Food Engineering Reviews
https://doi.org/10.1007/s12393-024-09368-4

Ohmic Heating Technology for Food Applications, From Ohmic Systems to Moderate Electric Fields and Pulsed Electric Fields

Leire Astráin-Redín[1] · Sebastián Ospina[1] · Guillermo Cebrián[1] · Ignacio Álvarez-Lanzarote[1]

Received: 30 June 2023 / Accepted: 6 February 2024

Abstract
Ohmic heating (OH) of food has been investigated for many years as an alternative to conventional heating because it allows fast and homogeneous heating. The processing parameters that influence the most uniformity of the heating in OH are the electric field strength and the frequency. Therefore, recent trends have focused on studying the application of frequencies in the order of kHz and electric fields higher than 100 V/cm. In this regard, and considering only the applied field strength in a way to easily differentiate them, three ohmic systems could be distinguished: OH (< 100 V/cm), moderated electric fields (MEF) (100–1000 V/cm), and ohmic-pulsed electric fields (ohmic-PEF) (> 1000 V/cm). The advantages of applying higher electric fields (MEF and ohmic-PEF) over OH are, on the one hand, their much higher heating rate and, on the other hand, their capability to electroporate cells, causing the release of intracellular ionic compounds, and therefore, uniformizing the electrical conductivity of the product. This strategy is especially interesting for large solid foods where conventional heating applications lead to large temperature gradients and quality losses due to surface overtreatment. Therefore, the aim of this work is to review the state of the art of OH technologies, focusing on MEF and ohmic-PEF. The advantages and disadvantages of MEF and ohmic-PEF compared to OH and their potential for improving processes in the food industry are also discussed.

Keywords Ohmic heating · Electro-technologies · Food processing

Introduction

Many processes in the food industry are based on thermal treatments, including microbial inactivation, cooking, baking, blanching, evaporation, dehydration, and thawing [1, 2]. Conventional heating (CH) systems used by manufacturers to apply these treatments to solid, particulate, or viscous products involve heat transfer from the thermal source to the cold center of the food. In these kinds of products, heat transfer occurs by thermal conduction, which is very slow. On the other hand, to ensure that heat treatment is correctly applied, which is essential in pasteurization and sterilization processes, the coldest point must receive the required treatment to guarantee food safety and stability. Thus, CH of solid food products is not only very time-consuming but also results in the overtreatment of the food surface, potentially affecting its quality and, therefore, leading to products that are far away from fresh food [3]. All this makes CH systems unable to meet today's demand for minimally processed products that maintain the freshness of food.

For this reason, in recent years, alternative thermal technologies have been investigated to achieve rapid and volumetric heating while trying to minimize the impact of heat on food quality [4–6]. These novel technologies include systems based on electromagnetic heating (radiofrequency and microwave) and ohmic heating (OH). This review will focus on the latter with a special emphasis on the different ways developed in the last years to apply it.

OH is based on the electrical resistance that conductive materials (such as food) offer to current flow. Due to the Joule effect, when an electric current flows through them, the electrical energy is directly converted into thermal energy by heating the food itself [7]. Thus, the heating is considered volumetric being more uniform than CH. In addition, heating is faster, energy consumption is lower, and product quality is improved compared to traditional systems [8, 9]. Although studies on the environmental and energy

✉ Ignacio Álvarez-Lanzarote
ialvalan@unizar.es

[1] Departamento de Producción Animal y Ciencia de los Alimentos, Tecnología de los Alimentos, Facultad de Veterinaria, Instituto Agroalimentario de Aragón, IA2-(Universidad de Zaragoza-CITA), Zaragoza, Spain

impact of the application of OH are still scarce, Ghnimi et al. [10] observed energy savings of 65% in pasteurization treatments; the energy efficiency of the ohmic system was 77% while that of the conventional system was 25%. Furthermore, in the same study, a 41% reduction in CO_2 emissions was determined when using the OH system.

By contrast, the major disadvantages of OH are the electrochemical reactions and the erosion of the electrodes happening as a consequence of its application, especially when it is applied directly to foods. To address this problem, alternating current is applied, different electrode materials have been evaluated (best results were obtained with titanium), and the process has been optimized by applying higher frequencies of the order of kilohertz (due to the inhibiting of Faraday reactions) [11–13]. In addition, food products are often complex matrices composed of different components, in different physical states, and with different thermal and electrical properties, which means that OH is usually not as uniform as expected, and the process has to be optimized. It should also be noted that process parameters such as the electric field strength, frequency, electrode material, and the geometry of the treatment chamber also influence the uniformity of heating [6].

The application of OH for food preservation has been researched since the nineteenth century [14]. However, in recent years, new ways of application have started to raise interest. These new systems involve the application of higher electric field strengths with the aim of achieving faster heating rates and improving heating uniformity. Moderate electric fields (MEF), which in general apply electric fields higher than 100 V/cm, have been the most widely investigated strategy. It has been demonstrated that the application of MEF could promote the electroporation of eukaryotic cells which favors the outflow of intracellular material that would make the electrical conductivity of the whole food more uniform, improving the uniformity of heating and increasing the speed of heating [15]. Thus, the application of MEF has been studied for osmotic dehydration, cooking, spore inactivation, pasteurization, enzyme inactivation, and fermentation. More recently, the application of pulsed electric fields (PEF)—which work at electric fields higher than 1000 V/cm—as an OH technology for microbial inactivation [16, 17] and for blanching of vegetables [18] has also been proposed since it can result in an even faster heating and higher electroporation.

Some very good reviews on the application of OH in the food industry can be found in the literature [2, 6, 19–21], but to the best of our knowledge, none has been focused on comparing and discussing the major benefits and drawbacks of each one: OH, MEF, and ohmic-PEF. Therefore, the aim of this work is to present an update on OH technology, with a special focus on these two new ways of applying it: MEF and PEF technologies.

Basic Aspects of Ohmic Heating

OH consists of the application of electric fields of 20–100 V/cm, frequencies of 50 Hz to 30 kHz, current intensities of up to 5000 A/m^2, and maximum power of up to 480 kW [22]. As long as an electric field is applied, a certain amount of current flows through the food, which causes it to heat up, regardless of the intensity of the electric field and the way in which the heating is applied (continuous or pulsed).

OH or direct resistance heating is based on Joule's law (Eq. 1) in which the heat (Q, joules) generated is linearly proportional to the resistance (R, ohms) of the product but proportional to the square of the current (I, amperes) over a time (t, seconds).

$$Q = I^2 \cdot R \cdot t \tag{1}$$

In the case of OH for food processing, Joule's law can also be expressed as

$$W = \int_0^t \sigma E^2 dt \tag{2}$$

where σ is the electrical conductivity of the treated medium or product (S/m), E is the electric field strength (V/m), and dt is the time (s) during the electric field strength is applied [23]. The reason for using this simplified equation is to get a better understanding of the effect of OH on food as the electric field is directly related to cell electroporation and electrical conductivity which is a food characteristic. Nevertheless, these points will be discussed in more detail below.

