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Review Article

Effect of Ohmic Heating on Food Products: An In-Depth Review Approach Associated with Quality Attributes

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Nowadays, the market is full of lists of products produced by way of vivid processing, blended formulation, and other novel formulation practices. In a similar vein, ohmic heating (OH) has proven to be a successful replacement for traditional procedures. Although the microbial burden is substantially reduced, the aforementioned method also controls the sensory and functional qualities of meals. OH is regarded as a thermal treatment option that is less damaging to food constituents in comparison to traditional thermal methods. The said processing method retains vivid food constituents that are widely acknowledged under the significant nutritional and functional category, hence addressing healthy longevity. Furthermore, OH is the least severe category of thermal operation in competition with the most technologically advanced food processing operations. The current study emphasizes the crucial relevance of knowing the effects of OH on food ingredients, which will serve as a basis for optimizing this novel approach for a wide range of food products. The effects of OH on quality characteristics such as color, flavor, and texture are thoroughly investigated, offering vital insights into OH's capacity to maintain and enhance the sensory aspects of food items. Furthermore, the study looks at the effect of OH on nutritional contents, emphasizing the need to strike a careful balance between ensuring microbiological safety and retaining the nutritional integrity of treated foods. This literature survey closely examines the impact of OH on microorganisms, enzymes, color, and rheological and textural attributes of food, along with the deterioration of diverse bioactive substances, including phenolics and carotenoids, as well as vitamins. Besides, the paper explains the effect of the inactivation mechanism of microorganisms. The findings serve as a platform for future research and development, as well as a road map for the effective deployment and commercialization of OH technology in a variety of food industries.

1. Introduction

Prevention, reduction, and elimination of pathogenic microflora and their toxins are the supreme motives of food processing operations, despite having sound quality produce. Hygiene operations alone never fulfill this target adopted by any food enterprise to contribute to food safety and food security aspects of a nation. Moreover, in this way, the obtained food eatables are a source of excellent quality that contributes somehow to the development of a healthy nation and also boosts the economy of the country [1, 2]. For the most part, food products are processed using conventional heating techniques, but conventional technologies are part of systems until a new process or technology comes into existence. The sluggish heat transfer rate obtained through these conventional systems is detrimental to food constituents. They somehow absorb high heat as the product surface, allowing more surface hardness and lowering product quality [3]. For the above-mentioned reasons, there is a dire need to explore some novel heating methods.

OH is one of the novel thermal heating techniques that utilize alternating current to heat up the food product, wherein the electrodes are immersed in the food product, the current is distributed, and the food gets heated up (Figure 1). Heat is equally induced across the entire bulk of the food during OH hours [4]. OH results in more and faster heating, is cleaner and more environmentally friendly, and maximizes food nutritional content recovery. OH can cause

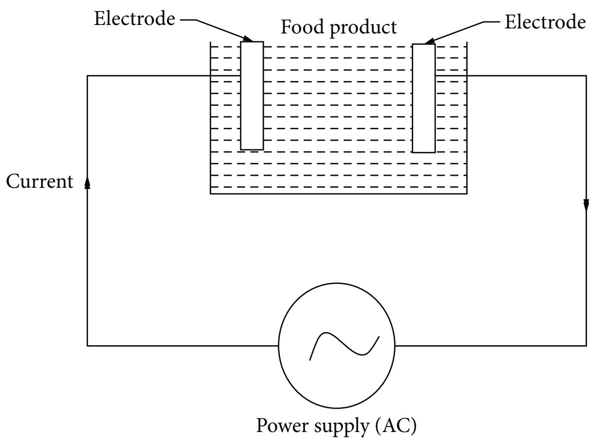

Figure 1: Schematic diagram of OH setup.

things to heat quickly and uniformly without causing thermal harm to heat-treated materials [5]. OH is less altered by modifying the thermal characteristics of foodstuffs than by various heating techniques such as induction and microwave heating. OH results in improved thermal efficiency during juice processing. This is due to the faster conversion of alternating current into thermal energy [6]. With the passage of the current, a homogeneous temperature distribution will be easily obtained. Also, it generates no waste after heating the material, and there is no need for steam or hot water for heating [7]. Because it delivers homogeneous heating with a low-temperature gradient, OH has numerous advantages over traditional heating technologies [8]. With homogenized heating, both phases of the product, such as the solid and the liquid, are heated at a higher pace during OH. Because there are no heated surfaces, surface fouling is reduced during ohmic heating. It also reduces the possibility of heat damage to the sample. Ohmic heating also yields high-value finished goods with minimal anatomical, nutritional, or sensory modifications [4].

The paper elaborates on the benefits of using OH in terms of the quality parameters of various food products and their effect on various microorganisms and pathogens. Based on the literature, it gives a clear understanding of the inactivation mechanism and the changes in various attributes of a variety of food products treated with OH. The investigation of the effects of OH on food ingredients is critical for optimizing this technique for diverse food items. It enables researchers to create techniques that reach the needed levels of safety and quality while minimizing negative impacts on the nutritional, sensory, and structural elements of food. The current study examines the impact of OH on the nutritional composition of food, extensively highlighting the microbiological safety aspects and preserving the nutritional quality of processed food items. This comprehensive review would help researchers and scientists have a clear understanding of the effect of OH on various quality aspects of multiple food products and would certainly help entrepreneurs check for loopholes so that the technology can be commercialized.

2. Impact on Food Quality

The OH technology has several advantages over traditional methods, such as retaining the nutritional value of the food, destructing bacteria and enzymes, and reducing fouling [9]. Based on recent studies, the effect of OH on food quality and various food constituents is shown in Figure 2. The impact of OH on quality parameters has been reviewed for different food products. Extensive studies have been carried out to understand the effects of ohmic heating on the quality of different fruit and vegetable juices (Table 1). Many of them reported that the quality of fruit juices was preserved due to the inactivation of enzymes like PPO. Some researchers have observed reductions in bacterial counts in vegetable juices like tomato juice. Processing conditions like time and temperature also affect the juice quality. Ohmic heating applications in meat products have also been proven. Studies have been undertaken in chicken, meat, fish, and egg to understand the effect of OH in various quality aspects. Apart from the benefits of reducing the harmful microbes from meat products, ohmic heating helps to reduce the total cooking time (Table 2). Ohmic heating has been successfully applied in milk to reduce the microbial load. Many of the researchers have attempted OH of milk at different processing conditions and reported its impact on milk quality (Table 3). They observed an enhanced shelf life of ohmic-heated milk when heated to around 75°C. The energy requirement for pasteurization was also less in OH milk compared to conventional pasteurization [10]. Table 4 illustrates the effect of OH on the quality of milk products like flavored milk, whey, and infant formula. Researchers reported enhanced antioxidant activity, reduced processing time, etc., for different milk products with different processing conditions. Apart from fruit and vegetable juices, OH finds applications in fruit and vegetable paste, pulp, etc., for maintaining quality by reducing microbial load and enzymatic activity (Table 5). Ohmic heating applications are wider nowadays, and researchers have investigated the possibility of OH in fruit peeling [11], texture improvement in noodles [12], rice bran oil extraction [13], etc. Table 6 depicts the effects of OH on various quality aspects of some other food products, which are not discussed in Tables 1–5.

