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Professional paper

APPLICATION OF OHMIC HEATING IN THE FOOD INDUSTRY, IMPACT ON FOOD COMPONENTS AND "HURDLE APPROACH"

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Abstract

The application of thermal processes in the food industry causes a decrease in the quality of the final product, such as nutritional value and organoleptic characteristics. Many alternative methods offer uniform and rapid heating and provide the desired microbial lethality without reducing overall product quality. Ohmic heating is an emerging technique for food processing that has been used in recent decades as an alternative to conventional heating. It is a rapid heating method with big potential in the food industry.

More particularly, ohmic heating of food is used for microbial inactivation, blanching, fermentation, gelatinization, peeling, evaporation, drying, extraction, pasteurization, and sterilization. This review summarizes the application of ohmic heating to different types of food products, the impact on food components, as well as the synergistic effect of ohmic heating with other non-thermal preservation techniques as well as the case of its combination with packed food items.

The optimization of the ohmic heating approach reduces the duration of the process, achieves microbial and enzyme stability, increases the yield, and preserves the organoleptic and bioactive components in food commodities. Applying ohmic heating in combination with other non-thermal food preservation techniques such as UV-C radiation, pulsed electric field, high pressure, ultrasound, vacuum and the addition of preservatives contributes to reducing the intensity of the applied electric field, the temperature, and the treatment. In addition, it contributes to the extension of the shelf life as well as preserving the nutritional and organoleptic quality of food.

Keywords: ohmic heating, food processing, conductivity, synergism, nutritional quality

1. Introduction

Thermal methods are of great importance for food processing and preservation. They are used to achieve microbiological stability, and enzyme inactivation, improve texture, increase digestibility, and extend the shelf life of foods. In terms of thermal processes, the most commonly used are pasteurization, sterilization, and drying of food items. The use of high temperatures in these processes causes a decrease in the quality of the final product's nutritional value and organoleptic characteristics. These methods relatively do not meet the requirements of energy efficiency, waste recycling, and environmental sustainability (Indiarto & Rezaharsamto, 2020; Alkanan et al., 2021). On the other hand, consumer demands for minimally processed and safe food products with natural taste, and ingredients, with preserved bioactive components, such as vitamins and antioxidants, have increased trend in the last decade. Therefore, alternative methods of uniform and rapid heating are needed to achieve the desired microbial lethality without reducing the overall quality of the food products (Alkanan et al., 2021).

The use of novel thermal and non-thermal food preservation technologies can meet consumer demands and deliver high-quality processed food without additives and with a long shelf life (Hosseini et al. , 2022). An alternative method to thermal methods is the use of electricity.

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Ohmic heating is one of the thermal methods based on the use of electrical energy that has been used in recent decades (Jan et al., 2021).

2. Ohmic heating

Ohmic heating is an excellent alternative heating method, it is a fast method with a wide potential in the food industry, water distillation, waste treatment, chemical processing, etc. Conventional methods of food heating, in general, generate thermal energy from outside and transfer it to the food through conduction, convection, and radiation, thus conventional methods are intensive energy-consumers, while ohmic heating produces heat directly from inside the material and has no limitations such as low heat transfer coefficient and heat losses (Hosseini et al., 2022; Alkanan et al., 2021). Ohmic heating is one of the most economical alternatives available to the food industry for thermal processing as it is based on electricity only. Therefore, it has a wide application in the processes of pasteurization, sterilization, drying, concentration, and extraction, as well as for the preservation of nutrients and sensory properties of food categories (Alkanan et al., 2021).

3. Principles of ohmic heating

Different food products are in general a complex matrix of several compounds, most of which are carbohydrates, proteins, fats, vitamins, minerals, water, color, and/or flavor compounds in a variable content. When these food materials contain sufficient water and electrolytes (mainly present as mineral salts), they act as charge carriers and allow the electrical current to pass through them thereby generating internal heat as a result of electrical resistance. Heat is generated instantly and volumetrically inside the food materials due to the ionic motion. The amount of heat generated is directly related to the current induced by the voltage gradient in the field, and the electrical conductivity (Joshi, 2018; Aurina & Sari, 2021). Electrical conductivity is a measure of how well a material accommodates the movement of an electrical charge. It increases in the presence of ionic substances like acids and salts and decreases in the presence of nonpolar components such as fats and lipids. Electrical conductivity additionally is very important because heat can spread quickly and evenly. The current is carried by ions, and therefore the conductivity increases with the concentration of ions present in the solution, their mobility as well and the media temperature. Field strength affects the heat transfer, increases electric field intensity, and electrical conductivity, and therefore has a faster heating rate (Aurina & Sari, 2021). The most significant process parameters during the ohmic heating of food composition are: electric field strength, temperature, duration, and frequency of electric current (Kumar et al., 2022). An illustration of the ohmic heating system is shown in Figure 1 (Aurina & Sari, 2021).