In addition to the electric field applied and the electrical conductivity of the food, frequency is also another parameter to consider when applying OH. OH can be applied by both direct and alternative current, although the latter is the most commonly used since direct current promotes corrosion of the electrodes [6]. Thus, frequency is defined as the number of cycles per second of a wave [20].

Considering Eq. 2, it is clear that the applied electric field (E) has a high impact on the heat generated by increasing quadratically the heating rate. That is one of the major benefits of the new ohmic technologies (MEF and ohmic-PEF) since they are based on the application of higher electric fields than OH heating. However, the electric field strength thresholds differentiating each technology are not clearly defined in the literature. Indeed, in some cases, OH and MEF are used indistinctly [24–26]. Thus, in order to establish clear and meaningful comparisons, the following definitions/limits will be used in this work: OH ($E < 100$ V/cm), MEF ($E = 100$–1000 V/cm), and ohmic-PEF ($E > 1000$ V/cm).

Electrical Conductivity

Food heated by OH must have a certain electrical conductivity to allow current to flow through them. The conductivity depends on the temperature, frequency, and food composition. Solid foods composed of different components do not have a uniform electrical conductivity throughout the product and thus, the application of pre-treatments (blanching, soaking, marinating, and vacuum infusion in salt solutions) to the different components that alter its conductivity has been investigated in order to reach an overall uniform conductivity [27, 28].

Due to the difference of conductivities within a product, heterogeneous temperatures occur, resulting in the presence of hot spots and cold spots. The current will go primarily through the areas with the least resistance, i.e., the areas with the highest electrical conductivity, so the hot spots will be found there. On the contrary, in those areas with a lower conductivity, there will be cold spots [6]. These areas with lower temperature will be the limiting zones when (and where), for example, determining the microbial inactivation by ohmic treatment. Moreover, in fatty products (non-conductive materials), OH is not effective; then the food safety cannot be guaranteed since regions coated with fat will not be heated and will not receive the heat treatment required for microbial inactivation [29–31]. A similar situation occurs with the extraction processes. Moongngarm et al. [32] used dehydrated stevia leaves that were hydrated with distilled water at 20%, 30%, and 40% (wet weight) and applied OH at 50 Hz and electric fields of 75–200 V/cm. At 40% humidity, the maximum temperature was 114 °C while at 20% humidity, the heating could not be applied due to the low conductivity of the product.

Another aspect to consider is that the electrical conductivity is temperature-dependent and will increase during the heating process. In liquid food, the conductivity increase is linear with temperature [33, 34]. However, in solid materials, this does not happen because during heating, cell rupture occurs, and intracellular ions are released, causing a sharp increase in conductivity and temperature [35, 36], as shown in Fig. 1 [37]. When potato samples were heated, two kinetics were observed: from 20 to 60 °C, the increase in conductivity was slower, but from 60 °C onwards, there was a faster increase. This correlates with the cell disintegration index shown in the right axis of the figure, increasing rapidly when 60 °C was reached, increasing up to 0.5 with final values of 0.85–0.90 (value = 1 means maximum cell rupture).

In this scenario, the application of ohmic-PEF on vegetables at electric fields higher than 1000 V/cm could result in early electroporation of the tissue prior to the actual rupture caused by heat at temperatures above 60 °C. This could make the conductivity of the material more homogeneous in the early stages of heating, thus improving the uniformity of heating and the speed. One of the methods used to evaluate electroporation in plants is the cell disintegration index by impedance analysis, which consists of measuring the proportion of permeabilized cells based on the frequency dependence of the electrical conductivity of intact as well as permeabilized plant tissues [38]. Figure 2 shows the cell disintegration index obtained by applying OH from 20 to 80 °C to carrot samples by two different systems: OH (54.2 V/cm, 12 kHz) and ohmic-PEF (1330 V/cm, 100 Hz).

The result for the cell disintegration index for ohmic-PEF was 0.87, whereas for OH was 0.51. This means that the electroporation effect when applying the ohmic-PEF would have been larger than with OH and, therefore, the release

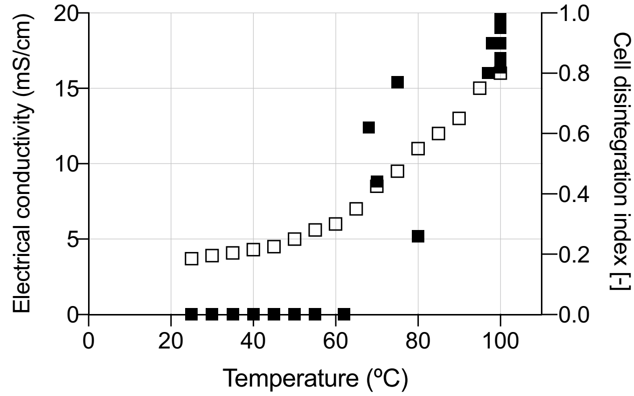


Fig. 1 Evolution of electrical conductivity (white-shaded box (□)) and cell disintegration index (black-shaded box (■)) in potato samples when ohmic heating was applied (Figure adapted from [37])

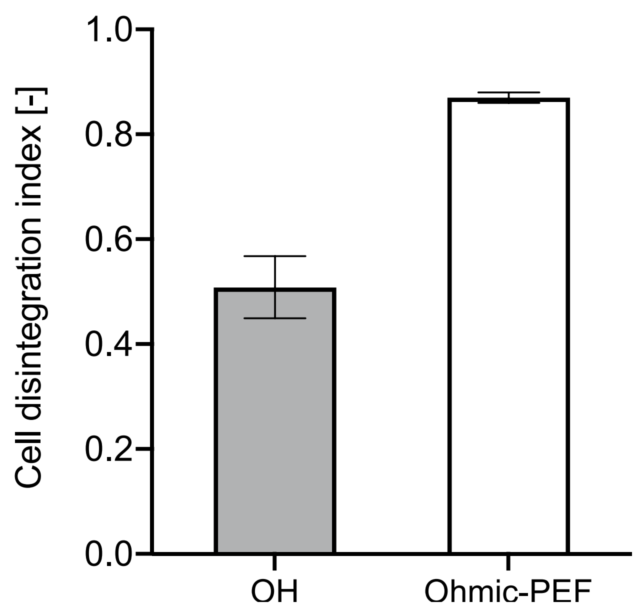


Fig. 2 Cell disintegration index of carrot samples when applying OH from 20 to 80 °C by ohmic system (54.2 V/cm, 12 kHz) and by ohmic-PEF (1330 V/cm, 100 Hz)

of ionic compounds would have been higher and then the electrical conductivities of the food treated by ohmic-PEF.

Electric Field Strength

The applied electric field in OH has a direct effect on two aspects. The first one, as ruled out from Joule's equation (Eq. 2), is the generation of heat whose increase is quadratically proportional to the applied electric field. That is, increasing the electric field will lead to huge temperature increases [16, 39]. Rascón et al. [40] applied OH to *Agave salmiana* samples at different electric fields (20, 30, and 40 V/cm), and the processing time to reach 90 °C was 250, 96, and 70 s, respectively. Therefore, the heating rate increased 1.37 and 3.57-fold when applying 30 and 40 V/cm compared to 20 V/cm.