2.1. Effect on Microbiological Inactivation. Microbial inactivation is necessary to enhance the shelf life of a food product. More than the permitted number of microorganisms causes deterioration and degrades the product's flavor, texture, and color. Researchers in pursuit of exploring various energy-efficient methods for inactivating microorganisms found OH to be a promising technology. Numerous investigations have shown that heating is mostly responsible for microbial inactivation during OH [14]. Due to the presence of the electric field in OH, minimal nonthermal cellular damage takes place. At low frequencies of applied alternating current (<60 Hz), cell walls develop pores by collecting charges and may have a more deadly effect. As illustrated in Figure 3, the electroporation process may explain the impact of OH on microbe inactivation [15]. Pores are formed during OH, and membrane permeability increases,

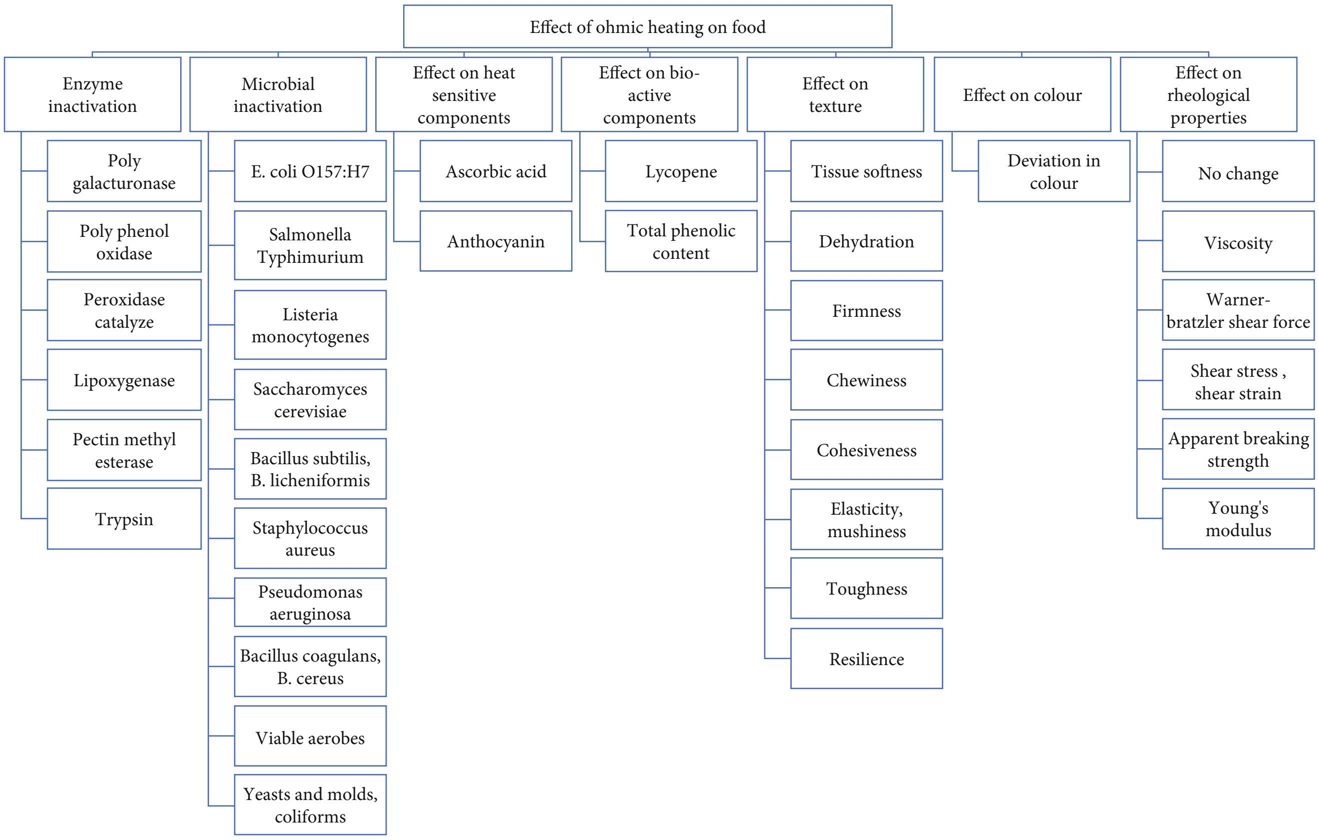

Figure 2: Effect of OH on various quality aspects of food.

resulting in electroosmosis and material diffusion across the membrane. Proteins and lipids are found in the cell membranes of living cells. The cell wall is a layer that covers the membrane of certain living cells, such as prokaryotes. With the introduction of an electric field during OH, charges build up in the cell membrane, creating dielectric strength and holes. It has something to do with the lipid composition of the cell membrane. Electroporation generates an increased outflow of intracellular components when the electric field is too strong [16].

Loghavi et al. [17] reported the effects of moderate electric fields (Em) on the production of bacteriocin (lacidin A) during fermentation and the kinetics of microbial growth in *L. acidophilus* (OSU 133). At a constant temperature of 30°C, different processes were compared, viz., normal fermentation (35 h), Em (1 V/cm, 60 Hz, 40 h), combinations of 12 normal fermentations (35 h), combinations of Em (1 V/cm, 60 Hz, for 40 h), combinations of Em (1 V/cm, 60 Hz, for the first 5 h), and discrete Em. It was observed that Em treatments had the maximum bacteriocin activity, but conventional fermentation at 37°C generated the least quantity of bacteriocin. Using varying electric fields and frequencies, Li et al. [18] investigated the feasibility of using OH to avoid brown enzymatic staining on the quality of water chestnut juice. The efficacy of the peroxidase enzyme could be improved by OH, but after that, the enzyme's activity started to decline rapidly. An increase in electrical conductivity during OH resulted in a higher level of enzyme inhibition. Similar results associated with enzyme inhibition were also reported by [19, 20]. The major advantage of OH-assisted blanching is a significant reduction in inactivation time [21–23]. Nonthermal activation behavior of OH plays an important role, especially in the case of enzymes and microbial inactivation [24].