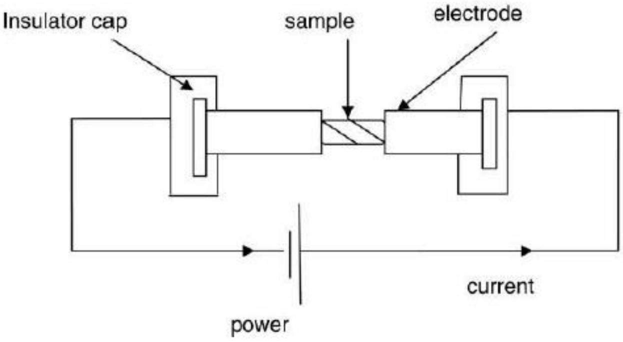

Figure 1. Ohmic heating is using alternating current (AC) as power supply and the current flows into the two electrodes in the circuit (Aurina & Sari, 2021).

The equipment for an ohmic heating system consists mainly of a heating unit, electrodes, a data recording system, an alternating current (AC) power source, a voltage control unit, and thermocouples (Alkanan et al., 2021). The equipment parameters that are important to be considered are electrode size, shape and composition, ohmic chamber size, and configuration. (Kumar et al., 2022). Since alternating current is used in ohmic heating, heating can be done continuously. As shown in Figure 1, the sample is placed between the electrodes, and an insulating cap is used to protect against injury while using (Aurina & Sari, 2021). The electrodes used should consist of highly conductive, low-cost, and non-corrosive material. The electrodes that are connected to the power supply should be in direct contact with the material for the electrical current to be connected, and the distance between the electrodes may vary depending on the system size used (Indiarto & Rezaharsamto, 2020). When the food ions are exposed to the electric field, they will move towards the electrodes of the source of the opposite charges, generating ion collisions and thereby increasing the temperature in the food. For ohmic heating, the material should have certain electrical conduction. Non-conductive material may become conductive by adding an electrolyte such as sodium chloride or soluble organic salt, which does not interfere with the reaction, or ionic solvents can be used because they are naturally conductive (Alkanan et al., 2021).

4. Application of ohmic heating in the food industry

Ohmic heating has great potential for application in the food industry. Ohmic heating of food is applied for microbial inactivation, blanching, fermentation, starch gelatinization, peeling, evaporation, drying, extraction, thawing, pasteurization, and sterilization. This method can be applied to various food products. In some food products,pre-treatments should be done to improve the ionic content and conductivity of the solid phase (Aurina & Sari, 2021; Indiarto & Rezaharsamto, 2020). The smaller the difference in the conductivity of the materials in the liquid and solid phases, the more uniform the electric flow is going to be distributed so that the generated heat can be evenly distributed (Hosseini et al., 2022). In this context, before the ohmic heating process, other pre-treatments can be made to homogenize the texture and to equalize the electric conductivity of the material to achieve uniform heating in all stages of the process (Indiarto & Rezaharsamto, 2020). Significant parameters of products treated with ohmic heating are viscosity, electrical conductivity, density, specific heat, and homogeneous or solid-liquid systems. (Kumar et al., 2022). Table 1 presents optimal parameters - voltage gradient, temperature, and duration of the process for different types of food of plant and animal origin.

Table 1. Optimal conditions for ohmic heating of different food categories

Product	Voltage gradient	Temperature	Time	Effect	References
Blueberry flavored dairy desserts	1,82 V/cm	90ºC	3 min	Preservation of bioactive components, increased antioxidant capacity.	Kuriya et al., 2020
Apple juice	14,21 V/cm	55,47ºC	2,43 min	Preservation of qualitative parameters, microbial inactivation.	Ashitha et al., 2020
Mango juice	40 V/cm	80ºC	1 min	Enzyme inactivation, higher vitamin C content, carotenoids and total phenolic content.	Abedelmaksoud et al., 2018
Mango pulp	20 V/cm	75ºC	3 min	Highest physicochemical and sensory properties. Longer shelf life.	Priyadarshini et al., 2023
Spinach puree	30 V/cm	60-90ºC	0-10 min	It has no effect on chlorophyll, carotenoids and puree color.	Yildiz et al., 2009

