Chapter 3

Ohmic Cooking in Food Technology

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Abstract

Cooking is an important process for food technology. Many foods must undergo a cooking process before they are consumed. Recently, it has been observed that especially cooked products have become more common in markets. At this point, the method used in the cooking process become more of an issue. Traditional heating techniques in the food industry utilize conduction, convection, or radiation to transfer heat from an environment like water, air, or oil to the food. However, due to the product size and shape, it can take a significant amount of time for heat to reach the center and achieve a safe internal temperature. This often results in uneven cooking, with some areas being overdone while others remain undercooked, ultimately compromising the product's quality (Kumar et al., 2014). As a result, alternative technologies are needed to address these challenges. Ohmic cooking is a promising emerging method for food processing that offers a potential substitute for traditional heat treatments. This technique produces heat internally by applying an alternating electric current directly to the food, the food electrical resistance produces thermal energy through joule heating. Essentially, in ohmic cooking, the food itself becomes a component of the electrical circuit (Jafarpour et al., 2022). Therefore, ohmic heating and cooking are of interest for food processing and industrial applications (Liu et al., 2007).This study presents the findings of investigations on ohmic cooking, the principle of ohmic cooking, the basic components of ohmic cooking, the advantages of ohmic cooking, the limitations of ohmic cooking, and the comparison of ohmic cooking with conventional cooking and the combination of ohmic cooking with other cooking methods.

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1. Introduction

Ohmic cooking, or Joule heating, works by applying an alternating electric current directly to the food, which generates heat interiorly. This technique provides quick and even heating, resulting in greater energy efficiency and enhanced food quality. Ohmic heating enables swift temperature increase in materials, usually occurring within seconds to a few minutes (Farahnaky et. al., 2018).

Ohmic cooking is commonly categorized as one of the 'innovative food processing technologies.' The key innovation of ohmic heating rests in its capacity to generate heat internally within the food, distinguishing it from other conventional heat processing methods that rely on heat transfer through conduction or convection, as seen in most heat exchange systems. The rate at which heat is generated per second (heating rate) is influenced by both the voltage gradient and the electrical conductivity of the material. The primary factor affecting the ohmic heating rate is the electrical conductivity of the material, which is influenced by various factors, including temperature, ionic strength, the microstructure of the material, the presence and concentration of a second phase, and the concentration of non-electrolytes, among others (Vicente et al., 2006).

Ohmic heating has been shown to efficiently process a variety of liquid and liquid-solid food products in a relatively short time. Research has demonstrated its effectiveness in pasteurizing juices. The efficiency of this method is influenced by external factors such as electric field strength and frequency, as well as internal factors like pH and sugar content. One of the key advantages of ohmic heating is the consistent temperature distribution within the product, which prevents surface overheating and helps maintain the food's sensory qualities. Compared to conventional thermal methods used in commercial settings, ohmic heating requires less energy and significantly reduces heating time. Some studies have found that the shelf life of foods treated with ohmic heating is equal to or even longer than that of those processed with traditional heat methods. Additionally, a wide range of research supports the conclusion that ohmic heating is highly effective in various food manufacturing processes, with minimum impact on the nutritional, functional, and sensory attributes of food, while enhancing product quality and contributing to enzyme inactivation (Alkanan et al., 2021).

1.1. The Principles of Ohming Heating

Ohmic heating derives its name from Ohm's Law which forms the basis of the process. The fundamental principle involves applying Ohm's Law, represented by the equation:

$R = V/I$

R (ohm) is the resistance between two points in a circuit, V is the voltage (volt) and I is the current (ampere) (Kumar et al., 2014; Aurina & Sari, 2021).

As stated by Ohm's Law, the electric current flowing through a conductor increases with the applied voltage and decreases with higher resistance. To generate electrical current, a power source or generator is essential. The electric current flows through the matrix via electrodes that contact the food. The electrode gap can be adjusted to achieve the desired electric field strength. Electricity from the generator travels to the first electrode, passing through the food placed in the electrode gap. The food's resistance to current flow causes internal heating. The current then moves to the second electrode and returns to the power source, completing the circuit. The insulator cap around the electrodes regulates the environment inside the device. The two primary factors affecting heat generation are the electric field strength and the residence time (Kour et al., 2023).