2.2. Effect on Color. The product's acceptance is influenced by its color. Heat may change the color of food, lowering its nutritional value. Large color changes occur due to electrochemical reactions when OH is done at a low frequency [25]. According to one study, ohmic-heated meat samples changed color less than in normal cooking [26]. In the case of ohmic-processed chicken frankfurters, a homogenous color shift was visually observed when OH was performed at 45, 50, and 55 V. The color values of samples heated at 50 and 55 V had no noticeable difference [27]. The impact of OH on sugarcane juice color alteration was investigated at 24, 32, and 48 V/cm. Compared to high voltage gradients (32-48 V/cm), the lower color change was noted to be reduced at 24 V/cm [28]. The internal color of a food product is more sensitive to changes in cooking temperature and holding time than the outside color. An increase in the ohmic cooking temperature induced vibrant color on the inside of the meat samples. For instance, with a constant holding time of 3 minutes and a cooking temperature of 70°C, the value of L^* was 29.1, which improved to 34.4 when the temperature was raised to 100°C. Ohmic cooking

Table 1: Effect of OH on the quality aspects of juices.

Product	Electrical parameters	Processing time	Temperature	Impact
Aloe vera juice [90]	0.15, 0.25, 0.5 V	3, 5, 10 min	24-25, 19-20, 21°C	Inactivated enzymes, reduced turbidity, and quality were maintained for 60 days
Concentrated tomato juice [91]	13.4 V/cm	190-250 s	60-63°C	5-log reduction in bacteria population
Tomato juice [92]	20, 15, 10 V/cm at 60 Hz	90, 180, 480 s		5-log reduction in *E. coli* O157:H7, *Salmonella Typhimurium*, and *Listeria monocytogenes*
[93]	25 to 40 V/cm	30 s	76°C	5-log reduction in *Salmonella Typhimurium*, *Listeria monocytogenes*
Mango juice [94]	40 V/cm	60 s	80°C	Improved functional characteristics, 96% inhibition of polyphenol oxidase, 90% pectin methylesterase inactivation. Total phenol content was 8% higher
Apple juice [95]	30, 35, and 40 V/cm		60, 70, and 80°C	Enrichment in apple juice quality was reported at 80°C at voltage gradient of 40 V/cm due to the higher inactivation of PPO
Apple juice [94]	30, 35, 40 V/cm at 60 Hz		60, 70, 80°C	Increase in phenolic content in ohmic processed samples (5.4%) compared to control (2.5%)
Apple juice [96]	25 kHz, 26.7 V/cm	30 s	100°C	Spores were completely inactivated
Mulberry juice [97]	0.014 S/m to 0.039 S/m	90 min	80-90°C	EC, heating rate, and anthocyanin degradation increased proportionally with temperature
Orange juice [98]	32-36 V/cm	0-200 s	60-90°C	More pectin esterase inhibition in ohmic-treated samples
Coconut water [99]	10 V/cm and 20 V/cm at 50 Hz	3–15 min	70, 80, or 90°C	Prevented pink discoloration. Retarded PPO activity for 21 days
Chopped tomatoes with juice [100]	240 kW		102°C	65% energy conservation with ohmic treatment
Pineapple juice [101]	16 V/cm	1 min	80 ± 2°C	Voltage gradient has a significant impact on enzyme inactivation. A higher degree of polyphenol oxidase inactivation and loss of total phenolic contents was reported with an increasing voltage gradient

Table 2: Effect of OH on the quality of meat products.

Product	Electrical parameters	Processing time	Temperature	Impact
Meatballs [102]	15.26 V/cm at 50 Hz	0 sec hold	75°C	Yeasts and molds decreased with complete eradication of *S. aureus* but failed to inactivate monocyte cells
Ground beef [32]	20, 30, 40 V/cm at 50 Hz	Variable	70°C	Fast cooking, higher firmness, no reduction in yield or fat loss after ohmic cooking
Meat [103]	50 Hz, 8.33 V/cm	7 min	95°C	No bacteria were detected. The target species was *Listeria innocua*
Green mussel meat [104]	100, 120 V	5, 10 min	72°C	Enhanced physical, microbial, and organoleptic attributes
Chicken breast [105]	120 and 180 V. Salt concentration 0.2 and 0.4%	80, 120, 180 s	75°C	Enhanced heating rate
Smoked fish pate [106]	5 V/cm	8.28 min	78°C	Lower processing time and energy consumption. pH value and TBA were also lower, whereas the volatile nitrogen content was higher in samples subjected to ohmic treatment
Whole egg [107]	0–180 V 20 kHz (max 8 A)	1, 3, 4.5 min	65.5, 67, 70°C	OH adversely affects viscosity but improves the foaming and gelling properties. The shelf life was reported to be 30 days at 4°C
Sausage [108]	230 V at 50 Hz	210 s	75°C	Causes greater *Listeria monocytogenes* inactivation compared with conventional heating, and the postpasteurization time decreased

Table 3: Effect of OH on heat treatment of milk.

Product	Electrical parameters	Processing time	Temperature	Impact
Milk [14]	20 kHz, 7.3 to 2.0 A current variation and 70-12 V	1-30 min	57-80°C	The inactivation of viable aerobes was studied. Results showed lower *D*-values in heated ohmic samples as compared to those of water bath-treated samples
Milk [109]	80, 110, 220 V	15 s	72°C	Shelf life of ohmic pasteurized at 4°C for 15 days (no change in acidity and pH)
Milk [110]	0, 4, 6, and 8 V/cm	5 min	90–95°C	Reduced Listeria monocytogenes viability along with suitable Lactobacillus acidophilus counts and improved gastrointestinal tract survival of microbes
Milk [111]	4, 8, or 12 V/cm	15 s	72–75°C	The end product, Minas Frescal cheese, had better sensory attributes and improved antioxidant as well as antidiabetic properties
Buffalo milk [73]	0-200 Hz; 0-200 amperes		72°C	Total visible colonies of molds, yeast, coliforms, and Salmonella and E. coli were completely killed
Sheep milk [10]	40, 70, 100V at 60 Hz; 8.33 V/cm		73 ± 1°C	Lesser energy consumption in comparison to the traditional pasteurization process along with shelf life enhancement of milk up to 2 weeks under refrigerated condition
Pasteurized lactose-free milk [112]	0.635 S/m to 1.230 S/m	30 min	25-65°C	No significant difference was found in overall outcomes associated with the total acidity, specific weight, and protein content between the treated samples

Table 4: Effect of OH on the quality of milk products.