Fish sausages	30 V/cm	66ºC	4 min	Fast and homogeneous method.	Shabani et al., 2022
Fish steak	75 V/cm	71.88ºC	5,75 min	Best organoleptic properties, reduction of hardness and water activity.	Kumar et al., 2014
Pork meat	21 V/cm	70ºC	2, 2.5, 3 min	Better meat texture, sensory acceptability.	Angel-Rendon et al., 2019
Minas Frescal cheese	4, 8, 12 V/cm	72-75 ºC	15 sec	Better sensory properties, and functionality of the cheese	Rocha et al., 2020
Chocolate milk beverage with prebiotics	30, 60 V	72-75ºC	15-20 sec	No changes in added prebiotics – galactooligosaccharides, higher content of bioactive components.	Silva et al., 2024

4.1 Pasteurization and sterilization: Ohmic heating is very often used for pasteurization or sterilization of food products resulting in excellent quality. It can be used for ultra-high temperature (UHT) sterilization of foods, especially for products that contain large particles (up to 2.5 cm) that are difficult to sterilize by other means (Aurina & Sari, 2022). The ohmic heating process is used to inactivate pathogenic microorganisms and spores (Alkanan et al., 2021; Kim et al., 2017). It can cause non-thermal damage to microbial cells due to exposure to the electric field. The D-value (the decimal reduction time) or the time needed to kill microorganisms for one log cycle is lower in ohmic heating compared to conventional heating; temperature and electric current strength have a significant impact on the inactivation of microorganisms (Indiarto & Rezaharsamto, 2020; Hashemi et al., 2019). Continuous ohmic heating is suitable for sterilizing highly viscous foods (Cho et al., 2017) as well as the use of ohmic heating has been demonstrated to be highly effective in maintaining nutritional and sensory characteristics, as well as achieving microbial and enzymatic stability in the pasteurization of fermented foods, for example, hot pepper paste (Cho et al., 2017), milk (Al-HilphyShirkole et al., 2018), orange juice (Leizerson&Shimoni 2005), etc.

4.2 Thawing: The ohmic heating system is an innovative method used in thawing frozen food. By using ohmic heating, frozen foods can be thawed by placing them between two electrodes and applying an alternating current to them. The advantages of this process include, water and wastewater are not generated, uniform thawing due to volume heating and the process can be easy to control (Aurina & Sari, 2021). In general, using ohmic heating to thaw frozen meat reduces mass loss and shortens thawing time (Duygu & Umit, 2015; Bozkurt & Icier, 2012).

4.3 Blanching and enzyme inactivation: Blanching with ohmic heating can significantly reduce the migration of solutes compared to conventional blanching, which improves the sensory properties of products, regardless of their shape or size (Aurina & Sari, 2021; Priyadarshini et al. 2023). According to Barron-Garcia et al. (2022), ohmic blanching of mushrooms reduces enzyme inactivation time and has a minimal impact on color and texture compared to conventional blanching. Enzymes are proteins that spontaneously accelerate chemical reactions and are considered vital catalysts. The presence of enzymes significantly reduces the shelf life of fruit and vegetable products, therefore, they should be inactivated. The mechanism of inactivation of the enzyme in the ohmic heating method is the same as in conventional heating, but with ohmic heating, there is greater energy efficiency and reduced inactivation time. The application of electrical and thermal energy when treating food individually or in combination affects the structure and function of enzymes. (Alkanan et al., 2021; Kostelac et al., 2020; Indiarto & Rezaharsamto, 2020; Shao et al., 2021). According to Mannozzi et al., (2019), by applying ohmic heating at a temperature of 80°C, enzymatic inactivation of fruit and vegetable juices was achieved while preserving their quality.

4.4 Fermentation: The use of ohmic heating in the fermentation process has a positive effect on the fermented products and reduces the fermentation time. For example, ohmic technology could be applied to fermented products such as cocoa and Arabica coffee to reduce the acidity of coffee beans (Sagita et al., 2020; Aurina & Sari, 2021); Robusta coffee fermented with ohmic heating is categorized as an excellent coffee with the best aroma, taste, and acidity (Reta et al., 2017).