The second aspect related to the electric field is the phenomenon of electroporation. Its occurrence is widely accepted when applying PEF as a non-thermal technology (1–40 kV/cm). However, due to the low electric fields applied (20–400 V/cm) in OH, there is no clear statement on this because it is very difficult to discern between the thermal and the purely electrical effect. Due to the interest of this point, it will be discussed in more detail in Sect. 4.

As discussed earlier, MEF and ohmic-PEF systems apply electric fields higher than OH. The application of MEF together with temperature (30–45 °C) has been demonstrated to favor the permeabilization of plant membranes [41]. This has been studied in extraction and concentration processes with positive results in both process optimization and product quality improvement [32, 42]. Moongngarm et al. [32] applied MEF (50 Hz) at 75–200 V/cm electric fields on stevia leaves to favor the extraction of steviol glycosides and phytochemicals. The application of 75 V/cm allowed to reach 75 °C after 100 s, while the application of 200 V/cm reached 110 °C after the same period of time. Moreover, stevioside extraction increased 3.15-fold and 3.80-fold when applying 75 V/cm and 200 V/cm, respectively, compared to the control. In the case of ohmic-PEF, electroporation of plant tissues also takes place as discussed above and shown in Fig. 2.

The distribution of the electric field inside the treated product is also important because it determines the heating rates and the extent of electroporation. However, for complex products, it is quite challenging, and therefore numerical simulation tools are needed. Shim et al. [36] simulated the OH (5 V/cm) of three samples with different conductivities (carrot, meat, and potato) immersed in a NaCl solution (3%) in the same treatment chamber. The conductivity of the solution was between 1.8 and 15-fold higher than that of the solid samples. The maximum electric field was located inside the carrot and potato samples (higher electrical conductivity than meat), and the areas of lower electric field were located in the areas between the solid samples. The same was observed by Casaburi et al. [43]. Nevertheless, more complex studies are needed in which not only simple solids (composed of a single component) but also mixtures of solids with components of different electrical and thermal properties are analyzed.

Frequency

As it has been indicated, the frequency of OH technology varies from 50 to 60 Hz. However, recent works have been focused on the application of frequencies in the kilohertz range. It has been observed that at higher frequencies, the electrochemical reactions of the electrodes that occur when applying low frequencies, or direct current are reduced [6]. For this reason, studies have recently been carried out using frequencies from 12 to 300 kHz [25, 37, 37, 44–49].

One advantage of using higher frequencies is the improvement of heating uniformity, a new approach that has recently been investigated. Gratz et al. [37] observed that by applying 300 kHz frequencies to potato tubers immersed in a salt solution with a conductivity of 5 mS/cm, the temperature gradient between the core and the edges was 1.5 °C, while at lower frequencies of 12 kHz, the value was 7.1 °C. The improvement in heating uniformity by increasing the frequency was also observed when numerically simulating the ohmic-PEF of agar cylinders at 100 and 200 Hz, in which the increase in frequency resulted in a reduction of the temperature gradient of the cylinder from 7 to 4.5 °C [50].

Treatment Chamber

OH can be applied in different ways: in solid foods, it can be applied in direct contact with the product with the electrodes or by immersing the food in a saline solution in a static process, while in liquids, it is applied in direct contact both in batch or continuous flow. In general, in batch systems, which lead to a more homogeneous distribution of the electric field, the chambers used are made of insulating materials with two parallel electrodes, which can be of different materials stainless steel, platinum, titanium, etc., at the ends. Some of the chambers can be pressurized in order to be able to apply sterilization treatments [51]. At an industrial level, tubular heaters are commercially available for continuous treatment of liquids or liquid-particulate mixed products with different chamber configurations (for more information see Ghnimi and Fillaudeau [52]).

Although OH is considered a volumetric heating, cold spots appear in the areas close to the electrodes [20]. This phenomenon has been extensively studied in the literature [16, 53–57]. Moya et al. [50] conducted a numerical simulation of heating at 2.5 kV/cm and 50 Hz to a technical agar sample and observed temperature gradients inside the sample of up to 30 °C when the treatment was applied at room temperature (Fig. 3).

For this reason, attempts have been made to minimize this problem by developing treatment chambers in which systems have been introduced to minimize heat loss through the electrodes (Fig. 4).

In the study conducted by Zell et al. [57], they evaluated the heating (230 V, 50 Hz) of mashed potatoes using different coatings for the chamber: with a thermal insulation material (mineral wool pipe insulation with an aluminum facing), with a hot water jacket, with a heating tape, and with a silicon heating panel. The latter panel design yielded the best results, with a minimum determined temperature gradient of 11.9 °C. From a similar approach, Gratz et al. [58] developed a treatment chamber with an inner part where the sample was located and a jacket coating it with salt water at the same conductivity as the sample (Fig. 4A). This design ensures that the heating rates of the sample (vegetable puree) and the saline solution are very similar, as the electrical conductivity is one of the parameters that determines the heating rate by OH (as it was explained in Eq. 2). Instead of covering the area where the sample was located, Astráin-Redín et al. [17] used two tempered electrodes by circulating hot oil (25, 32, and 39 °C) inside them (Fig. 4B). They were able to keep the electrodes at higher temperatures and minimize heat loss through them. When they applied 2.5 kV/cm and 50 Hz on agar cylinders contaminated with *Listeria monocytogenes* and tempering the electrodes at 39 °C (non-lethal temperature), an inactivation of 5 Log_{10} cycles was achieved after 23 and 26 s of treatment in the central and electrode contact zone, respectively. In this case, gradients of 5 °C would be estimated based on numerical simulation between the coldest and hottest points [50].

Moreover, due to the increasing interest in combined technologies to achieve a synergistic effect, Mok et al. [60] developed a cylindrical treatment chamber with a static electrode on the outside and a rotating electrode in the center so that the sample was located in the gap between the two electrodes (called Taylo-Couette flow) (Fig. 4C). In this way, they were able to apply shear stress during OH for the inactivation of *Escherichia coli* K12 in apple juice. The results showed a synergistic effect of both technologies achieving a 5 Log_{10} reductions after 6.2 min of treatment at 50 °C, 120 V/cm, and 2879 s^{-1}. However, information about the uniformity of temperatures inside the chamber is missing, so it is not possible to identify the cold spots or, if none exists, to verify the homogeneity of temperatures achieved. Using the same technologies, they evaluated this synergistic effect of MEF and shear stress with the subsequent addition of nisin to assess whether it improved their efficacy in gram-negative bacteria where antimicrobials are not effective because of the outer membrane. Inactivation of 5 Log_{10} cycles of *E.coli* K12 was achieved after 5 min of MEF application under shear stress (2879 s^{-1}) with a duty cycle of 0.99 and 100 IU/ml nisin [59]. Therefore, authors indicated that this MEF and shear stress combined treatment chamber would have a great potential to promote microbial inactivation and thus reduce heat application times even further, thus enhancing the sensory properties of the product.

Despite the good results obtained with these treatment chambers, all of them are designed at laboratory level and therefore, further studies are needed to scale them up to pilot plant and/or industrial scales.