Product	Electrical parameters	Processing time	Temperature	Impact
High protein vanilla-flavored milk [113]	6.96 V/cm	12 min	72°C	Enhanced antidiabetic, antioxidant, lower hydroxyl methyl furfural contents in high protein milk along with antihypertensive activities and rheological properties
Blueberry-flavored dairy desserts [114]	1.88, 3.64, 5.45, 7.30, 9.1 V/cm	3 min	90°C	Antioxidant activity was increased. Besides, at 1.82 V/cm, electric fields preserved the bioactive compounds more significantly
Sweet whey [60]	2, 4, 5, 7, 9 V/cm at 60 Hz	15 s	72–75°C	Adverse effects in antioxidant capacity and the ACE inhibitory activity of bioactive peptides with the increase of electric field
Whey protein [58]	250 V, 20A, 50 Hz	15 min	60, 70, 80°C	Least changes in the tertiary structure of whey proteins, finer whey protein aggregates along with the greater clarity of the whey protein dispersions
Lactoglobulin protein [115]	4 V/cm	15, 1, and 30 s	72.5°C 90°C 65°C	The allergic perspective of beta-lactoglobulin-based products
Infant formula [116]	40, 60, 80, 100, 120 V at 60 Hz	15 s	72–75°C	Higher electric field strength (24 V cm^{-1}) resulted in an 83% reduction in total processing time, helping to retain color and superior aroma due to the formation of volatile components
[117]	6 V/cm; 60 Hz	45, 24, and 4 min	50, 55, and 60°C	Greater inactivation effect of Salmonella within a reduced treatment time along with enhanced bioactive compound formation

Table 5: Effect of OH on the quality of paste, soup, and pulp.

Product	Electrical parameters	Processing time	Temperature	Impact
Tomato paste [118]	8.3 to 27.8 V/cm	60 s	67-80°C	3-log reduction in *E. coli O157:H7*, *Salmonella* population, and *TL monocytogenes*
Tomato soup [119]	60 Hz and 10 kHz	0, 15, 60, 120 s 0, 15, 30, 90 s 0, 5, 10, 30 s	121°C 125°C 130°C	Spores (Geobacillus S. thermophilus) were significantly reduced (5-log reduction)
Black raspberry pulp [63]	23, 60, 125 V	0-90 min	70-90°C	At increased voltage, anthocyanin degradation was higher, whereas it decreased by reducing the voltage
Tomato by-product [120]	4, 6, 11 V/cm	30 min	0-100°C	Improved polyphenol extraction (77%) compared to that of the conventional process. There was lycopene extraction by 4.93 g/gFW without using any organic solvent
Mango pulp [121]	15.0–20.0 V/cm			The phenolic profile and bioactive compounds of mango pulp were significantly preserved
Mango pulp [122]	10–20 V/cm		60–80°C	Retention of quality parameters and closeness to fresh sample

exhibited a substantial impact on a^*, which decreased at higher cooking temperatures [29]. The use of OH for the concentration of orange juice under a vacuum condition resulted in better color retention [30, 31]. The cause behind the improved color retention in OH is a better reduction in enzymatic activities in the case of OH as compared to conventional heating methods [2, 32].

2.3. Effect on Rheological Properties. Icier [33] explored the effect of OH on the rheological properties of reconstituted whey solutions. The whey solutions were heated from 20 to 80°C by applying different voltage gradients (20, 30, and 40 V/cm; 50 Hz) using the ohmic setup. The shear rate and shear stress values of whey solutions were fitted to the Herschel-Bulkley model, which yielded a satisfactory result. The flow behavior index values were temperature and concentration-dependent. The OH-treated whey solutions exhibited time-independent non-Newtonian behavior. Icier and Bozkurt [34] analyzed the rheological properties of a liquid whole egg by heating it from 4 to 60°C using OH (20 V/cm; 50 Hz). Liquid eggs exhibited thixotropic characteristics, and the power law model provided a more compelling explanation for the rheological behavior. Liquid whole eggs exhibited a higher thixotropic index at pasteurization temperature. The Herschel-Bulkley model was the most acceptable rheological model to study the effect of OH on food products like dairy products, apples, and quince juice [35–37]. Studies show that the rheological properties of the product treated with OH and conventional heating methods are found to be almost similar; i.e., no extra effect of current or electrical processing is seen on the rheology of food products.

Bozkurt and Icier [38] reported that similar rheological constants were observed for the processing of quince nectar with OH and conventional heating, which indicates that thermal effects dominated when it came to the rheological properties of processed food products. They studied the rheology of OH-treated quince nectar (10–40 V/cm; 50 Hz) using a variety of mathematical models. After fitting experimental data, the Herschel-Bulkley model was found appropriate at all temperatures. Non-Newtonian shear thinning behavior was observed in a wide range of temperature-time combinations (65–70°C and 0–30 min). The rheological characteristics of quince nectar remained the same postohmic and conventional heating treatment.

2.4. Effect on Texture. In the case of ohmic technology, heating occurs quickly and evenly; therefore, finished products retain tissue firmness. It has been reported that the protein matrices in ohmic-treated food samples are found to be more compact and denser, along with very little pore size in comparison to traditional processing [39].

Farahnaky et al. [40] used OH to prepare a variety of root vegetables and examined the effect on the texture of the vegetables using a texture profile analyzer (TPA). The results demonstrated that OH speeds up the softening process and that the softening rate is precisely related to the applied electrical potential. Chiu [41] experimented with cooking ham emulsion using OH and investigated the textural features of the ham emulsion. Compared to the conventionally cooked sample, ohmically cooked ham had a texture that was both more tender and chewier. Pineapples treated with OH had a greater degree of hardness than those that were treated with the traditional heating technique [42]. In a similar study, pineapple cubes underwent textural deterioration after being subjected to an electric field for 90 s [43]. OH is known to have a better reduction in enzymatic activity, thus preserving the original texture of the food product [43].

2.5. Ohmic Heating as Hurdle Technology. A combination of preservation techniques or hurdle technology is of interest due to its synergistic effects on microbial destruction and enhancement of food safety. Ohmic heating has also been used in combination with other methods for years. Shin et al. [44] reviewed the hurdle technologies based on ohmic heating in food processing applications. They reported that the pathogen inactivation rate was significantly higher when the ohmic heating was used in combination with other

Table 6: Effect of OH on the quality aspects of other food products.