4.5 Extraction: Ohmic heating can also be used for extraction, for example, of beet sugar, soy milk, juice, essential oils (thyme, peppermint, lavender), and plant pigments (β-carotene, lycopene, anthocyanins) (Loypimai et al., 2015; Indiarto & Rezaharsamto, 2018; Rodrigues et al., 2020). It can induce electro-permeability of cell membranes; the temperature and membrane damage can increase as electric current flows through the medium, resulting in fluid diffusion into the cellular structure (Indiarto & Rezaharsamto, 2020; Termrittikul et al., 2018). Furthermore, ohmic heating is also used for the extraction of certain components from plant waste because it heats the material rapidly with high energy efficiency, compared to conventional heating. It can be a suitable alternative method for the extraction of pectin industrially as well; Namely, ohmic heating gives the best results in terms of energy efficiency and yield of extracted pectin from orange waste at a voltage gradient of 30V/cm and a pH of 1.5 (Saberian et al., 2017). The bioactive components and carbohydrates that were extracted from the tomato by-product with ohmic heating had a positive prebiotic effect on the intestinal microflora (Coelho et al., 2023).

5. Influence of ohmic heating on macronutrients

The structural and functional characteristics of treated soybean milk protein with ohmic heating (17, 23, 30, and 37 V/cm) showed that the number of free amino groups increased by 14%, while the total sulfhydryl content and surface hydrophobicity decreased. The protein structure was not significantly changed. In traditional heating, soybean protein has been denaturalized. It can be assumed that ohmic heating is suitable for improving the functional properties, digestion, and absorption of soybean milk protein (Li et al. 2017). The maximum yield during extraction of soy milk with ohmic heating was found at 200V and 90oC. Soy milk's crude protein content and protein digestibility were significantly increased after ohmic heating. The highest amount of protein content in soy milk was found at 180 V and 80°C (Shivaji et al., 2020). By applying ohmic heating at 50 Hz and moderate electric field intensities up to 20 V/cm, there was a decrease of 36% in the immunoreactivity of the soy protein isolate. Conformational changes and electrochemical reactions caused by this technology can reduce the allergic properties of soybean (Pereira et al., 2021). The electric field effects and uniform heating probably accounted for the reduced tertiary structural changes and smaller particle sizes of aggregates of whey proteins. In this case, ohmic heating could be utilized as an alternative thermal treatment to change the protein conformation and physicochemical properties for specific protein functions (Sereechantarerk et al., 2021). Ohmic heating reduces the denaturation and loss of native whey protein when compared to conventional heating (Peteira et al., 2010). The thermal process with ohmic heating can modify the structure of the lentil protein, the degree of modification depends on the treatment temperature, electric field strength, and pH of the protein fraction extraction. Lentil protein extracted at pH 9 was more stable to temperature variations under ohmic heating. The hydrophobic surface and accessibility of sulfhydryl groups increased at low electric field strengths (5 V/cm). The Lentil protein extracted at pH 7 was greatly influenced by all thermal treatments. Ohmic heating has the potential to modify lentil protein structure depending on the extraction method (Miranda et al., 2023). In vegetable baby food sterilized by ohmic heating, there was no change in total amino acid content compared to conventional sterilization where there was a 35% reduction in essential and 9% in non-essential amino acids. Ohmic treatment may be successfully applied for sterilization of vegetable baby foods with maintained nutritional quality of proteins (Mesisas et al., 2016). Ohmic heating can modify the secondary and tertiary structure of peanut protein resulting in a more uniform and denser network structure, as well as improving the texture, firmness, elasticity, cohesiveness, and chewiness of peanut protein isolate cubes (Chen et al., 2023).

Furthermore, ohmic heating results in a shorter treatment time and less degradation of polyunsaturated lipids in cooked sausages enriched with polyunsaturated fatty acids (linseed oil) while during the conventional treatment of the same sausages, oxidation of polyunsaturated fatty acids and hydrolysis of triglycerides occurred (Patyukov & Pacinoski, 2015). Ohmic heating can replace conventional heating in the food industry for products containing starch because it does not affect the structure of starch gels, and there is no difference in other properties such as water holding capacity, sedimentation index, stability to freeze–thaw cycles and rheological properties (Silva et al., 2019).

6. The influence of ohmic heating on bioactive compounds in food

Ohmic heating is an alternative thermal treatment, which is considered to have less impact on bioactive compounds compared to traditional thermal processes. Since bioactive compounds have a high nutritional value and improve human health, they are very important. The preservation of these compounds during thermal treatments like boiling, pasteurization, and sterilization is a significant challenge in the food industry (Alkanan et al., 2021).