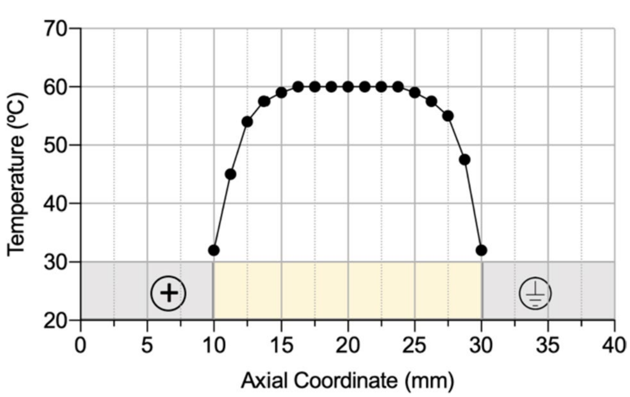


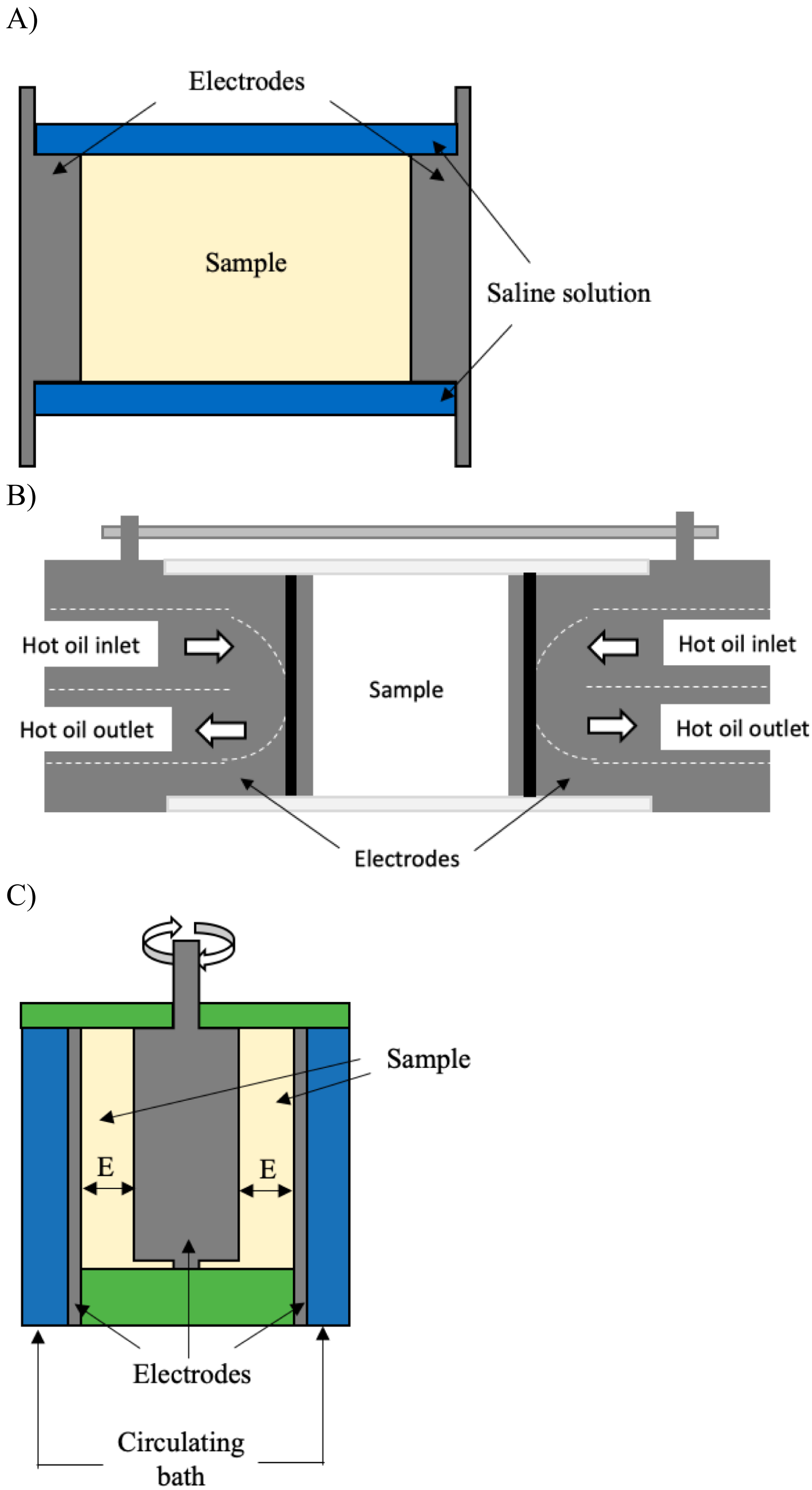
Fig. 3 Temperature evolution along a treatment chamber (electrodes plus agar sample) when ohmic heating is applied (2.5 kV/cm, 50 Hz) at room temperature (adapted from [50])

OH, MEF, and Ohmic-PEF

The first industrial application of OH appeared in 1920, and it was designed to heat milk in a continuous flow using an alternating current of 220 V at a frequency of 60 Hz [61]. Advances in technology have enabled the application of higher electric fields leading to the development of novel systems such as MEF and ohmic-PEF. However, although PEF technology is presented in this review as an OH system, for more than 70 years of research on this technology, it has been focused on its application as a non-thermal food processing technology based on the phenomenon of electroporation. Thus, PEF, as a non-thermal technology, has shown great results for improving mass transfer (improving juice extraction yields, polyphenol extraction during red wine maceration, accelerating vegetable drying, among others) and preservation processes (pasteurization of liquid food such as juice, milk, or liquid egg) [62–64].

Depending on the intensity of the electric field and the energy input applied, the treatment effect will be either more thermal or mostly cell electroporation (Fig. 5). The best-known effects are found in OH (low electric fields and thermal effect) and conventional PEF (high electric fields and electroporation effect at non-lethal temperatures). In the

Fig. 4 Treatment chamber configurations. **A** Chamber covered on the sides with saline water (adapted from [58]). **B** Chamber with the electrodes heated by the circulation of hot oil inside the chamber (obtained from [17]). **C** Chamber with a rotating electrode in the center of the treatment zone to apply shear stress during ohmic heating (adapted from [59])



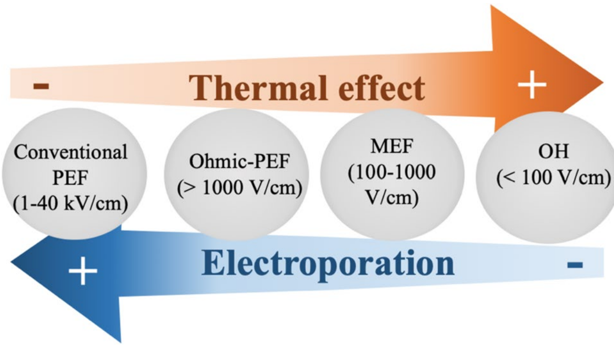


Fig. 5 Correlation between the ohmic technologies applied and the degree of occurrence of thermal and electrical effects