Product	Electrical parameters	Processing time	Temperature	Impact
Pear peeling [11]	426, 479, 532, 585, 638 V/m	30, 60 s		Finest peel quality at lesser concentrations of lye (2-3% NaOH). OH resulted in >95% peeled yields
Pulque (Mexican alcoholic probiotic beverage) [123]	120 V	3-12 min	50–70°C	Extended shelf life up to 22 days. Superior sensory acceptance
Noodle [12]	10, 12.5, 15, 17.5 V/cm at 60 Hz	90 s		Desirable texture and energy efficiency observed during ohmic cooking
Rice [124]	60 Hz	28 min	100°C	Consumed electrical energy was around 73–90% of conventional rice cookers
Black rice bran [13]	50, 100, 150, 200 V/cm	3 min	105°C	An increase in bioactive yield, as well as anthocyanin content, was found in ohmic processing when compared with the steam-assisted solvent extraction
Whole and decorticated pearl millet grain [125]	60 Hz	20-30 min	98 ± 2°C	Harder decorticated millet grains with greater lightness
Chinese chives [126]	11.5 V/cm and 5.3 V/cm	45 min	100°C	Time taken for extraction was found to decrease in comparison with the hydrodistillation technique of extraction
Cocoa fermentation [127]	5.97 V/cm	9.3, 13, 17 min	40, 45, 50°C	Fermentation temperature was achieved very rapidly in comparison to that of the traditional fermentation method (8-12 h)
Meat analogue [29]	30 V/cm at 60 Hz	1, 3, 5, and 7 min	70, 80, 90, and 100°C	Textural qualities similar to beef (104 N), higher system performance evaluation (0.75) (a)
Black cumin seed slurry [128]	650, 750, and 850 V/m		40, 50, 60, 70, 80, and 90°C	Electrical conductivity and specific heat values of slurry increase linearly with endpoint temperature and electric field strength (b)

physical or chemical treatments like high pressure, ultraviolet, and chemicals. Park et al. [45] studied the pressure-ohmic-thermal-sterilization treatment of low-acid foods like vegetable purees and reported its effectiveness in controlling bacterial endospores. Cho and Kang [46] investigated the combined effect of pulsed ohmic heating and UVA light on the inactivation of foodborne pathogens in foods like milk and orange juice. They highlighted its potential applications in pasteurization since they observed no significant change in vitamin and malondialdehyde. Table 7 depicts some other hurdle technology combinations where ohmic heating is used by researchers to enhance the intended target effects.

2.6. Effect on Enzyme Deactivation. Enzymes have a crucial role in improving food quality, boosting extraction yields, and recovering by-products. While enzyme activity is desired in a few processes, it also degrades food quality by altering the texture, flavor, and taste. As a result, it is important to suppress enzyme activity for a number of food processing operations [22]. Because of the existence of electric current during heating, OH has various nonthermal impacts on microbial and enzyme activity in addition to thermal ones. These nonthermal actions of OH, however, are only conceivable in enzymes that include prosthetic metallic groups, such as copper in polyphenol oxidase, iron in lipoxygenase, and zinc and magnesium in alkaline phosphatase [47].

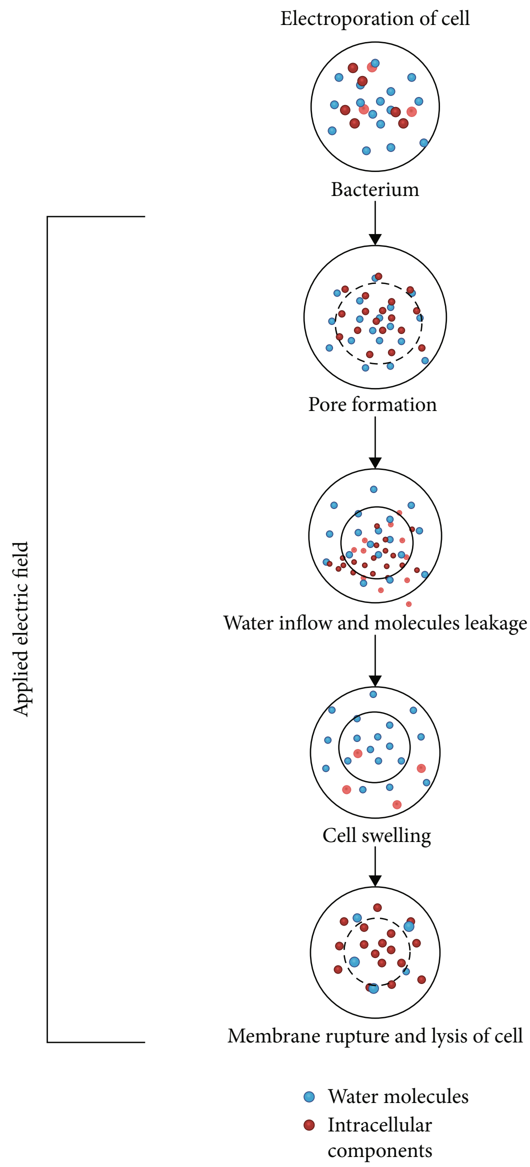

Figure 3: Mechanism of microbial inactivation in OH.

Since the enzymes have net charges and dipole moments, they move and rotate in reaction to external electric fields. According to certain research, the electric fields used during OH have a nonthermal inactivation impact on pectin methylesterase (PME) in tomato homogenate [48] as well as lipoxygenase and polyphenol oxidase in buffer solutions [49]. There is currently a scarcity of evidence on the nonthermal effects of MEF treatments on dietary proteins and enzymes [48].

For the proof of the above-mentioned concept, Samaranayake et al. [50] employed an electroprocessing apparatus designed to reduce ohmic heating and increase cooling during the application of electric fields. The introduction of mild electric fields leads to a substantial (P 0.05) inactivation of both PPO and POD enzymes in grape juice compared to the comparable controls without electric fields, as shown in the current work. Both experimental and modeling data indicate that increasing field intensity in conjunction with temperature control may increase the nonthermal inactivation impact of electric fields. Figure 4 shows the inactivation of enzymes during the OH process.