Several studies have shown that the stability of anthocyanins during heat processing depends on product properties and process characteristics. Analysis of the degradation of anthocyanin in blueberry pulp after thermal treatment using ohmic and conventional heating revealed that the degradation of anthocyanins increases with increasing voltage and dry matter content. In blueberry pulp heated by ohmic heating with lower voltage levels, the percentage of anthocyanin degradation was lower compared to conventional heating. However, anthocyanin degradation is higher at high electric fields (Sarkis et al., 2013). Also, in strawberries, cherries, and grape juice, there is a higher degradation of anthocyanins with increasing electric field strength and dry matter (Kaur et al., 2016; Ayoub et al., 2020). According to Somavat (2011), from investigations on the effect of ohmic heating on carotenoids (β carotene and lycopene) and phenolic components (phenolic acids, quercetin, and total flavonoids) in tomato juice, the results showed that ohmic heating did not affect the content of carotenoids and phenolic components in tomato juice. Ohmic heating is suitable for products with a high content of carotenoids and xanthophylls. Ohmic heated dairy dessert with blueberry under various conditions (1.82, 3.64, 5.45, 7.30, 9.1 V/cm, 90oC, 3 min), showed that the use of low electric field strengths (1.82 V/cm) led to greater preservation of bioactive components (phenolic components, anthocyanins) and increased antioxidant capacity (Kuriya et al, 2020).

Ascorbic acid decreases with increasing temperature and voltage gradient during ohmic heating of tropical fruit pulp. The best results for vitamin C retention were obtained using titanium electrodes at low voltage gradient, lower temperature and shorter treatment (Athmaseivi et al., 2017). High voltages of ohmic heating lead to a greater degradation of vitamin C compared to conventional heating. In addition to thermal deterioration, ohmic heating also results in electrochemical degradation as a result of several processes, such as electrode reactions and solution electrolysis (Joshi, 2018). Another study showed that acerola pulp treated with ohmic heating has higher ascorbic acid degradation at lower voltage compared to conventional heating, this is mainly due to electrochemical reactions (Jaeschke et al., 2016). Also, the retention rate of vitamin C after ohmic heating of water chestnut juice was significantly lower (10.6-11.4%) compared to conventional heating (14.7%) (Li et al., 2019).

7. Application of ohmic heating to foods of animal origin

In the dairy processing industry, ohmic heating is used to produce dairy products that are high-quality, safe, and nutritional. Milk is suitable for ohmic heating due to its high-water content, ionic components, and electrical conductivity. Particularly, it is used for pasteurized lactose-free milk because it has good electrical conductivity (Jafarpour & Hashemi, 2022; Indiarto & Nurannisa, 2020). Ohmic heating pasteurization of sheep milk ensured bacteriological stability during 2 weeks of storage under refrigeration, thus it has a significant use in the dairy industry (Balthazar et al., 2022). Milk with lower fat content showed higher electrical conductivity and microbial inactivation (Kim & Kang, 2015). Ohmic heating is suitable for the pasteurization of milk for manufacturing prebiotic fermented products, it has improved bioactive compound content as well as sensory acceptance (Silva et al., 2021). Additionally, cheese manufactured from pasteurized milk with ohmic heating and pasteurization of high-protein vanilla-flavored milk showed good results, significant microbial inactivation was achieved with a recommended electric field strength of 6.96 V/cm (Rocha et al., 2020; Rocha et al., 2022).

The use of ohmic heating has been increasing in the meat industry to ensure the quality and safety of meat products. The electrical conductivity of the meat and the efficiency of the ohmic process depend on the structure of the meat (type of meat, amount of fat, and moisture), the lean-to-fat ratio, and the direction of the electric current (Turp et al ., 2013). The electrical conductivity of beef is lower in meat with a higher fat content since fats have low electrical conductivity; they prevent the passage of current by covering lean particles, therefore uniform heating is not achieved (LIave et al., 2018). The use of an ohmic heating system to thaw frozen meat provides less weight loss and a shorter thawing time, therefore, ohmic heating is recommended for thawing meat to maintain its quality (Doygu & Umit, 2015). In the case of sausages, ohmic heating achieved good microbial inactivation, while it did not change the sausage's chemical composition, pH, lipid oxidation, cooking loss, or water holding capacity, it only minimally altered color and texture (Inmanee et al., 2019). Fish and fish products are also treated using ohmic heating, for example, ohmic heating of hot smoked fish pate (Aydin et al., 2020), fish sausages (Shabani et al., 2022), fish steak (Kumar et al., 2014) and fermented fish sauce (Kim et al., 2023) showed a significant reduction on process time, better organoleptic properties and energy efficiency compared to conventional heating method (Aydin et al., 2020).

