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REVIEW ARTICLE

Ohmic heating technology for food processing: a review of recent developments

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ABSTRACT

The novel technique of heating that utilizes the natural electrical resistance of the food material to produce heat and where electrical energy is converted into thermal energy is called ohmic heating. It can be considered as efficient and alternating thermal processing technology wherein food sample is placed between electrodes having a role of resistance in the circuit. This process involves heating of food by passing electric current throughout materials. Ohmic heating has a good capability to achieve fast and consistent heating in food materials, resulting in microbiologically secure and better quality foods. Compared to traditional heating techniques, this process has lesser heating durations while preventing hot surfaces and could decrease temperature gradients. Ohmic heating presents a broad range of vital applications like extraction, fermentation, cooking, evaporation, thawing, pasteurization, sterilization, aseptic processing, blanching, semi meatball cooking and drying process. This process results in minimal structural changes in product configuration and hence the nutritional value is preserved and yields exceptional processed quality food products in lesser operating time. This is uniform and rapid heating method where the heating rate depends solely on the field strength electrical conductivity. It is very essential to have the vital knowledge of mathematical models of ohmic heating and electrical conductivity of food materials in order to design the ohmic process optimally.

Keywords: Ohmic heating; conductivity; conventional heating; pasteurization; blanching; gelatinization

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INTRODUCTION

Heating is a vital step in the processing of foods and heat treatment is the most ordinary technique in the food sector for cooking, preservation, and enzymatic deactivation of raw materials. Traditional heating of food needs heat energy to be produced externally and then passed to the food based on the mechanism of conduction, convection and radiation. Traditionally heating of food results in very heterogeneous heat treatment and remarkable textural and microbial quality loss of foods (Icier, 2012).Heating food in a homogeneous manner is an indispensable factor to prevent food-borne diseases. Conventionally heating of food involves use of high temperature to inactivate food enzymes and destroy microorganisms resulting in adverse effects on nutritional content and sensory parameters. Thus, there is a significant need for techniques that result in uniform and rapid heating leading to desired microbial lethality without hindering or destroying the wholesomeness of product quality. Ohmic heating is an alternative heating method that has emerged in the past 20 years and has a growing demand for an alternative newer heating technique. Even though food fortification can prevail over nutritional degradation, sensorial attributes are difficult

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to retain. Today's consumer demands minimally processed and safe foods with natural flavor and ingredients, and preserved health-promoting nutrients. Ohmic heating or joule heating, electrical resistance heating, electroconductive heating or direct electrical resistance heating is the heating technique where heat is produced internally in the food being processed owing to its natural electrical resistance. Simply ohmic heating is an alternative and novel thermal processing technology wherein food materials are heated by passing an electric current through materials. According to Fryer et al. (1993), an ohmic heater is an electrical heating system that involves food's electrical resistance to produce heat. The most significant factors in the applicability of ohmic heating are the electrical field strength and electrical conductivity of the material. As electric current flows through the fluid, ohmic heat is produced directly instead of being transferred to fluid from a hot surface (Figure 1). Due to the uniform and rapid heating, this process results in high quality and safe foods. There are many applications of ohmic heating like evaporation, thawing, cooking, extraction, fermentation, blanching, pasteurization, sterilization, aseptic processing and in space missions of longer durations or the military field (Tankesh Kumar, 2018).

In the ohmic heating process, food components act as electric circuit elements where an alternating current (AC) flows, producing heat in the food based on its inherent effects of electrical resistance where the generated energy directly is proportional to the square of the electric field strength and the electrical conductivity of the product (De Alwis and Fryer, 1990; Ruan et al, 2001). Ohmic heating reduces the longer duration treatment time thereby causing minimal thermal damage to pigments, vitamins and some other elements (Sastry, 2005). In ohmic heating, high temperatures in particulate foods than liquid could be attained without fouling risk on heat transfer surface and burning of foods which is not possible for traditional heating methods. Ohmic heating has been proved feasible for a wide variety of food products viz., milk, fruit- vegetables and their products, meat products, seafoods, flours and starches etc. (An and King, 2007). Ohmic heating can validate any commercial process by producing high-quality food and safe foods. This uniform and rapid heating technique possess huge number of potential applications existing in food industries, chemical processing, waste utilization, water distillation, etc (Sakr and Liu, 2014). The main aim of the current review is to provide general information about the ohmic heating technique, with emphasis on its application in different aspects of food. This review is categorized into different divisions: (1) Common information about ohmic heating, (2) History and the principle of ohmic heating (3) Innovative uses of ohmic heating with a different application (4) Concluding remarks and future perspectives.