Castro et al. [49] looked at how food enzymes like polyphenol oxidase, pectinase, and lipoxygenase were affected by an electric field. The result showed that the electric field did not stop pectinase from working, but it did stop polyphenol oxidase and lipoxygenase from working. Similarly, Icier et al. [51] looked into how ohmic blanching affects the peroxidase enzymes in a pea puree. When ohmic blanching was compared to conventional hot water blanching, the results showed that ohmic blanching stopped peroxidase activity in less time. In another research, the effect of process factors on grape juice polyphenol oxidase activity was investigated [52]. The findings demonstrated that when a large voltage gradient was applied, the EC increased at a quicker pace, resulting in enzyme deactivation. Wilinska et al. [53] experimentally studied the inactivation kinetics of pectin methylesterase in various fruit juices in a temperature range of 52–66°C. Moreno et al. [54] studied OH-assisted osmotic dehydration and vacuum impregnation on apples' polyphenol oxidase (PPO) inactivation. These treatments were effective for PPO inactivation at 50°C. Jakób et al. [55] tested milk, along with fruits and vegetable juices, to determine the mechanisms of inactivation of alkaline phosphatase, pectin methylesterase (PME), and peroxidase. Demirdöven and Baysal [56] studied the effects of voltage gradient and temperature on the PME activity of orange juice. In both studies, a greater reduction in PME activity was found. When compared to traditional thermally heated juice (88.3%), OH reduced PME activity by 96 percent. It might be due to additional nonthermal effects along with thermal inactivation.

The potential association between the inactivation of enzymes and the nonthermal impacts of electric fields might be attributed to the perturbation of protein structural conformation. Enzyme denaturation may occur due to conformational alterations and disturbances in the tertiary protein structure, which may be attributed to the reorganization or breakdown of noncovalent connections, including ionic and H-bonds, as well as hydrophobic interactions [47].

2.7. Effect on Heat-Sensitive Compounds. The electrochemical process causes bioactive substances (ascorbic acid and carotenoids) to degrade during OH. Bioactive peptides are a class of biologically active molecules that exhibit beneficial properties, such as the ability to inhibit angiotensin-converting enzyme (ACE). These peptides are mostly derived from plant and dairy proteins, which undergo hydrolysis via processes such as fermentation or enzymatic action [57]. The suppression of ACE results in a decreased likelihood of heart failure and offers advantages in the reduction of blood pressure [58]. Bioactive chemicals have been shown to provide several health effects, such as antioxidant, anticancer, anti-inflammatory, antithrombotic, antidiabetic, antiobesity, antimicrobial, antifatigue, antihyperlipidemic, and hepatoprotective actions. Additionally, these compounds have been shown to enhance learning and memory [59].

Rinaldi et al. [60] observed a greater abundance of bioactive peptides in sweet whey when subjected to OH as

Table 7: Use of OH as a hybrid method/hurdle technology.

Treatment	Product	Conditions	Effect	Reference
Ohmicsonication	Apple juice	Sonication: 20 kHz; at 25°C by applying 100% of power (550 W) for 8 min; 5 s pulse duration	Less degradation of the bioactive profile along with highest inactivation of polyphenol oxidase (98%) was obtained by ohmic sonication in comparison to ohmic heating (97%), thermosensation (93%), and conventional heating method (91%)	[64]
Ohmicsonication	Orange juice	Sonication for 8 min at 25°C followed by ohmic heating at 40 V/cm, to 68°C for a holding time of 60 s	Maximum inactivation of pectin methylesterase was 96%, which was in the case of ohmic sonication in comparison to OH (95%), thermosensation (89%), conventional heating (90%), and sonication (29%)	[129]
OH+UV-C irradiation	Tomato juice	UV-C irradiation: 191.5 mJ/cm^2 light dose Ohmic heating: 13.4 V_{rms}/cm electric field strength; 210 s treatment time	Synergistic bactericidal effect by OH (1.84 reduction in *E. coli*) and UV-C irradiation (0.48 reduction in *E. coli*)	[27]
Ohmic vacuum heating	Orange concentrate	10, 15, 20, 25, 30 V/cm; 40 kPa absolute pressure	Less degradation in vitamin C in ohmic vacuum-treated samples (10-29.2%) in comparison to conventional (47.4%) and ohmic heating under atmospheric conditions (18-38.8%); total phenol components were more similar to fresh samples in ohmic vacuum heating with a difference of 8-21.3% compared to that of conventional methods (49.6%) and ohmic heating under atmospheric conditions (18.5-42.8%)	[79]
Ohmic-infrared cooking	Meatballs	Precooking at 15.26 V/cm	Reduction in microbial count; total mesophilic aerobic bacteria were found to be 1.96 and 4.50 logarithmic units based on treatment	[130]
Pressure ohmic thermal sterilization	Carrot	30 V/cm; at 600 MPa and 105°C	Most minor textural damage-higher crunchiness index (0.76) in comparison to control (0.57) and better color retention	[131]

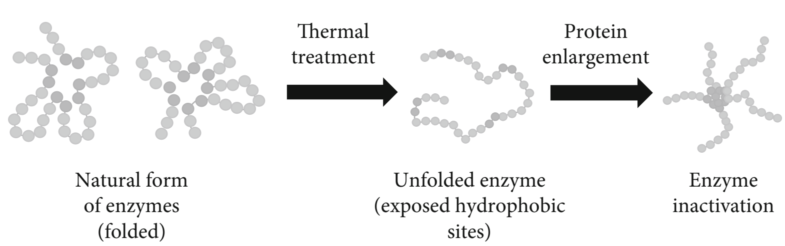

Figure 4: Enzyme inactivation using OH.

opposed to conventional heating. Furthermore, it has been shown that the generation of bioactive peptides during OH is more pronounced when smaller voltage gradients are used. In their study, Müller et al. [61] examined the impact of OH on the release of bioactive peptides. The experiments were conducted at frequencies of 10, 100, and 1000 Hz, with a voltage gradient of 25 V. Additionally, experiments were conducted at a frequency of 60 Hz, with voltage gradients of 45, 60, and 80V. It was discovered that, with the exception of the treatment at 80 V and 60 Hz, OH resulted in the production of a greater quantity of bioactive peptides compared to the traditional approach, across all specified parameters.

