nature. Nevertheless, the cost of electrical energy can be considered as a limitation to ohmic heating.

Milk pasteurization was the very first application of ohmic heating developed in the early twentieth century (Anderson & Finkelstein, 1919). This process was formerly known as "electropure process" and was stopped using due to lack of appropriate electrode material. By development of sterilization process of food materials having large particulates at the United Kingdom Electricity Council Research Center, more research into ohmic heating was recommended in the 1980s (Simpson, 1983; Simpson & Stirling, 1995; Stirling & Coombes, 1990). An enhancement in quality regarding particulate identity of food's color, and vitamin retention and longer shelf life for pasteurized food products by the industrial application of ohmic heating (compared to conventional heating) has been globally observed since the 1980s (Anderson, 2008; Castro, Teixeira, Salengke, Sastry, & Vicente, 2004; Leizerson & Shimoni, 2005a). A high-quality product with minimal structural, organoleptic and nutritional changes was produced by Rahman (2007) in a short operating time using ohmic heating. In this chapter, the influence of ohmic heating on the nutritional, textural and sensorial attributes of different foodstuffs such as fruits and vegetables, dairy, and meat products were highlighted and the advantageous and disadvantageous of using this technology on food quality were discussed.

1.2 Nutritional Properties

The time required to increase the cold point temperature in conventional heating may over process other parts of the food, which decreases the nutritional and sensory properties of food products. Emerging thermal treatments such as ohmic heating can be used to overcome this drawback of conventional heating operations by homogenous heating distribution throughout the products. The influence of ohmic processing on nutritional properties of different food products is discussed below.

1.2.1 Fruits and Vegetables

The nutritional interest of fruits and vegetables is due to the presence of high levels of fibers, vitamins, minerals, phenolic compounds and bioactive peptides (Septembre-Malaterre, Remize, & Poucheret, 2018). The degree of these components in fruits and vegetables depends on their variety, maturity, agronomical practices, postharvest operations and processing conditions such as heating operations. Vitamin C (ascorbic acid) is essential for the synthesis of collagen and its deficiency causes scurvy. Moreover, ascorbic acid is a natural antioxidant applied in the food industry to impede browning, discoloring and to improve the shelf life of food products. However, it is considered a heat-sensitive vitamin. The degradation of ascorbic acid in foods is influenced by factors such as oxygen concentration, light, temperature, pH, a_w (water activity) and the presence of metallic ions (Damodaran, Parkin, & Fennema, 2008). Several studies have evaluated the thermal degradation of vitamin C under different heating conditions including emerging technologies such as ohmic heating. The results of some of these studies are listed in Table 1.1.

Based on these results the influence of ohmic heating on vitamin C degradation depends on process conditions such as the voltage gradient and duration of ohmic heating. However, contradictory results have been reported for different products. These differences may be due to the dissimilarities in electrochemical reactions in these products. Nevertheless, in frequencies above 100 Hz, the occurrence of these reactions decreased, and degradation kinetics of ascorbic acid was not influenced by high electric field frequency. This shows that hydrogen donation tendency of the ascorbic acid molecule in redox reactions is not influenced by the rapid changes in the electric field (Mercali et al., 2014). In addition to the voltage gradient, the type of electrode has been proven to have significant effects on vitamin C degradation. Athmaselvi et al. (2017) determined the effect of titanium and stainless steel electrodes on ascorbic acid degradation in the tropical fruits (papaya, sapota, and guava) under ohmic heating and found that samples heated with titanium electrode exhibited better ascorbic acid retention. Louarme and Billaud (2012) studied the impact of conventional heating and ohmic heating on the degradation of vitamin C in apple and peach desserts. The results showed that in contrast to conventional heating, the ohmic heating had very little effect on oxidative degradation of ascorbic acid. In another study, Jaeschke, Marczak, and Mercali (2016) evaluated the influence of the

Table 1.1 Influence of ohmic heating on ascorbic acid degradation of fruits

Product type	Process condition	Result	Reference
Aonla pulp	Samples heated for 1 min at 90 °C at 11, 13, 15 or 17 V/cm	Low voltage gradients brought more ascorbic acid degradation	Singh et al. (2013)
Guava juice	Samples heated for 1, 3 and 5 min at 95 °C at 13.33, 16.66, 20 and 23.33 V/cm voltage gradient at 50 Hz frequency	High voltage gradients induced more ascorbic acid degradation	Chakraborty and Athmaselvi (2014)
Sweet lime juice	Samples heated with a temperature range of 27.4 °C to 85.4 °C at 30, 40 and 50 60 V/cm voltage gradient at 50 Hz frequency	High voltage gradients induced greater ascorbic acid degradation	Parmar, Tripathi, Tiwari, and Singh (2016)
Papaya, sapota, and guava	–	High voltage gradients induced greater ascorbic acid degradation	Athmaselvi, Kumar, and Poojitha (2017)
Acerola pulp	Samples heated for 3 min at 85 °C at a heating voltage of 120–200 V	High voltage gradients induced greater ascorbic acid degradation	Mercali, Jaeschke, Tessaro, and Marczak (2012)
	Samples were heated for 0, 20, 40, 60, 80, 100 and 120 min at 10, 10^2, 10^3, 10^4 and 10^5 Hz	Low voltage gradients induced greater ascorbic acid degradation	Mercali, Schwartz, Marczak, Tessaro, and Sastry (2014)

electric field on the degradation of carotenoid and ascorbic acid in acerola pulp at different temperatures (80, 85, 90 and 95 °C) during 60 min of heat treatment (ohmic or conventional heating). Different temperatures exhibited the same effects on degradation rates and the degradation process was similar in both heating methods, indicating that the electric field did not affect the mechanisms and rates of ascorbic acid and carotenoid degradation.

When a sample is exposed to an electric field, its molecules align with the oscillating electric field in a process known as polarization (Mercali et al., 2014). In acerola fruit, the polarization process did not influence the rate of ascorbic acid degradation in ohmic heating. This technology was performed under atmospheres with low or high oxygen contents at 90 °C in order to explore the impact of oxygen on the ascorbic acid and carotenoid degradation. They found that the degradation of carotenoid was greater under a rich oxygen atmosphere (Mercali et al., 2012). Similarly, Mercali et al. (2014) studied the effect of electric field frequencies (between 10 and 105 Hz) on the degradation of ascorbic acid in acerola pulp during ohmic heating and compared the results with conventional heating. Low frequency caused greater ascorbic acid degradation possibly because of the incidence of electrochemical reactions. However, these reactions were minimized at frequencies above 100 Hz and degradation rates of ascorbic acid were the same as for conventional heating.