HISTORY OF OHMIC HEATING

The ohmic heating concept is not a newer concept, it dates back to 1897 (Jones, 1897). In 1841, James Prescott Joule found that the transfer of electric current produces heat, hence this process is also referred to as Joule heating. The potential uses of ohmic heating were first found in the late 1920s as a flourishing commercial method, known as the "Electro-Pure" method (Anderson and Finkelstein, 1919). In the 1930s, around fifty industrial electric milk sterilizers were in process but then they disappeared in the 1950s (Getchell, 1935). In the early 20th century, this method was used extensively where the electric pasteurization of the milk products and various other foods was attained by passing fluids between plates with a significant difference in voltage difference among them (Alwis and Fryer, 1990; Palaniappan and Sastry, 1991). By using ohmic technology as the heating method of blanching to prevent the enzymatic discoloration of potato was described by Schade (1951). It was believed that the fatal effect can be due to electricity. However, the technique practically disappeared in subsequent years because of the inappropriate controls and inert electrode materials. From that time, this technique has gained less interest, apart from electroconductive thawing. Moreover, in the last years, a numeral of attempts has been made to utilize this technology in various food processing applications (De Alwis and Fryer, 1990).The first commercial ohmic heating method to sterilize the particulate foods was developed by APV Baker Ltd (Skudder, 1992).

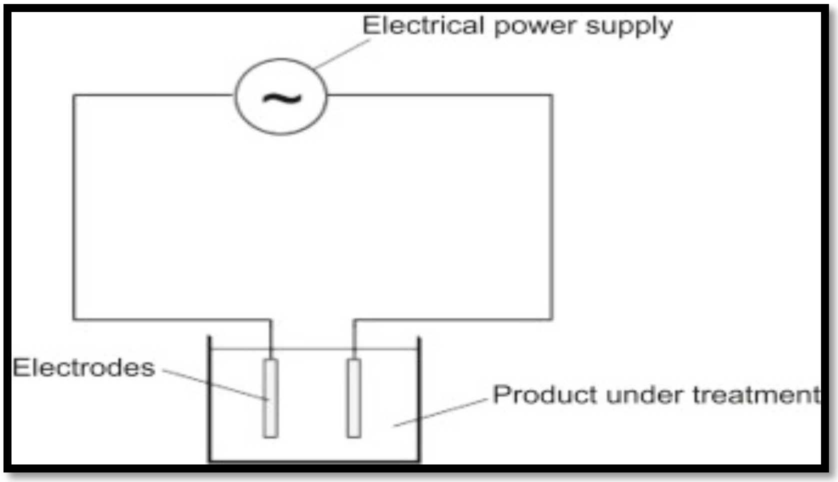

Fig.1 Schematic diagram illustrating the basic principle of ohmic heating (Sakr and Liu, 2014)

PRINCIPLE OF OHMIC HEATING

Most foods contain huge quantities of water level and soluble salts and these solutions can conduct electricity via electrolytic conduction. A schematic diagram illustrates the basic principle of ohmic heating is given in **Figure 1.** When electrolytes are kept in an electric field, the ions present in the electrolyte move towards the electrodes with opposite charge and generated heat due to the movement of ions in the electrolyte. Also, the moving ions within it collide with each other, which in turn create resistance for the movement of ions and increase its kinetic energy, and thus heat the material (Singh and Heldman, 2014). An ohmic heater is an electrical heating system that employs liquid's electrical resistance to produce the heat. Heat is generated within the fluid by Joule heating as an alternating electric current (I) by transferring through a conductive material having resistance (R), resulting in the generation of energy causing an increase in temperature (Zell et al., 2009). The electrical conductivity of some selected ohmically heated foods is given in Table 1.

Proper heating techniques of liquids involve heat transfer from a hot object. This heat could be produced directly via a hot medium such as steam through a heat exchanger like tube, plate and shell or directly through an electrical heating element. Such techniques need a temperature gradient for transferring heat to the liquid and under such conditions, the surface is at an elevated temperature than that of food material. Thus, results in the surface fouling for some specific foods which become burnt onto the hot surfaces minimizing rates of heat transfer and undesirably influencing the food. A major problem is witnessed regarding the heat transfer when heating viscous fluid and particulate foods where effective uniform heat transfer is hard to attain. Ohmic heaters overcome the aforementioned problems by eliminating hot surfaces from the heating of the fluids.