Sarkis et al. [62] examined the effectiveness of OH on anthocyanin degradation in blueberry pulp. Following the thermal treatment with ohmic and traditional heating methods, anthocyanin degradation in various fruits was assessed. The findings indicated that as the voltage and solid concentration grew, so did the deterioration. On comparing the OH-treated samples with traditionally processed samples, it was found that the percentage of degradation was lower with OH when lower voltages were used. With strong electric fields, the pulp processed during OH showed more anthocyanin degradation. The higher solid content of strawberries and sour cherries resulted in increased anthocyanin [2]. Mercali et al. [25] found that lower electric field frequency (<10 Hz) contributed to a significant increase in the quantity of ascorbic acid breakdown and color changes in acerola pulp. However, at higher frequencies, both heating techniques exhibited comparable rates of ascorbic acid breakdown and color changes. The kinetics of ascorbic acid decomposition is unaffected at higher electric field frequencies. OH of papaya, sapota, and guava pulps at temperatures ranging from 70°C to 90°C for 15 minutes was shown to degrade the amount of ascorbic acid from 9.72 to 41.56%, 12.46 to 58.21%, and 10.79 to 20.66%, respectively, according to the research done by Athmaselvi et al. [63]. The percentage of papaya pulp subjected to OH treatment, specifically at a temperature of 96°C for a holding period of 2 minutes at an electric field strength of 13.33 V/cm, was found to be 11.93% and 11.40% in two separate instances. Another study conducted by Sarkis et al. [62] used an OH process on acerola pulp at temperatures of 90 and 95°C for a duration of 50 minutes, using a voltage of 30 V. The results of this study indicated that there were no noteworthy alterations seen in the concentration of carotenoids. The proposed explanation pertained to the reduced availability of oxygen for the oxidation of these compounds, which may be attributed to the consumption of oxygen by anthocyanins.

The better heat-sensitive compound retention and antioxidant ratio have proven ohmic heating for a better processing method concerning the health of consumers [64]. Besides, research studies have demonstrated that OH is a better option for the inactivation of pathogens and harmful microorganisms as the inactivation of microorganisms is done with multiple mechanisms, unlike other thermal heat treatments, ensuring enhanced food and health safety (Tables 1–7). The detailed mechanism behind microbial inactivation is explained below.

3. Mechanisms behind Microbial Inactivation

3.1. Thermal Effect. The primary method by which OH destroys bacteria is through thermal action [65], which causes the disintegration of the microorganisms' membrane structure [24]. Ohmic technology inactivation of *Saccharomyces b.* yeast and *E. coli* was achieved at a frequency of 60 Hz. *D*-values for ohmic-treated samples were lower than those for water bath heating using the traditional technique. The decimal reduction values were 47.21, 294.62, and 149.74 at temperatures of 55.75, 49.75, and 52.3°C, respectively [66]. It indicates that there might be some other mechanism that could be acting during OH. The findings were not in agreement with many other investigations in which it is reported that a specific species of microorganisms may adapt differently based on the applied thermal profile [61].

3.2. Chemical Effects. OH causes chemical inactivation due to the production of free oxygen, chloride, complex hydro molecules, and ions. E. coli cells were completely destroyed when exposed to alternating current (50 Hz, 200 mA/cm^2 for 5 hours). The OH facilitated hydrogen peroxide production in the presence of a phosphate-neutral buffer solution ([67, 68]. During the OH process, compounds like free chlorine have a toxic effect on microorganisms. These molecules dissociate soon after the OH process and eventually become untraceable [65].

3.3. Electroporation. The electrical field and electric current both cause thermal and nonthermal damage to the cells, ultimately resulting in the inactivation of the microorganisms [69]. Cell membranes undergo progressive electroporation and rupture. It is the mechanism often associated with microbial destruction due to the applied electric field [70]. The mechanism of microbial inactivation in OH is shown in Figure 3. Electroporation causes excessive amounts of ions and intramolecular components to leak, leading to the death of cells [71]. The cells are said to "lyse" when their cell walls and cytoplasmic membranes undergo a significant amount of rupture and breakdown. The vast numbers of studies indicate that electroporation, which results in pore creation in the membrane and changes in cell permeability, is the main nonthermal mechanism of cell death during OH [65]. As a result, microorganisms can be killed at temperatures below their thermal death temperature. When the electric field intensity is above a certain threshold, the process of electroporation occurs. At this moment, the membrane conductance rapidly rises, which makes it possible for cellular material to escape the cell [65, 72].

According to some researchers, the nonthermal destruction of microorganisms during ohmic treatment is caused by the alternating current shock effect [65]; *E. coli* cells that were subjected to 50 Hz, 200 (+/−) 20 mA/cm^2 for 5 hours caused aggregation of DNA-related materials in the cells, which was followed by the leaking of cellular contents. The experiment was conducted in a phosphate-neutral buffer solution. Ohmic-treated E. coli cells had a greater amount of disordered material in the core regions of their cells, which was ascertained by electron microscopy [73]. Larger amounts of ATP and lactate dehydrogenase were secreted from *S. thermophilus* in milk when it was heated in a sublethal OH environment as compared to thermal treatment in a water bath. The findings suggested that the permeability of the cell membrane and the exudation of intracellular components were increased during OH, which suggests nonthermal damage to the microorganisms [74]. Because of the increased permeability, the cell may sustain irreparable damage as a result of the leaking of several biological substances. These molecules include amino acids, proteins, nucleic acids, and coenzymes. However, only a few studies have been able to establish the mechanism of electroporation and its particular impacts on the structure of cells and the components found within cells [65].

4. Effect of Food Matrices on OH

4.1. Electrical Conductivity of Food Product. The efficacy of ohmic heating is enhanced in matrices characterized by elevated electrical conductivity (EC). Those that include a substantial amount of water, such as fruits and vegetables, often exhibit greater EC in comparison to those with lower moisture content. Hence, OH is often found to be more efficient in such matrices [75].

4.2. Temperature. The temperature of the sample affects EC. Food's EC rises in a linear fashion with time. This might be due to a decrease in viscosity, a change in the structure of the biological tissue, or the release of gas bubbles. Reduced drag movement might also account for the increase in EC as temperature rises.

A substantial increase in EC with temperature was reported when beetroot was ohmically treated [76]. The influence of temperature on strawberry product EC was investigated [75]. Depending on the product, the findings revealed a linear relationship. Sour cherry juices, grape juice, lemon juice, and pomegranate juice showed similar results [77–79].

4.3. Nature of Food Sample. The concentration of electrolytes and the availability of free water inside the food are the two main determinants of food properties. The EC of food products exhibits a direct relationship with the concentration of electrolytes contained inside them. The ionic content of foods may be manipulated to either increase or decrease their electrical conductivity (EC) [80]. According to a study conducted by [81], it has been shown that there exists a positive correlation between the ionic concentration and the heating rate. Consequently, an increase in the ionic concentration leads to an elevation in the conductivity of the product. The behavior of EC is influenced by the presence of intermolecular connections.

Conversely, moisture content pertains to the amount of unbound water that is contained inside food. The water included in the meal exhibits the properties of an electric conductor. The increase in moisture content is positively correlated with the rise in electrical conductivity (EC), and conversely, the reduction in moisture content is associated with a drop in EC. However, it is important to note that elevated moisture content does not always lead to higher EC measurements. In fact, heightened moisture content tends to reduce the ionic concentration, hence resulting in a fall in EC. The rise in temperature to around 50 degrees Celsius leads to an increase in ionic mobility during the transformation of water into vapor [82]. Solid particles, on average, have a lower EC than liquids [2].