8. Application of ohmic heating to fruits and vegetables

Fruits and vegetables are suitable and most commonly used for ohmic heating treatment. Due to the rapid and uniform heating mode, ohmic heating has better performance in terms of microbial stability, enzyme inactivation and quality of fruit and vegetable juices, paste, pulp, puree etc. (Jafarpour & Hashemi, 2022; Kaur et al., 2016; Shao et al., 2021). Ohmic heating of orange juice achieves microbial and enzymatic stability and improves functional properties (Demirdoven & Baysal, 2014). It also has a better lethal effect on microbial spores compared to conventional heating of orange juice (Baysal & Icier, 2010). In addition, ohmic heating showed better retention of physicochemical properties during storage compared to conventional heating of watermelon juice (Ishita & Athmaselvi, 2017), grape juice (Ayoub et al., 2020), apple juice (Ashitha et al., 2020) and mango juice (Abedelmaksoud et al., 2018). Ohmic-assisted peeling has been successfully used for removing the skin of fruits and vegetables. Compared to traditional peeling, there is an improvement in product quality, peeling efficiency, product yield and energy efficiency (Gavarian & Sastry, 2020). Sterilized vegetable or vegetable-meat baby foods with ohmic heating showed a significant reduction in fatty acid oxidation, Millard reaction products and furan formation (70-90%) compared to conventional sterilization (Hradecky et al., 2017). Determining the optimal ohmic heating conditions is crucial for improving the process efficiency and the physicochemical and sensory properties of the products.

9. Synergistic effect of ohmic heating with non-thermal preservation techniques

The hurdle concept, in which the techniques of food preservation are combined, is of interest to scientists who aim to ensure the microbiological safety of food and maintain its nutritional value and sensory properties. The hurdle concept can be defined as "the combination of existing and novel preservation techniques to establish a series of preservative factors (hurdles) that any microorganism present should not be able to overcome". Novel technologies are effective, environmentally friendly, energy-efficient, non-harmful, and residue-free (Bigi et al., 2023).

In this context, there are a lot of practical examples that provide information for the hurdle approach to a variety of food items. For example, according to Kim et al. (2019) and Lee et al. (2013), the combination treatment of UV-C irradiation and ohmic heating, including simultaneous and sequential treatments, can be used as an effective hurdle technology, ensuring microbiological safety in juice products and other liquid foods. Ohmic heating and high hydrostatic pressure could be considered feasible technologies for fruits and vegetables, demonstrating the least textural damage, minimal impact on product color, and quality preservation due to minimal thermal exposure (Park et al., 2014; Rinaldi et al., 2020). In addition, ohmic sonication could be applied as a new mild thermal treatment in the production of juices with improved quality properties as well as it can be integrated as a substitute for pasteurization. (Abedelmaksound et al., 2019; Abedelmaksound et al., 2022). Moreover, it was observed that the synergistic effect of novel methods such as ultrasound and ohmic heating-assisted extraction of bioactive compounds from food materials has shown a positive effect on increasing extraction yield, saving time, and opening up a new horizon in the food industry (Kantar et al. 2021). The food processing industry can benefit from the use of the ohmic heating system combined with a vacuum as a rapid heating; this is a high-efficiency alternative that saves electrical energy consumption. Also, it may help preserve the nutritional value and quality of juice products (Alkanan et al., 2021; Hwang et al., 2022). Another case explains the use of ohmic heating and preservatives for processing the mango pulp and salsa with longer storage stability without compromising quality (Priyadarshini et al., 2023; Kim & Kang, 2017). Generally, the synergistic effect of ohmic heating with other technologies showed many positive benefits including a reduction in the processing time and temperature, as well as an improvement in nutritional properties with higher microbial inactivation, as presented in Table 2.

Table 2. The synergistic effect of ohmic heating with other food preservation techniques in selected case studies

Treatment	Product	Conditions	Effect	Reference
OH + UV-C irradiation	Tomato juice	13,4 V/cm, 210 сек., 63°C 191,1 mJ/cm^2	Significantly higher reduction of *E. coli O157:H7, S. Typhimurium* and *L.monocytogenes* ($p<0.05$) compared to individual treatment	Kim et al., 2019
OH + UV-C irradiation	Apple juice	3,7 W, 254nm, 1485 V m^{-1}, 20kHz, 65°C, 290s	6.39 ±1.30 log reduction of *E. Coli*, more than double that of ohmic heating alone (3.03 ±0.37) at the same temperature	Lee et al., 2013