The heat generation rate during ohmic heating is described by Samprovalaki et al. (2007):

$$Q= \sigma E2 \qquad (1)$$

Which is equivalent to the more familiar I^2R. Here Q is the internal energy generation rate (Wm^{-3}), σ is the local electrical conductivity ($S\ m^{-1}$) and E is the electric field strength ($V\ m^{-1}$). The voltage distribution is given by

$$\nabla (\sigma \nabla E) = 0 \qquad (2)$$

Thus depends on the electrical conductivity distribution in the medium and the geometry of the system. Equation (2) is different from Laplace's Equation (3) as it deals with the medium where the electrical conductivity is a function of temperature and position.

$$\nabla 2 \ E = 0 \quad (3)$$

Process parameters that affect ohmic heating are electrical conductivity of the material field strength, particle size, concentration and electrodes and frequency and waveform.

Table 1: Electrical conductivity of some selected ohmically heated foods (adapted from Sakr and Liu, 2014)

Material type	**Electric conductivity at 25ºC (S/m)**
Apple juice	0.239
Beer	0.143
Black coffee	0.182
Chocolate 3% fat milk	0.433
Coffee with milk	0.357
Pork	0.64–0.86
Sea water (TDS¼44.00 mg/L)	5.8
Sea water (TDS¼57.78 mg/L)	6.75
Sea water (TDS¼58.26 mg/L)	6.78
Sea water (TDS¼62.82 mg/L)	7.2
Tomato juice	1.697

ADVANTAGES OF OHMIC HEATING

- Low maintenance cost due to the lack of movable parts.
- Particulate food products and liquid with particulate mixtures can be heated well.
- The required temperature could be attained very rapidly.
- Quick even heating of liquid with quick heating rates.
- Better product quality, low cooking time and high energy efficiency
- Due to optimization of investment results in high efficacy and less capital cost
- An immediate shutdown of the device.
- No remaining heat transfer after the current shut down.
- High-energy conversion efficacy.
- A quiet eco-friendly system.

- Minimized fouling risk on heat transfer surface.
- High temperatures could be quickly attained. For example temperatures for ultrahigh temperature (UHT) processing.
- Low risk of product damage due to burning.
- Preserving the original color and nutritive value of foods, lesser processing time and high yield.

DISADVANTAGES OF OHMIC HEATING

- Deficient in generalized information.
- Requested adjustment as per the conductivity of the dairy products
- Narrow frequency band.
- Complex to control and monitor.
- Difficult coupling between temperature and electrical field distribution.

Table 2: Various industrial applications of ohmic heating (Sakr and Liu, 2014)

Process	Equipment	Industry	Application
Heat treating	Various furnace types, kilns, lehrs and ovens	Metal products, primary metals, fabricated, ceramics, glass	Hardening, enameling, coating, annealing, tempering
Fluid heating	Various furnace types, heaters and reactors	Food and agricultural products, petroleum refining and chemical manufacturing	Chemical production, food preparation, reforming, cracking, distillation, visbreaking, hydrotreating
Other heating processes	Various furnace types, heaters, ovens and reactors	Food and agricultural products, ceramics, glass, rubber and plastics, chemical manufacturing	Sterilization, chemical production, food production (including roasting, baking and frying)