Carotenoids are great antioxidants and some of them (e.g. carotene) have been proven to offer provitamin A activity. Carotenoid degradation occurring by isomerization or oxidation is the main reaction to its degradation, which depends on carotenoid structure (Rodriguez-Amaya, 2001). Achir et al. (2016) explored the influence of ohmic and conventional pasteurization on carotenoid protection in grapefruit and blood orange. The results revealed that xanthophyll losses reached 70% for epoxyxanthophylls and 40% for hydroxyxanthophylls in conventional heating, while losses were below 30% and 20% in ohmic pasteurization, respectively. Lycopene and β-carotene (carotene species) were stable in both heating treatments. Thus, ohmic pasteurization was suggested as a promising option for the preservation of xanthophylls. In another study, the vitamin degradation kinetics and changes in the carotenoid contents of orange juice samples heated by four different methods were investigated and better vitamin retention at all temperatures was reported using ohmic heating (Vikram, Ramesh, & Prapulla, 2005).

Mercali, Gurak, Schmitz, and Marczak (2015) studied the non-thermal impacts of electricity on the degradation of anthocyanin, in ohmic heating of jaboticaba juice and found that electric field did not influence the degradation rate of anthocyanins. Sarkis, Jaeschke, Tessaro, and Marczak (2013) compared the influence of conventional and ohmic heating of blueberry pulp on its anthocyanin degradation. They found that the degree of anthocyanin degradation under lower voltages was lower or comparable to those obtained during conventional heating. However, ohmic heating under high electric fields exhibited higher anthocyanin degradation. In the research conducted by Guida et al. (2013), the nutritional properties of conventional and ohmic heated artichokes were compared. The conventional cooking (boiling) or blanching of artichokes resulted in the loss of nutritional properties and reduction of antioxidant compounds owing to thermal degradation, oxidation, and leaching (Lutz, Henríquez, & Escobar, 2011). They also found that the rate of peroxidase and polyphenol oxidase inactivation in conventional heating was slower and phenolic compounds were degraded during heating. However, after ohmic heating, the total phenolic content was increased which might be due to the release of bound phenolics and also the breakdown of artichoke cells that increased the accessibility of the antioxidant compounds. With the increase of electric field strength (from 25 to 30 and 40 V/cm), the retention of total phenolic content was higher due to the faster polyphenol oxidase inactivation. Castro, Macedo, Teixeira, and Vicente (2004) determined the inactivation kinetics of pectinase, lipoxygenase, alkaline phosphatase, polyphenoloxidase, and β-galactosidase under ohmic and conventional heating. The thermal history in both heating techniques was made equal to investigate the enzyme inactivation caused by the electric field. The results showed that all of the enzymes in both heating operations followed first-order inactivation kinetics. They also found that the electric field did not influence the inactivation rate of β-galactosidase, pectinase, and alkaline phosphatase. However, the inactivation of polyphenoloxidase and lipoxygenase were accelerated in ohmic heating. The electric field removed the metallic prosthetic groups in lipoxygenase and polyphenoloxidase, changed the molecular spacing and increased the interchain reactions and facilitates the inactivation of these enzymes. Therefore, the ohmic-treated samples were demonstrated to present higher levels of antioxidants and phenolic compounds compared with conventional-heated ones.

Several studies have investigated the changes occurred in proteins and amino acids of fruits and vegetables during ohmic heating. For instance, Mesías, Wagner, George, and Morales (2016) assessed the impact of ohmic and conventional retort sterilization on protein quality and amino acid content of sterilized vegetable baby foods. The outcomes showed that heating did not influence the total content in proteins. Nevertheless, after retort sterilization, the degree of total essential and non-essential amino acids was decreased significantly. On the contrary, ohmic heating did not show a significant impact on the extent of amino acid and can be used instead of conventional sterilization in vegetable baby foods in order to preserve the nutritional quality of proteins. Moreno et al. (2017) enriched apples with L-arginine under ohmic heating, vacuum impregnation/ohmic heating or conventional heating. The greater L-arginine addition was obtained in vacuum impregnation/ohmic heating followed by ohmic treatment and in conventional treatment, less addition of L-arginine was observed. This behavior was suggested to be associated with the acceleration of mass transfer in apple particles due to osmotic diffusion and hydrodynamic mechanisms. In another study, the protein content of canned artichokes blanched with conventional and ohmic heating was measured by Guida et al. (2013). They reported that protein content was decreased with storage time in ohmic and conventional cooked samples, but a higher rate protein loss was observed in conventionally cooked samples. After three-month storage, the proteins loss in conventional and ohmic blanched samples was 74.1% and 41.3%, respectively.

Apart from the preservation of nutrients, ohmic heating has shown to prevent the formation of carcinogenic compounds such as furan. Hradecky, Kludska, Belkova, Wagner, and Hajslova (2017) investigated the furan formation in ohmic and conventional retort sterilization of baby foods (vegetable and vegetable/meat). Furan was significantly decreased (70–90%) in ohmic-heated samples due to decreased degradation of furan precursor in ohmic heating. The fatty acids oxidation and Maillard reaction products were greater in samples sterilized by conventional heating compared to ohmic-heated samples.

1.2.2 Meat Products

Meat is a substantial part of our diet and provides protein, minerals, vitamins, fatty acids, and energy (Hashemi Gahruie et al., 2017; Toldrá, 2017). The proteins of meat have high biological value due to the similarity of amino acid (types and proportions) to those in human muscles. Moreover, meat contains all of the eight essential amino acids (lysine, leucine, isoleucine, methionine, phenylalanine, valine, threonine, and tryptophan), which are not synthesized in the human body (Purchas, Wilkinson, Carruthers, & Jackson, 2014). Oxidation of amino acids results in the development of carbonyl groups, which react with free amines of proteins to form amide bonds. These reactions negatively affect the nutritional quality and digestibility of meat proteins (Gatellier, Kondjoyan, Portanguen, & Santé-Lhoutellier, 2010).