OH + PEF	Mixed animal by-product	25 kV-cm^{-1} 41ºC, 0.9ms	5 log reduction of *E. faecalis* and *E. Coli*, significant reduction in treatment time	Liu et al. 2020
OH + HPP	Carrots	600 MPa, 105ºC 30 V/cm, 0.1, 3, 5 min.	Reduction of treatment time, high quality and stable product, suitable treatment for low acid products	Park et al., 2014
OH + HPP	Peach Cubes in Syrup	98ºC, 100s 600 MPa, 3min.	Very low reduction of vitamin C (6%), high scores of sensory characteristics for consistency, color and quality	Rinaldi et al., 2020
Ohmicsonication	Orange juice	40 V/cm, 68ºC, 1 min. 25ºC 550 W, 20 kHz, 8 min.	Highest inactivation of pectinmethylesterase (96%), low reduction of vitamin C and highest content of total phenols, carotenoids and flavonoids	Abedelmaksound et al., 2019
Ohmicsonication	Mango juice	40 V/cm, 75ºC, 1 min. 550 W, 20 kHz, 8 min.	Best treatment for retention of vitamin C, total flavonoids, total phenolic content and improved quality properties	Abedelmaksound et al., 2022
OH + US	Extraction of phenolics compounds from cherry	40 V/cm, 50ºC, 20 min.	Higher yield of phenolic compounds up to 37%, reduction of treatment time by 34%	Kantar et al. 2021
OH + US	Whey protein concentrate	150 V/cm, 50 Hz, 15s 24kHz, 400W, 15 min.	Significantly improved the degree of hydrolysis, antioxidant activity and enhanced ingredients functionality	Alizadeh & Aliakbarlu, 2020
OH + Vacuum	Tomato paste	3,64 V/cm, 87,30ºC, 0.3 bar	Higher preservation of vitamin C, lycopene and sensory properties, lower concentrations of hydroxymethylfurfural and pectinmethylesterase	Alkanan et al., 2021
OH + Vacuum	Orange juice	27 kPa, 66ºC, 20, 25, 30 V/cm	Reduction in concentration time, higher viscosity, better color retention and less vitamin C degradation	Hwang et al., 2022
OH + Vacuum	Guava juice	14,95 V/cm, 550 mmHg, 50-70ºC	Higher preservation of juice quality compared to conventional vacuum concentration	Vangapandu & Bitra, 2023
OH + Vacuum	Pomegranate juice	7.5, 10,12.5 V/cm 180 mmHg	Concentration time reduced by 56% compared to conventional vacuum concentration	Icier et al. 2017
OH + Vacuum	Tomato concentrate	40 kPa 20, 25, 30 V/cm	Reduced treatment time by 10-30% compared to ohmic heating under atmospheric conditions, higher lycopene content, preservation of juice quality	Fadavi et al., (2018)
OH + Preservatives	Mango pulp	1% potassium sorbate, 0.5% sodium benzoate and 0.5% citric acid, 20 V/cm,75ºC	Microbial stability in a refrigerator for a period of 90 days	Priyadarshini et al., 2023

OH + Preservatives	Salsa	0.2 mg/g carvacrol, 60 Hz, 12,1 V/cm. 50 s.	More than 5 log inactivation of *E. coli O157:H7*, *S. Typhimurium* and *L. monocytogenes*, the microbial inactivation was 0.6 and 2.1 log in single treatment with carvacrol and ohmic heating respectively	Kim & Kang, 2017

OH – Ohmic heating, UV - C irradiation – Ultraviolet C irradiation, PEF – Pulsed Electric Field, HPP – High Pressure Processing, US – Ultrasound

10. Ohmic heating of packaged food

Ohmic heating through an electrically conductive food package is a new approach to heating the food and its package as a whole after packing to minimize the risk of post-process contamination, avoid expensive aseptic packaging lines, and meet consumer needs (Kanogchaipramot et al., 2016; Kamonpatana, 2018). This approach involves the passage of electric current through a package located in a conductive medium, whereby the food in the package is heated while avoiding contact with the electrodes (Kanogchaipramot et al., 2016). A food packaging material that allows the electrical current to pass through it will permit the sterilization of food products, as the food's microbial inactivation occurs inside the packaging material (Alves et al., 2021). However, most packaging materials are inappropriate for ohmic heating since polymer film is generally an electrical insulator that blocks the passage of the current, while metal foil is a good electrical conductor that results in excessive current and risk of equipment damage (Kamonpatana, 2018; Kanogchaipramot et al., 2016). To increase the electrical conductivity of the package, a laminate could be used, consisting of a certain combination of an inner polyethylene (PE) film, aluminum foil, polyester with an outer nylon layer, and two (or more) V-shaped metal foils used as electrodes placed between the folded laminate pouch. This method has been observed to have uneven heating of the food, with cold zones on the non-electrode sides as well. However, there are ways to overcome this, and there are currently better solutions (Kamonpatana, 2018): one solution proposed by Kanogchaipramot et al. (2016) to eliminate the cold zones at the edges and corners of the package, is necessary that the conductive medium has a higher electrical conductivity than the food in the package.