APPLICATIONS OF OHMIC HEATING

Pasteurization in dairy industries

The ohmic heating process was utilized to pasteurize milk in the near beginning of the 20th century, where milk was pasteurized by passing electricity through parallel plates (Quarini, 1995). During the past two centuries, newer and developed materials and different ohmic heating technique designs have been introduced. GBEC (Great Britain Electricity Council) granted patent on continuous flow in ohmic heating and authorized to the APV baker company. One of the most essential heat treatment transactions in the dairy sector is pasteurization as well as sterilization. In recent times, the electrical conductivity of lactose-free milk was calculated by applying ohmic heating device and the properties electrical conductivity of lactose-free milk was measured and was observed high enough for applying ohmic heating. Metal contamination of milk samples that were pasteurized by the traditional and ohmic process was also compared (Suebsiri et al. 2019). Recently the utilization of ohmic heating with the parameters (OH, 4, 8, or 12 V/cm, 72–75 °C/15 s) to pasteurize milk proposed for the production of Minas Frescal cheese (Minas a fresh white and soft Brazilian cheese, faintly salty, with low acidic nature) was investigated. The cheese was analyzed for bioactive constituents with functional activities including antihypertensive antioxidant and antidiabetic activity, volatiles profile, fatty acid profile, sensory evaluation and rheological parameters. Ohmic heating enhanced the sensory properties of Minas Frescal cheese while as reduced the hardness, elasticity, and firmness, hence can be an interesting alternative to form Minas Frescal cheese, with desired effects on bioactive and sensorial attributes (Rocha et al., 2020).

Role of Ohmic heating in fruits and vegetables

Plant products are the most suitable and often employed for ohmic heating according to the recent literature. This is due to the fact that generally, fruits and vegetables demonstrate enough conductivity to attain the requisite temperatures in less than 1 min at relatively less electric field strengths (E<100 V/cm) (Palaniappan and Sastry 1991) (Wang and Sastry, 1997; Sarang et al., 2008). In fruits and vegetables, heat treatment is used for preservation and processing purposes. Earlier traditional heating was most common technique used to heat fruits and vegetables and this process resulted in high product quality damage occurs because of low convective or conductive heat transfer especially in can processing or aseptic processing systems for particulate food products (Zell et al., 2009). Some novel and innovative methods such as inductive, microwave, ohmic heating etc., have emerged as alternative methods to conventional heating processes. The chief disparity between ohmic heat treatment and other electrical processes is that electrical energy is dissipated directly within the food. However besides heating of vegetables and fruits, the applied electric field in ohmic heat treatment results in an alteration in some nutritive and quality parameters viz., deactivation of micro-organisms, enzymes and dilapidation of heat-sensitive components, alteration in cell membranes, pH, viscosity, color as well as rheology (Kaur et al., 2016).

The ohmic heating technique is widely acknowledged by the industries for processing liquid and solid-liquid mixtures (Stirling, 1987) and is mostly used in sterilization, ultra-sterilization and pasteurization of foods with better quality. The juice produced by ohmic heating contains higher concentrations of flavor compounds and has two times longer sensory storage life than conventionally pasteurized juice (Leizerson and Shimoni, 2005). Recently, ohmic heating has been used for the sterilization of guava juice (Elzubier et al., 2009). Castro et al. (2004) showed the dilapidation of ascorbic acid in strawberry-based products pasteurized by both traditional and ohmic heating. They concluded that the applied electric field did not affect vitamin C degradation. Ohmic-heating treatment with high-temperature can be significantly utilized to pasteurize fresh orange juice with minimum sensory changes. Consequences of ohmic heat treatment on the orange juice quality were investigated and a comparison to the samples pasteurized at 90 °C for 50 s and treated at various temperatures such as 90, 120, and 150 °C for 1.13, 0.85, and 0.68 s in an ohmic heating device was made. Ohmically heat treatment resulted in decreased pectin esterase activity by 98% and the decrease in ascorbic acid calculated up to 15%. Similarly, ohmic-heated orange juice preserved high amounts of the 5 representative flavor components as compared to the heat-pasteurized juice (Leizerson and Shimoni, 2005). In another study electric fields significantly affect enzyme inactivation (Pectin esterase inactivation) by ohmic heating in orange juice than did by traditional heating (Funcia et al., 2020).