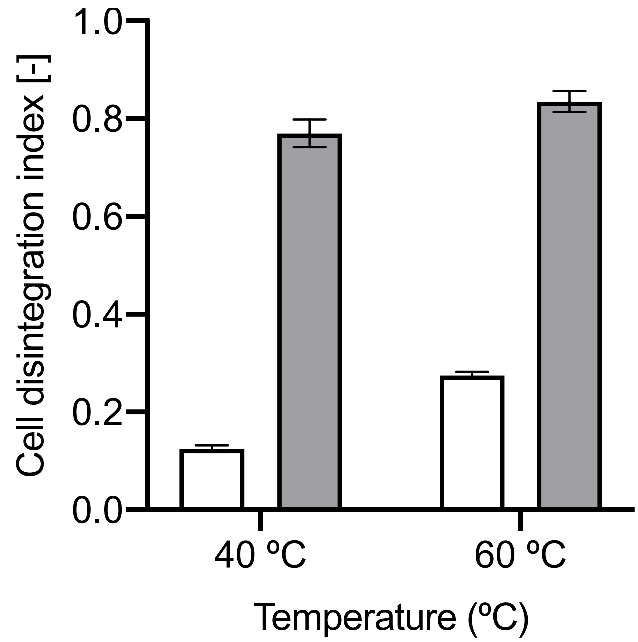


Fig. 6 Cell disintegration index at different stages of blanching of carrots blanched in water at 85 °C (unfilled bars) and by ohmic-PEF heating at 1330 V/cm and 100 Hz (grey bars). Adapted from Astráin-Redín et al. [18]

middle are MEF and ohmic-PEF where thermal effects and electroporation occur together, and it is very complex to analyze each of them separately since there are many parameters to consider (cell type, frequency, electric field, and treatment temperature, among others).

Regarding MEF (E < 1000 V/cm), research has been carried out since the beginning of the twenty-first century [65] in order to achieve non-thermal (electrical) effects. Several studies have been conducted on its application for salmon salting [26, 66], osmotic dehydration [67], cooking [68, 69], spore inactivation [70], pasteurization [71], and enzyme inactivation [24, 72]. Recently, its great potential for fermentation processes has been identified, as MEF induces a stress-response that reduces the lag phase and increases the concentration of desirable fermentation products, as well as reaching the fermentation temperature quickly and homogeneously [73].

The application of PEF technology as a non-thermal system or as a thermal system depends on the processing parameters (electric field, specific energy, and treatment time). In conventional PEF (non-thermal process), electric fields are applied in order to minimize temperature rise and promote electroporation. In order to do so, food with low electrical conductivity is preferred and low-energy treatments in the form of high electric fields (1–40 kV/cm), short pulse widths (1–20 µs), and micro- and millisecond treatment times are applied [74]. Conversely, ohmic-PEF is designed to induce a rapid, volumetric heating of the food over longer treatment times (in the order of seconds or minutes) by applying higher energies. In general, Ohmic-PEF allows a higher electric field strength (> 1000 V/cm) to be applied than that used in MEF heating (< 1000 V/cm). The purpose of applying electric fields even higher than those applied in MEF is to favor cell electroporation during the first seconds of the treatment when temperatures are not yet high (< 50 °C). Thus, favoring the release of intracellular ionic compounds and improving the uniformity of the electrical conductivity of the food. Figure 6 shows the cell disintegration index (measured by impedance analysis) of carrots blanched in water at 85 °C and by ohmic-PEF at 1330 V/cm and 100 Hz [18]. When the samples reached 40 °C, the conventionally blanched carrots had a cellular disintegration index of 0.13, whereas those that had received ohmic-PEF showed a value of 0.77. Tissue disintegration would be mainly due to electroporation generated in the first seconds of treatment at low temperatures as the electric field is enough for plant cell electroporation (< 5 kV/cm) [75].

In addition, it has also been reported that the application of ohmic-PEF at electric fields of 3750 V/cm to agar cylinders improved the heating uniformity by reducing the temperature gradient between the cold and hot spots of the sample from 8 to 4 °C [50]. Nevertheless, this way of applying PEF for ohmic heating purposes is very recent, and there are hardly any studies about it. Due to the fact that the application of ohmic-PEF is very recent, the equipment is currently not optimized for it, and it is not powerful enough to apply ohmic large-scale treatments.

Mechanisms of Action

The thermal effect is, by nature, the main mechanism behind the application of OH. However, some studies have reported the presence of a non-thermal effect (due to the electric current) that would increase cell permeabilization and the degree of microbial and enzyme inactivation by the generation of sublethal or additional damages [76, 77]. In this section, the effect on cells (eukaryotic and prokaryotic cells) and the effect on enzymes will be discussed.

Effects on Cells

It is well known that the application of enough intense electric fields leads to the disruption of the membranes of cells by the formation of pores. This phenomenon is known as electroporation and occurs when a minimum electric field is reached, which depends on the size of the cells (see Eq. 3) [78].

$$ITV = \frac{3}{2}|E|r\,(\cos\theta) \tag{3}$$

where ITV is the induced transmembrane voltage, E is the electric field strength, r is the cell radius, and θ is the angle of the position of the cell in relation to the direction of the electric field. Therefore, for microbial cells (size of 1–10 µm), a minimum electric field strength of 10,000 V/cm [79] would be needed whereas for eukaryotic cells (size of 40–200 µm), the minimum value is 100–1000 V/cm [80]. During OH, in which the applied electric field is less than 100 V/cm, electroporation would not theoretically occur, but in MEF and ohmic-PEF treatments, where higher fields (> 100 V/cm) are applied, eukaryotic cells could be permeabilized.

Eukaryotic Cells

Non-thermal effects derived from the application of MEF and PEF result in the permeabilization of eukaryotic cells when sufficiently high electric fields are applied for electroporation to take place. The application of a MEF treatment at 200 V/cm and 10 pulses or 133 V/cm and 100 pulses caused the permeabilization of the tonoplast membrane of onion cells [81]. In other words, considering Eq. 3, a smaller number of pulses is needed to reach the induced transmembrane voltage when applying higher electric fields. Therefore, the application of ohmic-PEF would allow an earlier cell electroporation than would be achieved with MEF.

In plant tissues, non-thermal effects are most clearly observed at temperatures below 50–60 °C since thermal breakdown occurs above these temperatures [82]. For example, applying MEF treatment at 100 V/cm to sugar beet effectively damaged the tissue at moderate heating temperatures of 50–60 °C and treatment below 100 s. At such treatment conditions, the thermally induced damage effects were inessential, and the observed disintegration was mostly of an electroporation nature [83]. For the ohmic-PEF, a tissue disintegration of 0.77 at temperatures of 40 °C has also been observed in carrots [18]. Based on this effect, the cellular breakage caused by the application of MEF and PEF-ohmic would enhance extraction processes by improving mass transfer. Therefore, many studies on MEF technology have focused on the extraction of components [32, 82].