Dai et al. (2014) measured the carbonyl contents of ohmic and water bath cooked pork meat under refrigerated storage. No significant differences were observed between ohmic and water bath cooked meat and all of the samples contained the same levels of carbonyls. Protein oxidation was also attributed to the reduction of free thiol groups, which were changed into disulfide bonds. The formation of disulfides promoted protein aggregation and negatively affected the nutritional quality of meat (Gatellier et al., 2010; Lund, Lametsch, Hviid, Jensen, & Skibsted, 2007; Santé-Lhoutellier, Astruc, Marinova, Greve, & Gatellier, 2008).

Cooking has remarkable effects on nutritive values of meat due to the occurrence of physicochemical reactions. One of the most important factors affected by heating is the oxidation of lipids, which negatively affects the quality and acceptability of meat products (Fuentes, Ventanas, Morcuende, Estévez, & Ventanas, 2010). Lipid oxidation promotes the formation of free radicals that are responsible for myoglobin oxidation (Kim, Huff-Lonergan, Sebranek, & Lonergan, 2010). Moreover, oxidation of fatty acids leads to the formation of a variety of low aroma threshold products such as aldehydes and ketones. These volatile compounds lead to off-flavor in cooked meat (Toldrá, 2017). Dai et al. (2014) determined the thiobarbituric acid reactive substances (TBARS)-values of ohmic and water bath cooked meat samples. The ohmic heated samples showed lower levels of lipid oxidation and a slower rate of increase in oxidation during storage. Non-heme iron, one of the main catalysts of lipid oxidation, was also lower in ohmic-cooked samples. Zell, Lyng, Cronin, and Morgan (2010a) reported similar findings for turkey samples after cooking by ohmic and conventional heating processes. Their results showed that ohmic-treated samples had lower lipid oxidation and sulfur-flavor-compound compared to conventional-heated samples. This might be due to the prolonged exposure of the outer layers of turkey meat to high temperature, denaturation of myofibrillar proteins and thermal degradation of membrane phospholipids under conventional cooking. In another study, δ-tocopherol was incorporated into beef patties cooked with impingement and ohmic heating. To control lipid oxidation, samples were assessed using an ethanolic carrier (Wills, Dewitt, Sigfusson, & Bellmer, 2006). The results revealed that ohmic-cooked samples contained significantly higher TBARS than impingement-cooked samples. Patyukov and Pacinovski (2015) applied conventional and ohmic heating on polyunsaturated fatty acids (PUFA) fortified cooked sausages. The results showed that conventional cooking led to an obvious deterioration of fat in sausages. Triglycerides were hydrolyzed and PUFA were oxidized during conventional heating. However, short heating time using ohmic technology decreased the deterioration of fatty acids and ohmic-treated samples showed significantly lower oxidation. The settings of the ohmic heater during heating had significant influences on the oxidation of lipids. In a study performed by Kim, Hong, Park, Spiess, and Min (2006), frozen pork patties were ohmically thawed under different power intensities and found that the TBARS increased proportionally to the power intensity, and induced lipid oxidation in pork patties.

Thawing is a critical stage to guarantee the microbial and nutritional value of food products. Several studies have confirmed that this operation must be carried out rapidly to prevent microbial growth and nutritional losses caused by leaching of soluble proteins (Roberts, Balaban, Zimmerman, & Luzuriaga, 1998). Duygu and Ümit (2015) compared the quality of meat samples thawed in a refrigerator, at room temperature or ohmic heating. The fastest thawing was obtained in the samples treated with ohmic heating. An increase in pH value and a decrease in a_w were observed with all thawing methods. However, the ohmic-thawed samples had the highest a_w value. Water activity depends on water loss and ohmic heating resulted in the least weight loss. Since the loss of water-soluble vitamins and proteins were in coincidence with water loss, ohmic thawing could preserve the nutritional quality of thawed foods. Thus, ohmic heating was suggested as an efficient technique in thawing. The influence of ohmic heating on heavy metals has also shown promising results. Bastías et al. (2015) assessed the influence of ohmic heating and blanching at different temperatures (50, 70 and 90 °C) on lead (Pb) and cadmium (cd) content in Chilean blue mussel (*Mytilus chilensis*). The results showed that Pb and Cd content in fresh mussels were reduced by ohmic heating and the greatest reduction was observed in ohmic-treated samples at 90 °C.

1.2.3 Dairy Products

Dairy products are great sources of beneficial nutrients such as minerals and vitamins, which improve bone health, prevent dental cavities and osteoporosis. They also reduce the blood pressure and risk of colon cancer (Wells, 2001). These nutritional benefits make milk an important food item in our daily diet. The composition of fatty acid in milk, predominantly polyunsaturated fatty acids (PUFA) have also significant effects on nutritional properties of dairy products (Hurtaud & Peyraud, 2007). Heating conditions may have substantial influences on the extent of these components. Similarly, the findings of Pereira, Martins, and Vicente (2008) revealed that the profile of short-chain and medium-chain free fatty acid was not affected by heating operation and no significant variations were observed between raw, conventional and ohmic pasteurized milk. Pereira et al. (2016) determined the effects of ohmic heating on unfolding, denaturation and aggregation kinetics of WPI proteins. Their results showed that ohmic heating increased the formation of linear structured protein aggregates and their size was impacted by the electric field intensity. They also found that these aggregates could be used for the encapsulation of bioactive compounds. In another study, Roux et al. (2016) used steam injection and ohmic heating for sterilization of liquid infant formula and compared their effects on soluble proteins and vitamin C. The degree of soluble protein denaturation was similar for both heating methods, while ohmic heating better-preserved vitamin C. Irudayaraj, McMahon, and Reznik (2000) stated that the extent of protein denaturation in the ohmic-sterilized milk was significantly lower than commercial UHT milk. Castro, Macedo, et al. (2004) examined the influence of conventional and ohmic heating on milk proteins using polyacrylamide gel electrophoresis (PAGE). The results showed that raw, conventional and ohmic treated samples presented the same electrophoresis pattern. Roux, Courel, Ait-Ameur, Birlouez-Aragon, and Pain (2009) investigated the occurrence of Maillard reaction in a model infant formula under ultra-high temperature (UHT) by ohmic heating. Five heating temperatures (100−140 °C) were selected and samples were taken during the operation (heating and holding) and examined for early Maillard reaction products (MRPs), such as furosine, advanced products such as advanced glycated end products (AGEs) and carboxymethyllysine (CML) and final products such as melanoidins. The results showed that Maillard reactions in model infant formula were highly dependent on time-temperature treatment and the amount was increased with ohmic heating temperature and time.