Electrical conductivities of different fresh fruits like peach, pear, pineapple, strawberry red apple were determined at a temperature of 25-140°C by (Sarang et al., 2008). The impact of ohmic heating on juice extraction from apples was studied by Praporscic et al. (2006) and the most excellent juice yield was perceived when the plant tissue was treated electrically at a modest temperature of 50 °C. Viscosity and electrical conductivity of apple were studied in fruit juices by Singh et al. (2008) and these parameters such as electrical conductivity and viscosity were measured at a temperature of 25-70°C during ohmic heating. Similarly, Lima et al. (2010) assessed the effect of temperature on ascorbic acid degradation of ground cashew apples by ohmic heating. Jakob et al. (2010) showed the inactivation kinetics of pectin methyl esterase in ohmically heated fresh apple juice. In a dissimilar study, electrical conductivity as a function of temperature for blueberry pulp was studied during the operation and construction of an ohmic heating system by Sarkis et al. (2013). The comparison studies between traditional and ohmic heating manifested that when low voltages were employed, the extent of depletion was lesser or similar to those acquired by traditional heat treatment. Marczak et al. (2013) studied the depletion of anthocyanin in blueberry pulp post-heat treatment by involving traditional and ohmic heat treatment. In another study, the impact of ohmic heat treatment on the carotenoid content of citrus fruit juices viz., blood orange and grapefruit was studied recently by Achir et al. (2016). Sarang et al., (2008) determined the electrical conductivity of peach and pear at a temperature of 25-140°C. Moreno et al. (2011) examined the impact of ohmic heat treatment on the osmotic dehydration kinetics and microstructure of pears. Similarly, Shynkaryk et al. (2010) examined the impact of electric field frequency on the ohmic heating rate of peaches. This study revealed that the required time to attain the desired temperature is merely and highly dependent on the frequency. Darvishi et al. (2013) studied pomegranate juice with emphasis on the impact of ohmic heat treatment on parameters like the performance of the system, heating rate, electrical conductivity, and pH of pomegranate juice. Parameters including electrical conductivity, ohmic heating rate, and pH were dependent on the voltage gradient used (30–55 V/cm). Likewise, in another experiment lemon juice was heated on a laboratory scale static ohmically at voltage gradients of 30–55V/cm (Darvishi et al., 2011). Castro et al. (2003) evaluated the consequences of electric field strength and different thermal treatments on the electrical conductivity of strawberry-based foods and studied the vitamin C depletion kinetic. The impact of ohmic on textural characteristics of cylindrical pieces of red beet was studied and compared with conventional and microwave processes (Farahnaky et al., 2012). In another study, the consequences of collective effects on ohmic heat treatment and pulsed electric field treatment on the extraction of juice from sugar beet cuts of diverse sizes were studied (Praporscic et al., 2005). Recently the impact of ohmic heat treatment on some physical (moisture, oil content, texture, and color) properties of carrot cubes were evaluated. Using high voltage and then frying for 60 seconds was found to be effective in decreasing the hardness, firmness and decreasing of L* value as it was found with 150F samples. The undesirable result of increased oil absorption during frying and decreasing moisture content was due to increased voltages (Ismail et al., 2019). Similarly, ohmic heating has been studied in Pea and Potato, Radish, Tomato and Turnip etc (Icier et al., 2006; Jakob et al., 2010; Imai et al., 1995; Singh et al., 2008; Lima et al., 1999). Hence, it can be concluded that ohmic heating has potential applications in vegetable and fruit processing.

Ohmic heating in meat and meat products

Ohmic heating is an alternate technique for cooking meat and meat-based products due to its property of rapid heat generation. This is a well known among the electro-heating techniques and incorporates the meat product's resistance for the conversion of electric energy into heat. A study was carried out on pork, chicken and beef meat cuts using ohmic heating in which the sterilization temperature range of 25–140°C was used. The results conferred a more conductive nature of lean meat as compared to the fat portion in meat products (Sarang et al. 2008). Consumer acceptance is primarily determined based on the color, a basic attribute of meat and meat-based products that are not affected by the initial fat content and various voltage gradients of ohmic heat treatment used for beef cooking (Bozkurt and Icier, 2010). Significant white color was observed in meat samples processed through ohmic heating as compared to the samples processed through the conventional methods of cooking. This is supported by the studies of Zell et al., 2010) in whole beef muscle and turkey meats respectively and the credit was attributed to the longer times of exposure.

Besides color, ohmic heating also affects the meat and meat product's texture. Studies have shown that meat proteins denature through cooking leading to various changes in structure. Among the structural changes, cell membrane destruction, muscle fiber shrinkage (transversal and longitudinal), connective tissue solubilization and shrinkage, and sarcoplasmic proteins gel formation and their aggregation are prominent ones (Tornberg, 2005). During ohmic thawing, the voltage gradient is a significant factor that affects the beef textural properties such as chewiness, gumminess, springiness and hardness. Comparatively, Icier et al.

(2010) reported that samples treated with ohmic thawing showed the least destruction in proteins and a reduced fat globules removal than the samples treated with the conventional thawing methods. Ohmic heating leads to the toughening and shrinkage in collagen through uniform exposure to higher temperatures for a short period (Bozkurt and Icier, 2010). Prior to this, Zell et al. (2009) witnessed the role of ohmic heat treatment in toughening the beef muscle samples when expressed in Warner–Bratzler peak load values.