1.2. The Role of Electrodes in Ohmic Heating

In ohmic heating, electrode surfaces function as an interface between a solid-state conductor and a liquid or semi-solid conductive medium. These interfaces play a vital role in ensuring efficient current transfer into the heating environment. From an electrochemical perspective, it is well established that both the physical structure and chemical composition of electrode surfaces significantly affect the interfacial phenomena occurring at the electrode–electrolyte boundary. With certain electrode materials, specific electrochemical reactions may exhibit sluggish kinetics or may not proceed at all, while with different electrodes, the same reaction may happen more rapidly under identical conditions. Therefore, understanding the behavior of electrodes in ohmic heating is essential to prevent or control electrochemical reactions by selecting suitable electrode materials (Liu et al., 2007).

1.3. Key Components of Ohmic Cooking Systems

Ohmic cooking operates through the integration of several essential components that collectively enable efficient, uniform, and precisely controlled heating. These elements are fundamental to achieving optimal outcomes in terms of both product quality and energy performance. The power source, electrodes, and the electrode spacing collaborate to generate the electric field required for consistent internal heating of the food matrix. Meanwhile, components such as the insulator cap and cooling system play a crucial role in maintaining operational safety and system stability. Accurate and responsive temperature regulation ensures that cooking is consistent and preserves the desired sensory and nutritional characteristics of the food. By carefully selecting electrode materials and optimizing system parameters, ohmic heating setups can be customized for a broad spectrum of food types, enhancing both processing efficiency and final product quality. The following provides an overview of the core components of an ohmic cooking system and highlights their significance in the overall process.

1.3.1 Power Supply

The power supply serves as a fundamental component of an ohmic cooking system, responsible for delivering the electrical current that flows directly through the food to generate internal heat. It must be capable of precisely regulating both voltage and current in accordance with the specific electrical and thermal properties of the food being processed. This regulation is essential to ensure safe and efficient system operation, maintaining a stable and consistent energy input throughout the cooking cycle. By controlling the intensiveness of the electric field applied across the food matrix, the power supply directly affects the heating rate and consistency, thereby playing a critical role in achieving the desired thermal performance and product quality (Suh et al., 2006).

1.3.2. Electrodes

Electrodes function as the primary conductive elements in an ohmic cooking system, responsible for delivering electrical current directly into the food matrix. They are commonly constructed from high-conductivity, corrosion-resistant materials such as stainless steel or graphite to withstand extended operational conditions without degradation. Positioned in direct contact with the food, the electrodes facilitate the flow of current through the product, inducing volumetric heating. The overall efficiency and performance of ohmic heating are significantly impacted by the selection and configuration of electrode materials. Appropriate material choice ensures stable electrical conductivity, minimizes the risk of electrochemical reactions, and supports consistent thermal transfer. Additionally, factors such as electrode surface area and spatial arrangement play a crucial role in promoting uniform current distribution and achieving homogeneous heating throughout the product (Liu et al., 2007).

1.3.3. Food Product (Heating Medium)

In ohmic cooking, the food itself serves as the medium for heat generation, with its electrical resistivity playing a key role in determining how effectively electrical energy is converted into heat. Foods with higher resistivity produce more heat when exposed to the same electrical current, resulting in faster and more efficient heating. One of the main advantages of ohmic cooking is its ability to heat food uniformly throughout, from the inside out, thereby reducing the risk of overcooking or uneven heat distribution, which is often encountered with traditional heating methods (Kour et al., 2023).

1.3.4. Electrode Gap

The electrode gap, which is the distance between the electrodes, is a critical parameter influencing the efficiency of the ohmic heating process. This gap directly affects the intensity of the electric field within the food product. A smaller gap generally results in a stronger electric field, leading to faster heating, while a larger gap weakens the field and slows down the heating rate. By adjusting the electrode gap according to the specific characteristics of the food being processed, uniform heat distribution can be achieved. Optimizing the gap size is essential for enhancing energy efficiency, reducing cooking time, and ensuring consistent product quality throughout the process (Jayasinghe et al., 2009).

1.3.5. Insulator Cap

The insulator cap encases the electrodes and is essential for ensuring both safety and operational efficiency in the ohmic cooking system. It serves to prevent accidental electrical contact and shields the system from potential short circuits. By directing the electrical current exclusively through the food product, the insulator cap protects other components from damage. Additionally, it helps control the environmental conditions within the cooking chamber, preserving both the food's quality and the integrity of the electrodes during the process. Effective insulation is crucial for maintaining food safety while enhancing the durability and longevity of the system (Suh et al., 2006).