1.3 Textural Properties

The texture is one of the most significant quality characteristics of foods. The textural parameters of food products such as fruits, vegetables, meat and meat products, cereal-based foods, and cheeses are determinant in palatability of these food materials. They have also remarkable influences on their price. Hence, reaching the desired textural quality of food products has major financial importance. Usually, the food processing operations are designed to change the textural properties of food products and dominantly these changes are directed to weaken the food structure and make it easier to masticate. However, sometimes the textural changes are inadvertent and usually undesirable (Bourne, 2002). Ohmic heating technology has been extensively investigated and used in a variety of food processing operations and the results have revealed that it can modify the textural properties of food products.

1.3.1 Fruits and Vegetables

The structural integrity and textural quality of fruits and vegetables are mostly related to the middle lamella, cell wall and the turgor within cells (Waldron, Parker, & Smith, 2003). Among these parameters, plant cell walls play an important role in the textural properties of plant-based foodstuff (Van Buren, 1979). The plant cell wall consists of three major polysaccharides namely cellulose, hemicellulose, and pectin. There are also varying levels of structural proteins and phenolic compounds in the cell wall. The cellulose provides the microfibrillar component of the cell wall, while hemicelluloses are bound to cellulose and pectin by hydrogen linkages. Postharvest operations and storage have dramatic influences on structural integrity and biochemical composition of plant cells. During most of the food processing operations, the texture firmness and structural integrity of cells are lost and lead to loss of turgor and crispiness. Generally, processing or storage does not notably influence the firmness caused by the cellulose and hemicellulose. However, pectin could be influenced by the enzyme-catalyzed reactions during thermal treatment, which causes remarkable changes in fruit and vegetable products.

Ohmic heating leads to obvious damage to the cell membranes and enhances the mass transfer processes. Moreover, membrane rupture significantly increases the electrical conductivity of plant tissues and influences the heating process. Shynkaryk, Ji, Alvarez, and Sastry (2010) investigated the ohmic heating of peaches at an electric field strength of 60 V/cm and frequencies between 50 Hz and 1 MHz. The textural measurements of samples heated at lower frequencies showed a significant loss of textural strength. They stated that the application of a low-frequency electric field causes the cell membrane electroporation, increases the electrical conductivity of the product, and increases the texture-softening rate. Generally, the texture relaxation data showed even higher stages of tissue damage at low frequency. Thus, high-frequency ohmic heating would minimize the texture degradation of peach tissue. They reported that combination of operation parameters (200 kHz at 60 V/cm to 65 °C for 8 s) minimized the textural damage of peaches during the thermal preservation. The study carried out by Olivera, Salvadori, and Marra (2013) focused on the influences of ohmic heating on textural properties of fresh potatoes, carrots and apples under 1100, 2200, and 3300 V/m electrical field gradient. The authors compared the results with the raw untreated samples. They cut the samples into cylinders (h = 9.0 mm, d = 30 mm) and ohmically heated them for 60, 120, 180 or 240 s. The compression test of the samples treated by ohmic heating differed from raw samples for all cooking conditions and firmness was reduced with the heating time. The electric field intensity had also a great influence on the textural properties. In potato and carrot, significant firmness disintegration was observed only for the electric field strength of 2200 V/m and higher. However, apple samples were more sensitive and exhibited an obvious firmness-decreasing trend with the electric field strength. The differences in texture softening of these products can be described by the differences in their tissue structure, cell size and the amount of air cavities.

The utilization of ohmic heating for blanching of artichokes was investigated by Guida et al. (2013) and compared with conventional heating. The authors concluded that the texture of the artichokes blanched by the conventional method was not homogenous. The core areas showed lower texture softening but the outer part was over-processed and excessively softened. This could be attributed to the non-uniform heating of artichokes due to low heat transfer by conduction in conventional blanching. They also found that the samples treated by ohmic heating offered lower hardness compared to those processed by conventional heating due to higher heating rate in ohmic treatment compared to conventional heating. Kamali and Farahnaky (2015) compared the textural properties of ohmic, microwave and conventionally cooked radish, cabbage, potato and turnip by texture profile analysis. The ohmic heating was performed at 220 and 380 volts. Ohmic heating at 380 V had greater texture softening effects for all of the studied vegetables in the order of radish > turnip > potato > cabbage. In contrast to microwave and conventional cooking, the cohesiveness of samples was increased in ohmic heating with cooking time. Cooking regardless of heating method increased the springiness. However, ohmic heating had greater effects on this parameter, which could be due to limited structural damage Chiavaro, Barbanti, Vittadini, and Massini (2006). Ohmic-cooked turnips presented a more compact structure with smaller pores compared to other heating methods. However, conventional and microwave cooking caused structural damage and wall thinning. In another study by Farahnaky, Azizi, and Gavahian (2012), the effects of ohmic, conventional and microwave heating on the textural parameters of red beet, carrot, and golden carrot were examined by texture profile analysis (TPA) at different heating times. They found that ohmic heating not only caused more texture softening rates but also the final hardness, gradient and compression energy of ohmic-heated samples were significantly lower than those of other treatments. Jittanit et al. (2017) found the same results for rice samples. They compared the ohmic cooking of rice with the conventional heating in an electric rice cooker. They used four types of rice samples including two varieties of white rice (KDML105 and Sao Hai), brown rice, and germinated brown rice (KDML105). They found that it is possible to ohmically cook all types of rice by using salt solution (0.1 M) in the mixtures to increase the electrical conductivity. The electrical energy consumption in ohmic cooking was approximately 73–90% of energy consumed in the electrical rice cooker. The texture of the samples cooked by ohmic heating was meaningfully softer than the samples cooked by electric rice cooker and the extent of difference was dependent on the rice type.