Microbial Inactivation

Microbial inactivation by heat is due to the alteration of several cellular components such as the outer and inner membrane, the peptidoglycan cell wall, the nucleoid, the cell's RNA, the ribosomes, and diverse enzymes, which lead to the loss of the cells' potential to multiply, and they ultimately die [84]. On the other hand, the application of high electric fields causes the loss of membrane selective permeability, which produces an imbalance in cell homeostasis and can lead to cell death [85].

Most studies on microbial inactivation by OH focus only on the inactivation kinetics [86–88], while very few deal with its mechanisms of action and are mainly related to spore inactivation [51, 70, 89]. The inactivation of vegetative cells by OH treatments is considered primarily thermal, although studies have reported additional inactivation related to the effect of electroporation when an electric field is applied (Table 1). However, although the application of PEF (electric fields > 20,000 V/cm) together with mild temperatures (< 50 °C) has been shown to favor the electroporation of bacterial membranes [90, 91], the electric fields applied in OH, MEF, and even ohmic-PEF, are significantly lower. Nevertheless, Pereira et al. [88] studied *Listeria monocytogenes* inactivation by OH when a treatment of 6 V/cm, 60 Hz, and 60 °C was applied to whey dairy beverage. In order to compare with the heat treatment only, samples were treated using a water bath. The results showed that for the inactivation of 4 Log_{10} cycles, 2.73 min and 4.35 min were necessary when applying OH and CH, respectively. These results have to be taken with care, and more detailed research is necessary since in this last study, no time–temperature profiles were shown, assuming that the heating phase until the sample reached the holding temperature did not affect the inactivation.

The additive effect on microbial inactivation when applying OH is a controversial subject.

In order to compare both heat and ohmic technologies, the same temperature–time profile should be applied [92] or mathematical models based on heat resistance data have to be used [16, 17]. Schottroff et al. [92] made a great effort to achieve a reliable working method in which the heating kinetics would be the same for both technologies and in which no hot or cold spots would occur. After testing several systems, the use of a capillary batch system allowed to applied the same temperature ramps for OH and conventional heating [51, 77]. In these conditions, no additional inactivation was observed for *Microbacterium lacticum*, *Listeria innocua*, *Staphylococcus carnosus*, *Escherichia*

Table 1 Evaluation of the presence of additive effects in the inactivation of microbial vegetative cells by ohmic heating

Microorganism	Sample	Treatment conditions	Additive effect	Notes	Reference
Escherichia coli O157:H7	Buffered peptone water (pH = 7.2)	**OH treatment:** electric field strength: 30 V/cm; frequency: 20 kHz; holding temperatures: 55, 58, and 60 °C **Conventional heating:** water bath at 55, 58, and 60 °C	Yes; (2.50 × more)	Time–temperature profiles were not shown (they assumed that the heating phase until the sample reached the holding temperature did not affect the inactivation)	[87]
Salmonella eneterica serovar Typhimurium			Yes; (2.00–3.26 × more)		
Listeria monocytogenes			Yes; (2.70–4.50 × more)		
Salmonella enterica serovar enteritidis	Pomelo juice	**OH treatment:** electric field strength: 30 V/cm; frequency: 50–20,000 Hz; holding temperature: 52, 55 y, and 58 °C **Conventional heating:** water bath at 58 °C	Yes; z-values of 4.6, 4.9, and 5.3 °C for OH at 60 Hz, 500 Hz, and conventional heating, respectively	For conventional heating, the sample was inserted into glass tubes which were immersed in the bath, while for OH heating, it was in direct contact with the electrodes. No time–temperature profile was shown	[86]
	Buffered peptone water		Yes; z-values of 5, 5.2, and 6 °C for OH at 60 Hz, 500 Hz, and conventional heating, respectively		
Listeria monocytogenes INCQS 00673	Whey dairy beverage	**OH treatment:** electric field strength: 6 V/cm; frequency: 60 Hz **Conventional heating:** water bath Inactivation treatments: 57.5 °C/38 min; 60 °C/11 min; 62.5 °C/4.5 min, and 65 °C/ 4.5 min	Yes; the time required for a 4 Log_{10} cycles reduction at 60 °C was 2.73 and 4.35 min for OH and conventional heating, respectively	No time–temperature profile was shown (they assumed that the heating phase until the sample reached the holding temperature did not affect the inactivation)	[88]
Microbacterium lacticum; *Listeria innocua*; *Staphylococcus carnosus*; *Escherichia coli*; *Saccharomyces cerevisae*; *Rhodotorula glutinis*	Ringer's solution; stress medium (30° Brix and pH 3.8)	**OH treatment:** 55.5 V/cm and 12 kHz; 41.7 V/cm and 300 kHz; heating up to 67 °C **Conventional heating:** capillary batch setup; heating up to 67 °C	No	Identical time-temperatures profile for OH and conventional heating	[92]
Listeria monocytogenes STCC 5672	Technical agar	**OH treatment:** electric field strength: 2500 V/cm; frequency: 50 Hz **Conventional heating:** Thermoresistometer for determining the D-values and z-value	No	The experimental inactivation by OH matches the inactivation simulated with the Geeraerd model for the applied time–temperature ramps	[17]
Salmonella Typhimurium 878	Technical agar	**OH treatment:** electric field strength: 2500–3750 V/cm; frequency: 50 Hz **Conventional heating:** Thermoresistometer for determining the D-values and z-value	No	The experimental inactivation by OH matches the inactivation simulated for the applied time–temperature ramps	[16]

coli, *Saccharomyces cerevisae*, or *Rhodotorula glutinis* at two different frequencies 12 kHz (55.5 V/cm) and 300 kHz (41.7 V/cm). Likewise, Astráin-Redín et al. [17] conducted inactivation of *Listeria monocytogenes* at 50 Hz by employing a batch cylindrical chamber, but instead of using liquid samples, they used a solid technical agar cylinder. This allowed them to select the sample area as the central zone, and the zone close to the electrodes whose heating rates were different (1.10 °C/s and 0.88 °C/s, respectively). Based on the time–temperature values of ohmic heating and the thermoresistance values of *L. monocytogenes* from conventional heating ($D_{58}=2.277$ min; *z*-value = 5.37 °C), they modeled inactivation and observed no difference between experimental and simulated inactivation based on the microbial thermoresistance.

A second point which could explain the additional inactivation by the non-thermal effect of OH would be the presence of compounds generated/released due to the electrochemical reactions from the electrodes. This phenomenon is enhanced when OH is applied by direct currents or at low frequencies with long pulse widths (> 20 µs) [93]. Nevertheless, it should be noted that for non-thermal PEF treatments at high voltages, and if the PEF system is well designed, the outflow of metal ions into the food is minimal [94]. Therefore, the application of ohmic-PEF could also help to minimize these electrochemical reactions by applying shorter pulse widths (3 µs), medium electric fields (1000–5000 V/cm), and reduced heating times. In addition, the use of platinum electrodes and the application of frequency in the kilohertz range have also been found to minimize electrochemical reactions of the electrodes [11, 12].