Effect of Ohmic heating on microbial inactivation

In low-frequency ohmic heating, cell walls can build up loads and make pores, resulting in a decreased D-value as compared to traditional heating methods. Ohmic heat treatment was widely used in microbial destruction through its thermal effect in the recent past. Moreover, ohmic heating is used as an effective method of milk pasteurization without any harmful effect on proteins suggested by a comparative study between ohmic and traditional heating methods based on the deactivation potential of viable aerobes and *Streptococcus thermophilus* 2646 in milk (Sun et al. 2008). A similar study confirmed the higher effectiveness of ohmic heating at 30 V/cm in inactivating the spores of *Alicyclobacillus acidoterrestris* by 5 log units in orange juice pasteurization than the conventional methods (Baysal and İçier, 2010). (Somavat et al., 2012) tried to study the mechanism of ohmic (frequency= 60 Hz and 10 kHz) and traditional heating (Temperature=121, 125 and 130 °C for 4 holding times) process in inactivation of *Geobacillus stearothermophilus* spores (ATCC 7953) and concluded an increase in spore inactivation. Moreover, compared to conventional heating, ohmic heating caused an increased inactivation of *Bacillus coagulans* spores in tomato juice. Another recent comparative study of ohmic and traditional water bath heating based on the bacterial deactivation and *Escherichia coli* O157:H7recovery kinetics concluded with the extension of the lag phase in the recovery stage in ohmic treated samples than the control samples (Shao et al., 2019).

Role of Ohmic heating in enzyme stabilization

Another aspect of ohmic heating is in the field of enzyme inactivation. For example, the complete polyphenol oxidase inactivation in apple cubes was reported by using ohmic treatments at various temperatures (30 °C, 40 °C, 50 °C), 13 V/cm for 90 min (Moreno et al., 2013). A current experiment confirmed that ohmic heat treatment significantly increases the inhibition of lipase enzyme thereby increasing stabilization of rice bran than by steaming method (Loypimai et al., 2015). Kinetic parameters changed through the application of ohmic heating at several incubation temperatures in milk and juices (fruit and vegetable), however, the mechanism involved was the same as in the conventional indirect heating as reported by a study focused on the inactivation of alkaline phosphatase, pectin methyl esterase and peroxidase (Jakób et al., 2010).

Extraction of compounds by Ohmic heating

When it comes to the extraction of biomaterials from plant cell walls, ohmic heating represents an efficient, fast and uniform heating method as used in soymilk extraction from soybeans (Kim and Pyun, 1995) replacing the traditional methods of electrical heating sucrose extraction from sugar beets (Katrokha et al., 1984). Moreover, apples heated by ohmic heating resulted in a significant juice yield increment as compared to the control samples (Lima and Sastry, 1999). Halden et al. (1990) showed the potential application of ohmic heat treatment to increase dye diffusion in beet. Recently pectin was extracted from orange juice by the assistance of ohmic heating which confirmed use of the highest voltage resulted in the upsurge in the yield (Saberia et al., 2017). Lakkakula et al. (2004) found that the amount of extraction of anthocyanins and lipids from rice bran increased. Ohmic heating also increases the levels of α-oryzanol, α-tocopherol, phenolic compound, and antioxidant activity in rice bran (Loypimai et al., 2009). Moreover, ohmic heating helps in the fast and increased percentage of total phenols from the red grape pomace using an electric field strength of 100-800 V/cm and 0-50 % of ethanol to water (E/W) percentage (El Darra et al., 2013). The extraction of food-grade phytochemicals from colored potato (a good source of bioactive compounds) was found to be significantly enhanced along with other phenolic compounds, and the study conferred low power requirement for their extraction (Pereira et al., 2016). The study also confirmed the extraction enhancement due to the electric fields applied during ohmic heat treatment.