1.3.2 Meat Products

The texture is one of the most important quality characteristics of meat and meat products and depends on some factors such as the properties of myofibrils and connective tissues, the pH, and the fat content and its distribution. The textural properties of meat can be modified significantly by changing the conditions of refrigeration, storage or cooking (Mathoniere, Mioche, Dransfield, & Culioli, 2000). Most heating operations applied in meat processing are based on convective, conductive, and/or radiative mechanisms from a heated medium (e.g. water, air, oil, etc.) to the meat product. However, it may take a long time to conduct enough heat into the core of meat products and it causes over-processing in most of the parts of the product, which negatively affects the quality (Wills et al., 2006). Therefore, during the past few years, alternative heating techniques such as ohmic heating have gained importance in meat processing and several research projects have been performed to evaluate the suitability of ohmic heating for meat and meat products processing. Some of these studies are summarized in Table 1.2. Most of these findings revealed that the ohmic-cooked samples had a firmer texture than the conventional-cooked ones.

The generation of high temperature in ohmic cooking results in more collagen shrinking and toughening of meat (Dai et al., 2014). Greater water release and more extensive protein denaturation in ohmic heating have been reported to increase the firmness of meat products (Zell et al., 2010a). Moreover, ohmic treated samples had more uniform structure compared to the conventional-cooked samples. The main reason for this behavior is that in ohmic heating, the heat is generated throughout the samples homogeneously and a uniform protein network is formed within the product, which results in a firm and uniform microstructure. On the contrary, during conventional cooking of meatballs in hot water, the heat was not transferred to all parts of the sample simultaneously; hence, a temperature gradient was formed within the sample and led to a heterogeneous structure. Engchuan et al. (2014) reported that conventionally cooked pork meatballs had a heterogeneous structure with cracks inside its matrix. Ohmic heating has also been applied for seafood processing and has increased their firmness due to the rapid inactivation of endogenous proteinases, which lead to further retention of undamaged myofibrillar proteins and improves the gel network structure. Also, the uniform unfolding of myofibrillar proteins in ohmic heating improved the textural properties of ohmic-heated seafood (Chai & Park, 2007; Tumpanuvatr & Jittanit, 2012). However, samples treated with lower voltage gradient showed higher breaking force. Apparently, proteinase inactivation is not the only factor affecting the gel structure and gel network also depend on the aggregation of proteins. When high voltages are applied, the heating time is very short, and the gel network will not develop properly, as a result, the textural parameters would decrease (Foegeding, Allen, & Dayton, 1986). In another study, Özkan et al. (2004) studied the cooking of hamburgers with a combination of ohmic and conventional heating as well as conventional heating and observed no significant differences in the quality and the mechanical properties of the obtained samples.

Table 1.2 Influence of ohmic heating on textural properties of meat products

Product type	Process condition	Textural test type	Result	Reference
Frankfurters	In ohmic heating, the voltage gradient was 3 and 5 V/cm at 50 Hz supply. The conventional steam cooking was performed at 80 °C for 2 min	Texture profile analysis (TPA)	No significant difference occurred between samples cooked by steam or ohmic methods in hardness, energy, cohesion, gumminess, and chewiness	Shirsat, Brunton, Lyng, McKenna, and Scannell (2004)
Hamburger patties	In ohmic heating, voltage was remained constant at 50 V and current started from zero and reached 13 A. While in conventional cooking samples were placed between the heated plates of the grill at 180 °C	Compression test	The mechanical properties of the samples cooked by ohmic or conventional heating are very similar	Özkan, Ho, and Farid (2004)
Ground beef	Ground beef samples with different fat contents (2%, 9%, and 15%) were ohmically (20, 30 and 40 V/cm) and conventional heating was performed on the grill (90 °C) for 18 constant periods (90 s) until reaching a center temperature of 70 °C	Warner–Bratzler shear force	Ohmically cooked ground beef cylinders were firmer than conventionally cooked samples and the voltage gradient did not affect the quality of cooked meat. The ohmic cooking time was increased as the fat content increased due to the poor electrical conductivity of fat	Bozkurt and Icier (2010)
Beef cuts	Samples were thawed from 10 to 18 °C by applying different voltage gradients (10, 20 and 30 V/cm) during ohmic treatment whereas conventional thawing was applied at constant temperature (25 °C, 95% RH)	Texture profile analysis	Ohmic thawing resulted to obtain harder thawed beef cuts than conventionally thawed ones	Icier, Izzetoglu, Bozkurt, and Ober (2010)
Turkey meat	Intact turkey meat was cooked using low-temperature long time (LTLT) and high-temperature short time (HTST) protocols in a combined ohmic/convection system and compared to conventional steam cooking	Texture profile analysis (TPA)	No significant differences between ohmic LTLT and mean values of conventional treatments were found, however, the ohmically cooked HTST displayed a significantly firmer texture	Zell et al. (2010a)
Whole beef muscle	Samples were cooked in a combined ohmic/convection heating system to low (72 °C, LTLT) and high (95 °C, HTST) target end-point temperatures. A control was also cooked to an end-point temperature of 72 °C at the coldest point	Warner-Bratzler shear force	Warner-Bratzler shear force values showed no significant differences between treatments indicating a similar level of tenderness amongst the products	Zell, Lyng, Cronin, and Morgan (2010b)

(continued)

Table 1.2 (continued)