Everything discussed earlier is related to the inactivation of vegetative cells. However, it seems that OH could be a promising alternative for bacterial spores inactivation, which are very resistant to preservation technologies [95]. Spore stress resistance is believed to be due to different factors including its complex multilayered envelopes, the low water content of the core, and the presence within the later of small acid-soluble proteins (SASP) that protect the chromosome and high amounts (up to 10% of dry weight) of dipicolinic acid (DPA) and divalent metal ions, together with the low water content of the core [95–98]. In some cases, the application of OH treatment has resulted in higher inactivation of *Geobacillus stearothermophilus* [77], *Bacillus licheniformis* [99], and *Bacillus subtilis* [51, 70, 100, 101]. In a study conducted by Schottroff et al. [51], an OH treatment of 60 V/cm, 84 µs of pulse width with a temperature increase of 1.1–1.3 °C/s up to 108 °C was applied for the inactivation of *B. subtilis* PS533. Conventional heating and OH followed the same heating kinetics but for $F_{121°C}=4.4$ s, the ohmic inactivation was 2.2 Log_{10} higher. Thus, in order to determine which cellular component of the spore structure was being affected by OH, several trials were carried out on mutants that lacked the genes involved in spore resistance. The results indicated that these differences were not related to any/major effect of OH on the envelopes, DPA release was comparable to that generated by conventional heating.

Therefore, further research is needed to assess which cellular components are affected by the application of OH, and how the processing parameters (electric field) influence both vegetative cell and spore microbial inactivation.

Enzyme Inactivation

The application of food preservation treatments also involves the inactivation of enzymes. As described for microbial inactivation, the thermal effect would be the major cause of enzyme inactivation, but an electrical (non-thermal) inactivation has also been reported in the literature [102–104]. In this case, this non-thermal effect would be related to changes in enzyme structure leading to increased structural dynamics and reduced cohesion of the protein [105]. The application of rigid body dynamic models has shown that the exposure of enzymes to an electric field induces electrophoretic translational motion which make enzymes behave as if they were at a higher temperature than their surroundings [106, 107]. It has also been observed that the magnitude of these non-thermal effects is very field-strength and treatment-time dependent. Consequently, this can be used as a tool to improve the efficacy of OH treatments for enzyme inactivation [108].

In a recent study, Samaranayake et al. [104] evaluated the application of ohmic inactivation of PPO and POD enzymes in grape juice when 82 and 87 V/cm OH treatments were applied at 65 and 75 °C. The results were statistically significant only for a temperature of 75 °C where the application of electric fields increased the inactivation rate by 33.15% for PPO and 55% for POD. Additionally, they simulated the molecular motion in response to the electric field and the temperature and reported that the operating temperature could be reduced by increasing the electric field strength. Moreover, the PPO inactivation in pineapple juice was evaluated by heating at 80 °C and different electric fields (16–36 V/cm). The results showed that for the same treatment temperature, enzyme inactivation increased with increasing electric field, i.e., an increase from 16 to 36 V/cm resulted in a reduction of the residual enzyme activity from 0.67 to 0.10. In this sense, it seems that ohmic-PEF could still lead to better results as higher electric fields are applied.

Applications in the Food Industry

OH has been extensively investigated in various thermal food processes focusing on pasteurization and enzymatic inactivation of liquid products, extraction of compound from vegetables and fruits, peeling, cooking of meats, concentration of fruit juices, and thawing of fish. There are several publications related to OH [20, 21, 65, 93, 109] using the majority of them electric field strengths lower than 100 V/cm. Table 2 summarizes the recent studies (last 5 years).

Food Preservation Based on Microbial and Enzymatic Inactivation

In order to guarantee the safety, nutritional, and sensory quality of food, it is necessary to achieve a certain level of microbial and enzymatic inactivation. However, the required inactivation must be achieved in the whole food. When heat treatments are applied using conventional systems, some areas result over-treated to ensure that the cold points reach the required level of inactivation. Ohmic pasteurization is successfully applied to liquid or viscous foods where heating is more uniform than in solid foods due to the homogeneity of electrical conductivity. Pasteurization by OH has been widely studied for fruit and vegetable juices and purees as well as for milk [71, 116, 118, 119, 121].

The application of ohmic pasteurization allowed to reduce processing times and energy consumption by applying rapid and volumetric heating. Several studies have been conducted by applying ohmic technology. Giuliangeli et al. [117] applied a treatment of 0.21 V/cm at 60 Hz to guava pulp at 60, 70, and 80 °C for 110 min. A reduction in energy consumption of 93% and a constant heating rate of 0.16 °C/s were observed, which was 2.6-fold higher than conventional heating. Similarly, Balthazar et al. [121] reported 73% energy savings when pasteurizing sheep's milk at 8.33 V/cm and 60 Hz; Gratz et al. [58] reduced sterilization time of carrot purée by 51–60% by applying 62.5 V/cm at 12 kHz; Kuriya et al. [145] reduced the pasteurization time of dairy dessert by 43% by applying 9.1 V/cm and 60 Hz. This improvement would be amplified by applying higher electric fields such as those used in MEF and ohmic-PEF. Astráin-Redín et al. [17] applied ohmic-PEF (2.5 kV/cm and 50 Hz) for the pasteurization of agar cylinders contaminated with *L. monocytogenes* and observed a reduction of the treatment time of 83.3–99.3% compared to conventional heating.

Furthermore, this improvement in processing times also results in products with better nutritional and sensorial properties by minimizing the thermal impact. Therefore, much research has focused on studying the impact of ohmic pasteurization on nutritional compounds and sensory properties of the food. Improvements in the color of OH-pasteurized peaches were observed by Rinaldi et al. [120] who found better redness values due to higher phenolic compound content. Debbarma et al. [116] applied an ohmic treatment of 17.10 V/cm for 40 s on orange juices, and improvements in the final values of β-carotene (no degradation), total phenolic content (12.22%), and color were found. However, Dhenge et al. [119] applied ohmic pasteurization to orange juice and observed no improvements in viscosity, total phenolic content, ascorbic acid, total antioxidant capacity, and browning. On the other hand, when MEF treatment at 120 V/cm, 60 kHz, and 80 °C / 7 min was applied to carrot juice, better color, higher antioxidant capacity, and better carotene content were obtained compared to those treated by a conventional pasteurization at 80 °C during 7 min [127].

As already pointed out above, it is very complex to compare between treatments as it has to be done for the same lethality, and in many cases, this has not been calculated or reported. Similarly, treatment conditions may also vary widely: batch *vs*. continuous, different foodstuff, etc. Furthermore, in some cases, there is missing information about the ohmic parameters applied.

Regarding dairy products pasteurized by OH, Silva et al. [146] analyzed sensory parameters such as bitterness, brightness, and fluidity and concluded that applying electric fields of 10 V/cm and temperature of 90 °C during 3 s improved the consumer acceptance. However, Kuriya et al. [145] observed a negative effect on color, volatile profile, and rheological behavior in ohmic-pasteurized blueberry-flavored dairy desserts. Thus, the application of electric field strengths of 9–20 V/cm and temperatures of 72–75 °C during 15 s increased the degradation of monomeric anthocyanin, total polyphenols, and DDPH as compared to conventional heating.