1.3.6. Temperature Control System

Precise temperature regulation is vital in ohmic cooking to prevent both overheating and underheating of the food. The temperature control system consists of sensors that continuously monitor the temperature of the food and electrodes. These sensors send real-time data to a control unit, which adjusts the power supply to maintain the target temperature. Consistent temperature control is essential for preserving the food's texture, flavor, and nutritional value, while also preventing damage caused by overexposure to heat (Kour et al., 2023). This system ensures that the food is cooked uniformly and accurately, maintaining high-quality standards.

1.3.7. Cooling System

A cooling system is utilized to remove excess heat from the system, ensuring that optimal operating temperatures are maintained. It is crucial for preventing the overheating of the electrodes, power supply, and other critical components of the cooking system. Without proper cooling, heat accumulation could decrease system efficiency and shorten the lifespan of its components. The cooling system may incorporate air or water-based methods to effectively regulate the temperature and maintain the system's performance (Jayasinghe et al., 2009).

1.3.8. Electrode Material

The choice of material for the electrodes is critical to the system's performance. Materials such as stainless steel and graphite are commonly selected for their excellent electrical conductivity and resistance to corrosion. These electrode materials are durable, capable of withstanding prolonged exposure to both food products and electrical currents without deterioration. The material selection impacts both the efficiency of the heating process and the overall longevity of the system (Liu et al., 2007). Materials that are resistant to corrosion ensure the long-term effectiveness of the electrodes, reducing the need for frequent maintenance or replacement.

1.4. Comparing Ohmic Cooking with Conventional Methods

Studies comparing ohmic and conventional cooking have been reviewed and some of them are presented below.

Piette et al. conducted a study to assess the feasibility of ohmic heating as an alternative thermal processing technique for the cooking of processed meat products, specifically examining its effects on selected physicochemical and sensory quality parameters relative to those produced using conventional smokehouse methods. The study found that variations in electrical heating rate, core temperature endpoints, and a standardized 20-minute isothermal holding phase exerted negligible influence on the overall quality attributes of ohmic-cooked sausages. Notably, the ohmically processed sausages demonstrated comparable characteristics to their traditionally smoked counterparts across most measured parameters, with the exception of texture, which was consistently softer ($P > 0.05$) in ohmic samples (Piette et al., 2004).

De Halleux et al. investigated the applicability of a resistive (ohmic) heating cell for the thermal processing of Bologna ham, with a focus on evaluating its energy efficiency and pasteurization performance. Utilizing a prototype ohmic cooking cell, the study demonstrated the feasibility of conducting accelerated batch cooking operations. In comparison to conventional smokehouse techniques, the ohmic process achieved a substantial reduction in processing time—by approximately 90–95%—alongside significant energy savings ranging from 82% to 97% (De Halleux et al., 2005).

Bozkurt and İçier assessed the feasibility of ohmic heating as an alternative thermal processing method for meat products by comparing its effects on quality parameters with those of conventional cooking. In their study, beef samples containing different fat levels were exposed to ohmic heating under electric field strengths of 20, 30, and 40 V/cm, as well as to traditional cooking techniques. The findings indicated that ohmic heating offers a rapid and efficient alternative for thermal processing of meat products, with potential advantages in processing time and quality retention (Bozkurt & İçier, 2010).

Farahnaky et al. evaluated the impacts of ohmic heating on the stability of key bioactive constituents; ascorbic acid, flavonoids, and phenolic compounds, in selected vegetables including turnip, kohlrabi, radish, and potato, by comparing conventional and microwave processing methods. The findings indicated that conventional heating, due to its extended processing durations and higher thermal load, led to significant degradation of nutritionally valuable phytochemicals. Ohmic heating was found to enhance the rate of texture softening while promoting superior retention of vitamin C and other bioactive compounds, thereby demonstrating its potential as a more efficient and nutritionally favorable alternative to conventional thermal treatment systems (Farahnaky et al., 2018).