Product type	Process condition	Textural test type	Result	Reference
Surimi	For ohmic heating, the samples were heated to 90 °C at a frequency of 10 kHz at voltage levels of 100 and 250 V, corresponding to a voltage gradient of 6.7 and 16.7 V/cm respectively. For water bath heating. Samples were heated at 90 °C for 30 min	Penetration test	Ohmic heating with a voltage gradient of 6.7 resulted in firmer gels compared to 16.7 V/cm and the breaking force and deformation of ohmic heated samples were higher than those heated in a water bath	Tadpitchayangkoon, Park, and Yongsawatdigul (2012)
Pork meatball	Heating until the center temperature reached 74 °C in a boiling water bath at a rate of 4.9 °C/min and 4.9 °C/min or 24.5 °C/min in ohmic heating at 72 V	Yield strength	The texture of ohmically-heated meatball (at the heating rate of 4.9 °C/min) was stronger than that of ohmically-heated (at a heating rate of 24.5 °C/min) and conventionally-heated meatballs and the conventionally-cooked meatballs had the softer texture	Engchuan, Jittanit, and Garnjanagoonchorn (2014)
Pork meat	The pork meat samples were ohmically-cooked to a minimum end-point temperature of 95 °C at the cold spot by applying a 10 V cm^{-1} voltage gradient. While the conventional cooking time was approximately 83 min at 95 °C	TPA analysis	ohmically-cooked samples had significantly higher hardness, chewiness, and gumminess but same values of springiness	Dai et al. (2014)
Shrimp	Shrimps were cooked until the cold-spot reached 72 °C either by steaming in a conventional steamer or in an ohmic heating cell of 50 Hz at 120 V and 15A	Warner-Bratzler shear force (WBSF) and Kramer	The application of ohmic heating to shrimps did not affect their texture when compared to conventional cooking methods	Lascorz, Torella, Lyng, and Arroyo (2016)
	Maximally supply a 230-voltage using alternating current (60 Hz, sinusoidal)	Texture profile analysis (TPA)	No significant changes were seen for the textural parameters of different samples and shrimps achieved a comparable quality compared to conventional heating processes reported in the literature	Pedersen, Feyissa, Brøkner Kavli, and Frosch (2016)

Ohmic heating can be a promising option for thawing and has been proven to bring about fewer textural changes compared to conventional thawing. This behavior can be attributed to the higher denaturation rate in the myofibrillar proteins using the conventional method, which causes softer thawed products (Icier et al., 2010). The histology of beef cuts proposed by Icier et al. (2010) also confirmed these results and more deformation and loss of collagen fibrils were detected in beef cuts thawed by the conventional method. These changes occurred due to the contraction of myofibrils or denaturation of collagen fibril network.

1.3.3 Dairy Products

The application of ohmic heating is expected to have remarkable effects on the textural properties of dairy products. However, only a few papers have explored the influence of this technique on the textural properties of dairy products. The findings of Pereira et al. (2016) showed that the application of ohmic heating on whey protein isolate (WPI) resulted in the formation of linear structured proteins that had the potential to form gels and to be used as a thickening or gelling agent. In another research, Icier (2009) used ohmic and water-bath techniques for the heating of reconstituted whey solutions. It was found that the consistency coefficients of whey solutions decreased by increasing the thermal treatment time in both heating operations. They also reported that fast heating caused a delay in some processes such as the degradation and the gelation. It was concluded that the electrochemical reactions occurring during ohmic heating might be responsible for these textural changes.

1.4 Sensorial Properties

Heating operations such as ohmic heating may induce significant differences in the sensory attributes and acceptability of different food products. For instance, Christian and Leadley (2006) studied the impact of ohmic treatment on the quality of different products such as shelf-stable milk, soups, puddings, fruit juices, fruit concentrates, and liquid egg products. Rapid and uniform heating was observed with a decreased influence on the organoleptic properties of products. The effects of ohmic treatment on the sensorial properties of different food products are discussed in the following sections.

1.4.1 Fruits and Vegetables

Color, flavor, and texture are important quality characteristics influencing the consumer acceptance and sensory perception of fruits and vegetables (Oey, Lille, Van Loey, & Hendrickx, 2008). These parameters may be influenced by heat treatments such as ohmic heating. Tumpanuvatr and Jittanit (2012) compared the sensory attributes of conventionally- heated and ohmic-heated pineapple and orange juices. The results demonstrated that both heating systems deteriorated the sensorial attributes of fruit juices at the analogous level and the quality of processed juices was not dependent on the heating systems. In other words, the existence of an electric field in the ohmic system did not bring about an additional impact on the juice quality. In a research conducted by Dima, Istrati, Garnai, Serea, and Vizireanu (2015), a sensory evaluation by a group of seven panelists evaluated the appearance, color, taste, odor, and mouthfeel of fresh, conventional pasteurized and ohmic pasteurized vegetable juices. Ohmic pasteurized juices obtained a higher score than conventionally pasteurized juices and concluded that ohmic pasteurization has not a negative effect on the flavor of vegetable juices.

Color is one of the most important sensory attributes and has been extensively applied for quality evaluation of food products. Kim, Ryang, Lee, Kim, and Rhee (2017) exposed the apple juice samples to ohmic heating (frequency = 25 kHz, electric field strength = 26.7 V/cm) at 85–100 °C for 30–90 s and compared the results with the conventional heating. They found that the color values ($L*$, $a*$, and $b*$) of apple juice remained almost unchanged in all treatments, but the lightness and yellowness of ohmic-treated samples at 100 °C for 60 s were decreased. Kim et al. (2017) measured color parameters of $L*$, $a*$, and $b*$ and lycopene content to assess the quality of tomato juice. The results showed no significant changes between the color parameters and lycopene content of the treated and untreated samples. Aamir and Jittanit (2017) compared the influence of ohmic heating and conventional heating on Gac aril oil extraction. They reported that the amount of lycopene and β-carotene of Gac aril oil were increased by the extraction with the ohmic heating method. The color parameters of the extracted oil and residue obtained by conventional and ohmic heating were remarkably different from each other. The SEM images showed that ohmic heating caused more rupture on the cell wall of the Gac aril powder compared to conventional heating and the ohmically extracted oil was redder than that of the conventionally extracted one. This was reported to be due to the ability of the ohmic system to extract higher levels of red pigments (lycopene and β-carotene) from the Gac aril to the hexane solvent.

In a study by Jaeschke et al. (2016), the effect of ohmic heating on acerola pulp was studied. Fresh acerola pulp had an orange/red color, but the red color was lost and turned less intense during thermal treatment. The $a*$ values were greater at lower heating temperatures (80 and 85 °C) which can be attributed to the anthocyanin contents. Anthocyanin and ascorbic acid interaction cause their degradation and the occurrence of nutritional and color changes (Choi, Kim, & Lee, 2002). A slight variation was observed in $b*$ value after 60 min of conventional or ohmic heating, which was attributed to carotenoid concentration in acerola. The results revealed that the carotenoid content was not affected by heating. The $L*$ values decreased during heating due to the ascorbic acid degradation and non-enzymatic browning reactions. Mercali et al. (2014) measured the effect of electric field frequency and heating time on color parameters of acerola and observed a decline over the time for all treatment conditions, which indicated color changes during heating. Higher color changes were observed at low electric field frequency (10 Hz), which might be due to the incidence of electrochemical reactions. The color changes in ohmic blanched artichokes were measured by Guida et al. (2013) and the results showed that the brightness (L^*) of ohmic blanched artichokes was enhanced by increasing the blanching time. However, L^* values were significantly decreased in conventionally blanched samples due to the incidence of browning reactions. Moreover, both blanching methods decreased hue angle and chroma and increased $\Delta E*$ values. The fresh-like color of ohmic-heated samples was due to the uniform and fast heating rate, which inactivated the enzymes in a short period of time. The color of artichoke was well preserved in ohmic heating, whereas hot water (conventional) blanching changed their color from yellow/green to brownish/green.