4.4. Flow Characteristics of Food. The heating rate is affected by the thickness of the sample, the solid concentration inside it, and the acidity of the sample. The viscosity of a substance has a direct impact on its electrical conductivity (EC), since it is a feature that is dependent on temperature [33, 83]. In their research, [84] investigated the performance of OH in the context of very viscous liquids. It was shown that fluids with greater viscosity exhibited higher OH rates compared to fluids with lower viscosity, but several studies have reported contradictory findings [85]. It could be because of different reactions happening inside the reactor during the OH process, depending on what the heated sample is made of.

4.5. Particle Size. The condemnatory parameter to search out the heating rate among the two portions of food (liquid and solid) is particle size and concentration. The EC of a sample weakens as its particle size as well as concentration increases. The fluid sample gets heated slowly due to the high concentration. In a study, tomato and orange juice's increasing concentrations were shown to reduce EC and thus heating rate [80]. Similar findings were reported when the influence of concentration on heating rate was tested in apple and sour cherry juices [81]. Zareifard et al. [82] confirmed the same in the study conducted on two-phase food matrices. It was reported that an increase in concentration and particle size increased the heating time; i.e., the heating rate was reduced.

Chandarana [83] reported a similar study in which food with two parts (the liquid portion includes starch and salt, while the solid half contains carrot solids) was processed using OH. It was discovered that EC and particle size had an inverse relationship.

5. Regulatory Aspects and Health Concerns

The Food and Drug Administration (FDA) is entrusted with the responsibility of safeguarding the well-being of the general population. The organization has enacted and continues to enact rules for this purpose. When considering food processes, it is not feasible to include every intricate aspect of any potential food process without resulting in a cumbersome and unenforceable framework. Consequently, they comprehensively address the necessary processing requirements for ensuring the manufacture of food that meets safety standards. Therefore, new and improved ways of processing food can be developed, but it is up to the processors to show that these new methods work to make sure that safe food products are produced [84].

To facilitate information processing, the FDA actively promotes the practice of reaching out for clarification or guidance in cases where there may be inquiries or uncertainties about a certain product or method. It is highly recommended that, when a new process is being undertaken, the processor establishes contact with the FDA as soon as possible and maintains regular communication with them throughout the development phase. Early and ongoing communication with the FDA is advantageous for the development of any unique technique. The term "early" refers to a period occurring in the first stages of development. In this manner, officials from the FDA acquire knowledge and understanding of regulatory matters. This enables them to provide guidance to processors on matters that are of significant importance to public health. Instances have arisen in which innovative procedures were formulated and advanced, only to encounter a significant obstacle in the form of an unanticipated food safety concern. Due to its primary objective of safeguarding public health, the FDA is obligated to address this matter, regardless of the potential burdens it may impose on the processor [84].

There are two distinct categories of food additives, namely, direct and indirect. Natural additives refer to those substances that are intentionally added to food in order to have a desired effect. Indirect additives refer to those substances that are unintentionally included in food products. Indirect additives often permeate food products as a result of their interaction with packing materials or processing machinery [85].

The concept of safety is of paramount importance in various domains and contexts. Another issue of importance is the interaction between food and electrodes [86]. Electrochemical reactions refer to chemical processes that involve the transfer of electrons between species, often occurring at the interface between an electrode and the presence of electrodes induces the migration of metal ions into food [87], but the current legislation pertaining to food additives does not explicitly cover this particular kind.

The terminology included in Section 170.39 pertains to the broader topic of migration, specifically focusing on the migration of substances from materials used in processing or packaging. It is essential to seek consultation from the Food and Drug Administration's Office of Food Additive Safety. Concerning the ohmic electrodes and the food that needs to be prepared, the Office of Food Additive Safety needs to get a complete quantitative analysis of how the food and electrodes interact before they can move forward [84] so that any health hazards can be prevented.

In the context of OH, the presence of particles poses a dual problem due to their possible variations in thermal and electrical characteristics. Due to this, there may be hotspots (points with the highest heating resulting in nutritional loss because of overheating) and cold spots (particles with minimum EC, for example, milk solids acting as insulators). The objective of the process setup remains consistent, which is to provide sufficient heating of the slowest heating component or particle of the meal. Hence, in the establishment of this procedure, it is essential for the FDA to ensure the presence of a comprehensive evaluation that encompasses the whole processing of the food, including both the transfer of heat to particles and an assessment of the relative heating based on electrical factors [88, 89].

6. Conclusion

The application of OH is known to exert a noteworthy impact on the quality of food, owing to its ability to induce both thermal and nonthermal effects. Although the thermal effects of technology on food quality have been extensively researched, there remains a dearth of knowledge regarding its nonthermal effects on various food attributes such as texture, color, and taste. Further investigation is necessary to explore the thermal and nonthermal impacts of OH on a broader spectrum of food products and settings. The adoption of the ohmic process by the food industry has the potential to yield significant cost and time savings. Furthermore, in contrast to traditional methods, the process control provided by this technology is deemed more reliable. The aforementioned benefits suggest that OH has the potential to serve as a viable supplement to traditional methods within the realm of food processing, but the commercialization of OH techniques depends on compliance with food safety laws and guidelines. Literature reports that certain microbes may occasionally show signs of resistance to OH. The food matrix's composition and the existence of protective barriers are two possible causes of this resistance. Designing efficient OH procedures requires an understanding of the microbial resistance profile and its detailed impact on various food constituents, which is covered in this paper. On the other hand, research has been carried out, albeit on a limited scale, either within a laboratory setting or in a pilot facility. Thus, a more in-depth inquiry is necessary to evaluate the potential technical impediments and economic considerations associated with the extensive implementation of OH.

A limited sample size characterizes the bulk of research inquiries pertaining to OH. The presence of current control and fouling issues may be impeding the researchers' ability to continue with a substantial sample size. There is a need for the development of versatile, large-scale, and cost-effective ohmic heating equipment that incorporates an improved current control system in order to fulfill the demands of the food processing industry. This is because there is a clear link between the temperature of the food and its EC; as the temperature rises, so does the EC. This means that more current is needed and drawn. For this, research studies should be more focused on the current control and design of OH equipment. Besides, electrode mitigation should be broadly studied so that possible health hazards can be eradicated and the most suitable electrode type can be selected concerning food and health safety.

Conflicts of Interest

None of the authors have any conflicting interests.

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