Gavahian et al. investigated the effectiveness of ohmic and microwave heating techniques for Middle Eastern-style rice preparation, comparing them with conventional hotplate-based cooking, with particular emphasis on the alterations in physical and textural attributes of rice grains during thermal processing. The study found that microwave heating did not significantly reduce cooking time, whereas ohmic heating effectively mitigated several limitations associated with traditional methods, including extended processing duration, elevated energy consumption, and surface fouling. Ohmic heating demonstrated superior energy efficiency and reduced the thermal come-up time by approximately 48% compared to conventional cooking. Additionally, kinetic analysis of texture modification revealed that ohmic heating facilitated a higher softening rate of rice grains relative to other evaluated methods (Gavahian et al., 2019).

Tumpanuvatr and Jittanit compared the quality characteristics of brown rice cooked using ohmic and conventional methods, along with their respective energy consumption. The study found that ohmic heating significantly reduced the degree of retrogradation in the cooked rice samples compared to conventional cooking. However, the ohmic cooking system exhibited higher electrical energy usage, requiring approximately 1.7 to 2.6 times more energy than the conventional method under similar processing conditions (Tumpanuvatr & Jittanit, 2022).

Astráin-Redín et al. explored the application of specific power input and cooking value to evaluate product-process interactions and to compare performance with conventional cooking methods. The study aimed to evaluate the impact of varying specific power remarks on the texture and cellular injury of carrots, and to compare an optimised ohmic cooking process in comparison with conventional boiling based on physical properties and energy efficiency. The results indicated that ohmic cooking achieved greater softening and more extensive cell breakdown in carrot tissue compared to conventional boiling. Furthermore, the use of ohmic heating notably decreased both cooking duration and energy consumption (Astráin-Redín et al., 2024).

1.5. Combining Ohmic Cooking with Other Methods

There are some studies in the literature where ohmic and other cooking methods are carried out together. These are presented below.

Özkan et al. investigated the combined use of ohmic and plate heating for cooking hamburger patties, finding it highly effective in reducing cooking time and enhancing product safety. They summarized their experimental study on the hamburger patties quality cooked using both conventional and ohmic-assisted methods, evaluating various properties such as mechanical strength, oil content, and moisture levels. The findings indicated that no notable differences were observed in the characteristics of patties prepared using either cooking method (Özkan et al., 2004).

Choi et al. proposed the combination of ohmic and microwave heating to enhance the consistency of heat treatment in foods containing solid particulates. In their research, they developed and successfully validated simulated heating patterns for both solid and liquid phases under ohmic and microwave combination heating, accounting for dynamic fluid flow. They suggested that their findings could aid in the design of a continuous flow system combining ohmic and microwave heating technologies, which would minimise the risk of overprocessing or underprocessing during heat treatment (Choi et al., 2011).

Sengun et al. investigated the impact of a combined ohmic–infrared cooking system on the meatballs microbiological quality, where the meatballs underwent infrared cooking following an ohmic precooking treatment. The treated meatballs were analyzed for the presence of total mesophilic aerobic bacteria, molds and yeasts, *Clostridium perfringens*, *Staphylococcus aureus*, *Listeria monocytogenes, Salmonella spp*., and *Escherichia coli* O157:H7. The study concluded that this two-step cooking process effectively enhanced the microbiological safety of the meatballs (Sengun et al., 2015).

Uzun Özcan et al. examined the effect of ohmic cooking alone and its sequential application with infrared cooking on lipid oxidation and the formation of polycyclic aromatic hydrocarbons (PAHs) in beef. The study found that both lipid oxidation and PAH concentrations increased at higher ohmic voltages and elevated infrared temperatures. Optimal conditions, such as using 40 and 55 volts for ohmic cooking alone, and combinations like 40 V–325 °F or 40 V–375 °F for ohmic-infrared cooking, were identified to maintain TBARS values below the acceptable threshold (<1 mg/kg MDA). Additionally, PAH levels across all treatment groups remained below the legal limits set by the European Commission, indicating that the ohmic cooking process followed by infrared treatment is safe in terms of PAH content (Uzun Özcan et al., 2018).

Joe et al. created ohmic and vacuum integration heating system designed to process senior-friendly food products consisting of both solid components and liquid. By integrating vacuum and agitation with ohmic heating in multiphase food, they effectively reduced the base solution boiling point, improved the model food thermal consistency, and facilitated the softening of solid particles. This approach also helped prevent excessive heat treatment within the multiphase food. Moreover, this heating system with agitation shows significant promise for processing senior-friendly foods, enhancing the texture of solid-phase ingredients, and improving thermal consistency (Joe et al., 2021).