In addition to the effect of ohmic heating on the color of fruits and vegetables, several studies evaluated the effect of this processing on flavor. For instance, a better quality of strawberry jam in terms of color, flavor, and vitamin C content was reported using ohmic heating compared to microwave preservation technique, which was suggested to be due to the uniform and rapid heating and the absence of hot surfaces in ohmic heating apparatus (Avasoo & Johansson, 2011). Leizerson and Shimoni (2005a) investigated the impact of pasteurization of orange juice using ohmic heating in a very short time on its shelf life, which was compared to conventional pasteurization. In order to evaluate the quality of the obtained orange juice, the following parameters were studied: pectinesterase (PE) activity (i.e. cloudiness), ascorbic acid concentration, color, and flavor compounds (namely octanal, pinene, decanal, limonene, and myrcene). No significant difference was noticed between the two heating methods regarding PE activity and vitamin C concentration, although orange juice treated by ohmic heating appeared less cloudy. Similar effect on microbial load was observed for both heating methods during 105 days of storage. However, according to the sensory analysis, flavor in samples treated by ohmic heating was retained almost twice longer than the samples heated conventionally over a period of 100 days. The results showed that the characteristic flavor compounds were considerably higher in ohmic heated samples compared to conventional-treated juices (Leizerson & Shimoni, 2005b). Thanks to the presence of flavor compounds at similar levels, panelists were not able to differentiate between fresh and ohmic-treated juices. Similar results were observed by Anderson (2008) who demonstrated that the better flavor retention by ohmic heating was due to the shorter residence times and the absence of hot surfaces.

There are limited studies about the effects of ohmic cooking on other sensory attributes of plant-based products such as tenderness and crispiness. Hence, further studies need to be conducted to have a deeper understanding of the effect of this technique on the sensorial attributes of fruits and vegetables.

1.4.2 Meat Products

Sensory characteristics such as flavor, color, tenderness, and succulence have substantial influences on the acceptability of meat and meat products and can be affected by the cooking method. In ohmic processing, heat is distributed more rapidly and even throughout the product and result in improved flavor retention and structural integrity than the conventional heating methods. Shirsat et al. (2004) stated that the sensory evaluation of meat emulsion batters cooked by steam and ohmic heating had no perceivable difference. However, the study conducted by Zell et al. (2010b) exhibited that the color of ohmic-treated high-temperature short time (HTST) beef samples were more acceptable than low-temperature long time (LTLT) and conventionally cooked beef samples for the panelists. The ohmic heating offered a more uniform appearance, which was appreciated by the panelists. Moreover, the HTST treated samples were less juicy and firmer than the other products. These results were attributed to the higher cooking loss and end-point temperature in HTST samples. Accordingly, color and succulence of LTLT ohmic-cooked turkey meat were preferred to conventionally steam cooked samples, whereas the HTST treated samples were slightly firmer and less succulent. The conventional and HTST ohmic-heated turkey meat samples had a stronger odor intensity compared to LTLT-treated turkey meat samples (Zell et al., 2010a).

Generally, the color changes during cooking are due to myoglobin degradation through oxygenation, oxidation, and reduction reactions (Liu & Chen, 2001). Moreover, Maillard reaction has a significant role in surface color development in cooked meat products. In a study conducted by Engchuan et al. (2014), the influence of ohmic heating on color parameters of meatball was investigated. The hue angle and redness of conventional-cooked samples were higher than the ohmic-cooked counterparts. Similar results were reported by Bozkurt and Icier (2010) and Zell, Lyng, Cronin, and Morgan (2009) in ohmically and conventionally cooked beef muscles. They suggested that more browning reactions took place in the conventional-cooked meatballs compared to the ohmic-cooked samples. In the conventional method, the heat was mainly transferred by conduction and the outer layer of the meatballs would be much hotter than the core area. Consequently, browning occurred at the surface of conventional-cooked meatballs due to the high temperatures of the outer layer. However, in ohmic heating, the uniform temperature distribution inside the sample led to the formation of more homogeneous color and prevented the surface browning. Thus, the samples cooked by ohmic heating did not present a cooked crust, which is one of the disadvantages of ohmic cooking. Zell et al. (2009) also found that the samples heated at a slower heating rate had a slightly higher lightness and a^* and b^* values, which were lower than the samples heated at higher heating rates. These differences could be due to the dissimilarities of protein gel in meatball developed during fast or slow heating.

Dai et al. (2014) evaluated the color parameters of ohmic and water bath cooked pork and observed significantly lower a^* values but higher L^* and b^* values in conventionally cooked meat. Longer cooking time and higher exposure to oxygen in conventional cooking may induce increased oxidation of lipid and myoglobin pigments and inducing discolorations in conventionally-cooked meat (Fuentes et al., 2010; Ganhão, Morcuende, & Estévez, 2010). Shirsat et al. (2004) compared the color of ohmically and steam-cooked meat emulsion batter. Color assessments revealed that ohmic-cooked samples had lower hue angle and higher

$a*$ values compared to the steam cooked samples, while the panelists did not perceive the differences in the sensory evaluation.

Chai and Park (2007) determined the characteristics of fish proteins cooked with protein additives or starches under ohmic heating at 55 and 200 V. They found that surimi-starch gels that were ohmically cooked at 200 V were the most translucent samples after overnight refrigeration. This behavior might be due to the rapid heating time and reduced leaking of amylose chains into the gel system. Tadpitchayangkoon et al. (2012) reported substantial differences between ohmic and water-bath heated surimi gels. These changes could be attributed to rapid and short heating time in ohmic heating, which limited the browning reactions and preserved the whiteness of tropical surimi gels compared to water bath cooking. Moreover, the lightness depended on protein network structure and the differences in water-protein interactions under ohmic and water-bath heating resulted in changing the lightness of surimi gels.