The role of ohmic heating on β-carotene and lycopene extraction was also studied and compared with the conventional methods (Aamir and Jittanit, 2017). In their research, Gac aril oil was studied and the results confirmed that ohmic heat treatment increased the extraction yield of lycopene and β-carotene. Ohmic heat treatment has been applied to extract Vine Pruning residue (VPR) from lignocellulosic material in wine industries. Moreover, bioactive compounds extraction from the VPR was found to be increased by ohmic heat treatment than the traditional heating methods. The extract obtained was found to increase the bioactivities such as polyphenolic profile, total phenolic content (TPC), antimicrobial activity, antioxidant activity and anticancer activity due to the enhanced release of phenolics by ohmic heating (Jesus et al., 2020). The by-products of the tomato industry (peels and seed) otherwise rendered as wastage are an important bioactive source that can be used as colorant in commercial aquaculture. Moreover, these tomato wastes also contain naringenin, kaempferol and rutin where extraction could be increased by applying ohmic heating (Coelho et al., 2019).

Role of Ohmic heating in starch gelatinization

Ohmic heating also plays an important role in starch gelatinization, which represents an essential parameter in food processing. The applications of starch in food systems include the potential of retaining moisture, additive stabilization, and thickening property. Moreover, the electrical conductivity of the food product along with the formulation of the desired product decides whether the starch gelatinization is advantageous or disadvantageous. Wang and Sastry, (1997) reported that the electrical conductivity of food products was found to decrease with the degree of starch gelatinization and later proposed that the starch gelatinization could be detected by a sensor developed by using ohmic heating. Accordingly, a method was developed that uses the change in electrical conductivity by ohmic heating for measuring the starch gelatinization temperature (Li et al., 2004). Another study reported the effect of increasing gel functionality in seafoods (Yongsawatdigul et al., 1995). The change in electrical conductivity of native starch suspensions (with varying starch/water ratios heated ohmically with continuous agitation at 90°C with 100 V at 50 Hz and a voltage gradient of 10 V/cm) was found to be linear with temperature except for the gelatinization range. In jicama and cassava starches, ohmic heating helps in the heat generation, minimization of solid loss, optimizing the degree of gelatinization (%SG) and obtaining an adequate amount of gelatinization energy (Fernando et al., 2005). The crumb formation in pound cake batter forming the center of conventionally baked cake results due to the ohmic or electrical resistance (ER) heating and the mechanism is explained by the process of ohmic heating. A recent study reported that the temperature and the moisture gradient during the baking of pound cake are highly reduced by the ohmic heating (Deleu et al., 2019). A multifrequency ohmic heating system was used to determine the electrical conductivities of Alaska pollock surimi *(Theragra chalcogramma)* obtained from the American seafood at temperature 80ºC, alternating currents of 4.3, 15.5 V/cm voltage gradient and frequency range of 55 Hz to 20 KHz. The results witnessed the dependence of the electrical conductivity on the starch gelatinization occurring during heating (Pongviratchai and Park, 2007). Various industrial applications of ohmic heating are illustrated in Table 2.

In addition to the abovementioned applications, ohmic heating has gained popularity in different fields and is used in the processes like blanching, dehydration, evaporation, fermentation and many more (Cho et al. 1994; Cho et al., 1996; Mizrahi, 1996; Sarang et al., 2007; Icier, 2010; Allali et al., 2010; Allali et al., 2010; Assiry, 2011; Moreno et al., 2011; Moreno et al., 2012; Guida et al., 2013; Moreno et al., 2013; Cho et al., 2016; Moreno et al., 2016; Cho et al., 2017; Cokgezme et al., 2017; Icier et al., 2017; Sabanci and Icier, 2017; Gomes et al., 2018; Pereira, 2018; Sabanci et al., 2019; Gavahian and Tiwari, 2020).

CONCLUSION AND FUTURE PERSPECTIVES

Ohmic heating is an emerging technology used in heating foods internally due to inherent resistance and stands as an innovative alternative heating process in food systems. Ohmic heating has brought a revolution in the food processing industry because of its broad area of applications. The various factors such as applied voltage gradient temperature, concentration, particle size, frequency, and electrolyte concentration determine the rate of ohmic heating. Its advantages over conventional and innovative heating process techniques like induction heating, microwave heating and radio-frequency heating have drawn the great attention of all the researchers. In the early twentieth century, milk pasteurization was performed this commercial technique of heating. However, the high electricity cost and the lack of proper electrode material restricted the applications of this "electropure process" between the late 1930s and 1960s. Besides its tremendous applications in many food eras, there is a need to establish a complete knowledge for the mechanisms for mass transfer properties, and process design to develop industrial processes that can take benefits of these techniques.

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