Turgut et al. studied the combined application of ohmic heating and convective drying as an innovative approach to drying. Processing conditions, as the velocity of air, temperature of drying and applied voltage were examined to minimize the drying time of potato slices and to assess their impact on certain quality attributes of the final product. Ohmic assisted drying system effectively reduced both time and cost by eliminating the blanching stage in the drying process, owing to the substantial enzyme inactivation achieved (Turgut et al., 2022).

1.6. Advantages of Ohmic Cooking

The ohmic system has gained significant attention from researchers due to its high electrothermal efficiency, straightforward design, ease of equipment control, and consistent, rapid heating. Furthermore, its lack of waste byproducts and extremely low operational costs offer notable advantages (Ding et al., 2021).

In an ohmic heating system, the food experiences rapid and uniform heating (1°C/s) throughout, ensuring consistent temperature distribution in both solids and liquids when their resistances are similar. Additionally, heat transfer coefficients do not constrain the heating rate and temperatures suitable for Ultra High Temperature (UHT) processing can be efficiently attained in this system. In ohmic cooking, unlike conventional heating, heat transfer occurs without the presence of hot surfaces, eliminating the danger of surface fouling or burning, which reduces the need for frequent cleaning. Moreover, compared to microwave heating, the capital costs of the ohmic cooking process are lower. Ohmic cooking ensures that thermally sensitive foods or components are protected from localized thermal degradation due to the consistent distribution of heat and it boasts high energy conversion efficiencies (>90%). Furthermore, the ohmic process is well-suited for continuous processing (Sastry, 1994; Rahman, 1999).

Ohmic cooking enables exact temperature regulation, that is critical for maintaining both food safety and the quality of the final product. In certain applications, it can lead to lower nutrient degradation compared to conventional thermal treatments like extended boiling, owing to its rapid and uniform heat distribution. This efficiency allows for lower processing temperatures and shorter thermal exposure times. Furthermore, because heat is generated internally via electrical current, there is no reliance on external heating media such as water, thereby minimizing nutrient losses due to leaching. The swift microbial inactivation achieved through ohmic processing may also reduce the necessity for chemical preservatives.

Moreover, the limited thermal exposure helps preserve the structural and sensory integrity of the food, reducing the need for additional additives to restore quality attributes typically compromised by traditional heat processing (Dos Santos et al., 2024).

1.7. Limitations for Ohmic Cooking Process

Ohmic heating, despite its benefits like quick and uniform heating, has several drawbacks that can limit its use in food processing:

High Initial Equipment Costs: Establishing ohmic heating systems requires significant initial investment, which can be a barrier for small-scale operations. The initial investment in ohmic heating systems is higher compared to conventional methods (Alkanan et al., 2021).

Limited Applicability to Low Conductivity Foods: Foods with high fat content, especially those containing fat granules, do not heat efficiently with ohmic heating due to their low electrical conductivity, as they lack sufficient water and salts. This can lead to uneven heat treatment, where pathogenic bacteria within the fat granules are less exposed to the heat compared to bacteria outside the fat particles. Furthermore, as temperature increases within the system, so does the electrical conductivity of both the food and the solution due to enhanced electron movement (Alkanan et al., 2021).

Electrode Corrosion and Electrochemical Reactions: Another challenge is the electrode corrosion caused by the reactions of electrochemical, which not only influences the system efficiency and the food quality but also increases maintenance costs as the process continues (Alkanan et al., 2021; Jafarpour D. et al., 2022).

Potential quality issues: Certain studies have indicated that ohmic heating may negatively impact specific physical attributes of food products, including color stability (Jafarpour D. et al., 2022). Depending on the composition of the food matrix and the applied processing parameters, ohmic heating may adversely impact sensory attributes such as texture, color, and flavor. Additionally, a potential drawback is the migration of metallic ions from the electrodes into the food product, which could pose safety or quality concerns (Dos Santos et al., 2024).

Frequency Limitations: Some researchers have pointed out that one such disadvantage is its narrow frequency range (Alkanan et al., 2021).

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