Traditionally, meat emulsions are treated by water immersion or steam cooking. Lascorz et al. (2016) cooked shrimps by ohmic and steam cooking and found that all the color parameters (L^*, a^* and b^* values) of shrimp samples increased after cooking due to the release of astaxanthin from the carotenoproteins after denaturation. However, ohmic cooking of shrimps exhibited fewer color changes compared to steam cooking. This was suggested to be due to the short cooking time under ohmic heating.

1.4.3 Dairy Products

The flavor of milk is a key parameter of its quality and acceptance. Milk has a slightly salty and sweet taste owing to the presence of salts and lactose. Good quality milk has a bland but typical flavor with a nice mouthfeel (Thomas, 1981). Due to the bland flavor of milk, it can be the carrier of off-odors and flavors such as cooked, oxidized and rancid flavors (Azzara & Campbell, 1992). These unpleasant changes may occur during heating operations. The disruption of the milk fat globule membrane increases the accumulation of free fatty acids in the milk and leads to the formation of rancid flavors. Ohmic heating minimizes the generation of off-flavor compounds in milk and milk products because it does not promote more release of free fatty acids (FFA) (Ramaswamy, Marcotte, Sastry, & Abdelrahim, 2014). Irudayaraj et al. (2000) explored the impact of ohmic heating at different temperatures (135, 145, and 155 °C) and holding times (0.5 and 4.0 s) on UHT milk. They performed sensory evaluations and identified the volatile flavor compounds with gas chromatography (GC)-mass spectrometry (MS) to determine the influence of ohmic heating on organoleptic properties of UHT milk. They found significantly lower sour and stale flavors in the ohmic-heated samples compared to commercial UHT milk. In a study conducted by Roux et al. (2009), the color changes of infant formula during ohmic heating were measured. The lightness was decreased by temperature and heating time. However, increasing the temperature and heating time enhanced the *a** and *b** values, indicating that the redness and yellowness increased, which resulted in changing the color of the samples into brown. However, the results reported by Roux et al. (2016) revealed that the color of liquid infant formula remained unchanged with ohmic sterilization compared to that obtained after steam injection.

1.5 Advantageous and Challenges of Using Ohmic Processing on Food Quality

Application of ohmic processing has been reported to have several advantages over conventional treatment (Biss, Coombes, & Skudder, 1989; Khajehei et al., 2017). The foods objected to ohmic heating are uniformly heated in a well-controllable and rapid started process with the least thermal degradation. The lack of hot surface and its associated disadvantageous such as caramelization, fouling, and discoloration are among other attracting aspects. For foods in a container, the temperature in conventional heat processing must be high enough at the container walls to ensure sufficient heating of cold point (e.g. the center of big particulates) and guarantee the appropriate shelf life. This high-temperature can cause over processing and quality loss of the fluid (food) in contact with the walls. Due to the similar heating rate of particulates and the surrounding liquid, ohmic heating has overcome this limitation of conventional processing (Mojtahed Zadeh Asl, Niakousari, Hashemi Gahruie, Saharkhiz, & Mousavi Khaneghah, 2018). Because of the electrical resistance of the food components, heat is generated within the food as the electricity passes through it and both the liquid and solid parts will be warmed-up at the same time. The energy consumption is lower in the ohmic system and most of the energy is consumed at the control system and wires. The efficiency of ohmic heating is higher than 95% at most of the frequencies and using higher frequencies causes higher loss. Providing the high temperature using high-pressure steam (at a temperature of 200 °C, to increase the temperature of the product up to 180 °C, needs a pressure of 15 bar) in conventional processes is costly and limits its uses in the common processes. The high temperature (160–300 °C) used for sterilizing and partial hydrolysis of food waste before performing anaerobic digestion could be provided by ohmic heating. Flash depressurization is another way that can partially hydrolyze the particulates and so increase the volume of produced gas and also increase the bioavailability of nutrients after digestion.

The advantages of ohmic heating over conventional heating are summarized as:

- Rapid heating in short times for particulates and liquid, which can be usually achieved. This leads to protect vitamins and flavors compared with conventional heat exchangers.
- Low-temperature surfaces, resulting in a reduced risk of food damage from burning or over processing.

- Processing particulates or high solids' content. Low shear keeps particulate appearance and shape. Particulate products up to 3 cm are suitable for ohmic processing.
- High efficiency: 95% of the produced energy is transferred into the food.
- Highly controllable: suitable start-up and shutdown performance. Can be quickly joined with existing control systems.
- Robust/suitable resistance to fouling/good maintenance: automatic cleaning with standard clean in place operations effective due to minimal fouling of surfaces. Heaters can contain cooled surfaces for further mitigation into fouling with some foods.
- Suitable for foods with high viscosity.
- Suitable for high-temperature processing (e.g., working temperatures over 150 °C).
- Low-pressure and low shear drop all over the heaters.
- Can reduce the inefficiencies and infrastructure associated with the steam system.

The application of ohmic heating has several limitations that are summarized as:

- It is only suitable for foods with good electrical conductivity.
- Usually applied for those foods, which are pumpable and so ensure sufficiently suitable current transfer to and from ohmic electrodes.
- Designed units are mainly suited for a specific food conductivity range, while the design is much more difficult for extreme working conditions.
- The electric nature of this heating system means that the sites considering ohmic systems will need a good electrical supply, and the electrical energy cost compared with fuels must be taken into account when considering the ohmic system.

1.6 Conclusions

The results of these studies showed that ohmic heating is faster, less aggressive, and may improve the overall quality of products compared to the conventional heating systems. The high quality in ohmic-heated food products is attributed to the uniform heat generation throughout the product, which minimizes the overcooked areas in foods and preserves their texture, color, taste, and nutrients such as fatty acids, vitamins, amino acids, and phenolic compounds. Hence ohmic heating can be an appropriate alternative to conventional heating allowing food manufacturers to acquire high-quality products. However, the process variables such as temperature, voltage gradients, electric field frequency, and heating time play a dominant role in the quality of ohmic-heated samples. Therefore, these parameters should be selected cautiously to reach the desired quality in ohmic treated food products.

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