Moreover, the incorporation of conductive nanoparticles in the polymer matrix improves the electrical conductivity of potential packaging material. The research is going in the direction of the development of conductive biodegradable polymer nanocomposites (Tamjid et al., 2024). For example, conductive fillers, such as carbon particles, can significantly increase the electrical conductivity of the polymer material used for packaging. For ohmic heating and pulsed electric field, carbon black has been incorporated into polypropylene (PP) and ethylene vinyl acetate (EVA) as electrodes (Kamonpatana, 2018; Kanogchaipramo et al., 2016); while Alvez et al., (2021) proposed the incorporation of ZnO and reduced graphene oxide (rGO) nanoparticles to increase the electrical conductivity (0.1 S/m) of biopolymers such as alginate-based films. Incorporating starch and graphene into polyvinyl alcohol (PVA) significantly increased the electrical conductivity of the nanocomposite (Bin-Dahman et al., 2017). Polyethylene (PE) nanocomposites with silica nanoparticles (SiO2) and multi-walled carbon nanotubes increased electrical conductivity up to 1.1 x 10-4S/m (Bhong et al., 2024). The flexible bionanocomposite of cytosan and reduced graphene oxide (rGO) showed good electrical conductivity of 0.7 S/m in-plane and 2.1 x 10-5 S/m through-plane (Barra et al., 2019). Graphene-based nanocomposites, in addition to good barrier properties, are also used to improve the mechanical, thermal, and electrical properties of food packaging materials (Rossa et al., 2022). Sihori et al. (2019) reported that an Ag/PVA nanocomposite with triangular-shaped Ag nanoparticles distributed evenly demonstrated superior electrical conductivity of 3,45 x 10-4 Ω-1cm-1. It also increases the electrical conductivity and thermal stability of the package by incorporating CuO nanofillers (Gopitanth et al., 2024) and TiO2 nanoparticles (El Gohary et al., 2023). However, further research is needed for the development of suitable electro-conductive packaging with good electrical and thermal properties, as well as research on the migration and toxicity of packaging components to food during ohmic heating of packaged food (Kamonpatana, 2018; Garcia et al., 2018).

Conductive film via ohmic heating may offer significant benefits in food packaging, whether for liquid or liquid-solid food. The following requirements must be met by packaging to be commercially viable: optimization of the formulation of conductive packaging materials, every layer should provide a conductive window that allows electricity to pass through them to heat the food inside, metal foil should be avoided to prevent overheating and excessive current, the conductive film's shape and size should be designed to provide uniform heating, there should be no or minimal migration of contaminants from packaging material to food, thermal stability of material and reasonable price (Kamonpatana, 2018).

11. Limitations of ohmic heating

The industrial adoption of Ohmic heating requires addressing several limitations. One limitation is the possibility of negative effects on the chemical composition of the product; additional limitations include the high capital investment required for implementing ohmic heating technology and the corrosion of the electrodes due to electrochemical reactions (Hosseini et al, 2022; Alkanan et al., 2021). Furthermore, ohmic heating is not suitable for processing foods with a high-fat content due to fat's low electrical conductivity caused by the absence of water and salts. Therefore, the ohmic process conditions must be optimized according to the food properties to achieve the best result (Jafarpour & Hashemi, 2022; Alkanan et al., 2021). In general, it is complex to control, monitor, and achieve the required temperature and electric field distribution (Jan et al., 2020).

12. Conclusion

Ohmic heating is one of the most economical alternatives available to the food industry for thermal processing, as it is based on electricity only. It is widely applied in pasteurization, sterilization, drying, concentration, extraction, fermentation, microbial inactivation, thawing, enzyme inactivation, as well as the preservation of nutrients and sensory properties of food. Ohmic heating causes fast and uniform heating of food, which results in less thermal damage to food, shorter heating time, energy efficiency, better microbial stability, reduced degradation of plant pigments, and preservation of vitamins and antioxidants. Ohmic heating is widely used in the food industry to process food of both plant and animal origin.

Optimizing the process according to the type of food medium and final demands is crucial for achieving high product quality and achieve energy efficiency. Combining ohmic heating with other non-thermal food preservation technologies shows a synergistic effect - reducing of duration and intensity of the process, preserving nutritional components in food, and achieving microbiological and enzyme stability. Ohmic heating of packaged food is a new approach that provides minimization of the risk of post-process contamination, avoiding expensive aseptic packaging lines and meeting consumer needs.

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