Finally, in a study conducted by Kanjanapongkul and Baibua [126] on coconut water, they observed that ohmic pasteurization (10 V/cm and 50 Hz) prevented the pinkish discoloration caused by conventional pasteurization, which they attributed to the effects of electric fields on the PPO enzyme.

In summary, ohmic pasteurization would allow shorter heat treatments compared to traditional ones, which would improve the sensory qualities of the food but, depending on the matrices treated, in some cases, the electrical effect might negatively affect certain bioactive compounds.

Extraction

Many waste products from the food industry (skins, seeds, lees, etc.) are a source of valuable compounds including phenolic compounds, digestive fiber, hydrocolloids, pectins, organic acids, carotenoids, among others, which are used as natural additives [147, 148]. However, extraction processes involve the use of solvent that could be a danger for health or considered non-environmentally friendly solvents [149]. OH is one of the emerging technologies being investigated in order to reduce the use of these chemicals and favor a more environmentally friendly process [150].

Several experiments have been performed on OH-assisted extraction of valuable compounds in vegetables and fruits:

Table 2 Ohmic heating applications in the food industry

Process	Product	OH conditions	Effects	Reference
Cooking	Potatoes	**Frequency 12 kHz:** electric field: 55.6–111 V/cm; NaCl solutions: 1–5 mS/cm; power: 0.9–4.5 kW/kg; **Frequency 300 kHz:** electric field: 10–40 V/cm; NaCl solutions: 1, 2.5, and 5 mS/cm; power: 0.8–2.3 kW/kg	Reduction of cooking time when applying OH. Best heating uniformity: 300 kHz, high conductivities of the liquid medium and peeled potato. For the same cooking level, ohmic-heated samples were softer	[110]
Cooking	Rice (*Oryza sativa*)	Power: 1.4 kW; frequency: 60 Hz	Increased evaporation in OH. Saving 31% of energy consumption when applying OH. OH caused further softening and negatively affected the color	[111]
Cooking	Noodles	Electric field: 10–17.5 V/cm; distilled water; on/off cycle times	Electric field of 15 V/cm presented the best energy yield and texture values	[112]
Cooking	Marinated pork	Electric field: 21 V/cm; frequency: 60 Hz	OH allowed a reduction of the cooking times. No effect on cooking loss, color, or water-holding capacity	[113]
Cooking	Chicken meat	Electric field: 10 V/cm; frequency: 50–2000 Hz; until 75 °C	Cooking time was reduced up to tenfold by applying square wave MEF at 50 Hz. At 2000 Hz and sine wave, WSP (water-soluble protein) was better preserved	[69]
Cooking	Beef	Nutri-pulse e-cooker: < 175 V/cm; MEF device: 57.5 V/cm; 72 °C/ 2min	Time to reach 72 °C: e-cooker 1.16 min, MEF 0.86 min, conventional 14.12 min. OH did not affect the tenderness of the samples. Better cook-loss values when applying e-cooker followed by MEF, both better than those obtained conventionally	[68]
Cooking	Basil-based sauces	Electric field: 3.12, 4.16, and 5.20 V/cm; samples with 0.43–3.25% of salt	The pure pesto was hardly heated when MEF was applied due to the high-fat content. The higher the salt content, the higher the conductivity, and the faster the heating	[114]
Baking	Gluten-free bread	Electric field: 64.9 V/cm; frequency: 12 kHz; three-step heating profile: 5 kW for 15 s; 1 kW for 10 s; 0.3 kW for 80 s	The solubility of the added protein positively influences the final volume of the ohmic bake. Bread obtained by ohmic baking has no crust and better quality than normal bread	[49]
Baking	Cake batter	OH for pre-baking; continuous flow (injection); electric field: 22, 33 y, 48 V/cm; frequency: 50 Hz	Temperature heterogeneity was observed in OH. Hot spots at the electrode borders where the electric field was higher and the flow velocity lower	[115]
Pasteurization	Carrot juice	Batch treatment; electric field: 15–25 V/cm; frequency: 60 Hz; processing time: 40–90 s	Optimal treatment conditions: 17.10 V/cm y 40 s. Ohmic treatment improved the final values of beta-carotene, total phenolic content, and color	[116]

Table 2 (continued)

Process	Product	OH conditions	Effects	Reference
Pasteurization	Guava pulp	Electric field: 0.21 V/cm; frequency: 60 Hz; treatment: 60, 70 y, 80 °C durante 110 min	There was no difference in color between ohmic and conventional heating. OH reduced energy consumption by 93% and increased carotenoid content at 60°C compared to CH	[117]
Pasteurization	"Aguamiel" of *Agave salmiana*	Batch treatment; Electric field: 20, 30, and 40 V/cm; temperatures: 70, 80, and 90 °C; holding time: 5, 10, 15 s	Ohmic pasteurization effectively inactivated the *E. coli*, yeasts, and *Lactobacillus* population. Increase (18.3%) of soluble solids (°Brix) in the ohmic treatments. Best color values at electric fields of 20 V/cm	[40]
Pasteurization	Apple juice	Batch treatment; electric field: 20 V/cm; frequency: 60 Hz; temperatures: 75–94 °C	Additional inactivation when applying OH at temperatures of 75, 80, and 85 °C. At higher temperatures 90 and 94 °C, no further inactivation was observed	[118]
Pasteurization	Orange juice	Continuous treatment (2000 L/h); temperature up to 97 °C; (no further information is given)	OH-treated juices have a lower acceptability value by the panelists than high-pressure ones. OH did not differ from conventional treatments in terms of viscosity, total phenolic content, ascorbic acid, total antioxidant capacity, browning index, and suspended pulp	[119]
Pasteurization	Peach cubes in syrup	Continuous treatment (1700 L/h); treatment: 25 a 98 °C	Samples treated with OH showed a higher redness and a higher total phenolic content. OH preserved the texture and color of the samples better	[120]
Pasteurization	Milk	Electric field: 8.33–20.80 V/cm; flow treatment: 0.018–0.077 kg/s	MEF reduced energy consumption by 63% compared to 72 °C/15 s pasteurization. The MEFs achieved good sanitary quality without increasing the temperature above 22 °C. An extension of the useful life from 9 days (conventional) to 15 days was achieved by applying 20.80 V/cm at a flow rate of 0.018 kg/s	[71]
Sterilization	Carrot-based purees	Batch treatment; electric field: 62.5 V/cm; frequency: 12 kHz; temperature 120–125 °C	No extra microbial inactivation when applying OH. OH allowed a reduction in treatment times (51–60%) and *C*-values (21–41%). 41–64% reduction in furan formation when applying OH	[58]
Sterilization	Canned coconut milk	Batch treatment; voltage: 350 V; frequency: 50 Hz; pressure: 1.5 bar; 121.1 °C/ 2 min	Ohmic treatment reduced energy consumption by 32%. Samples treated with OH showed minimal physicochemical changes and reduced off-odor formation while maintaining a better appearance	[9]

Table 2 (continued)

Process	Product	OH conditions	Effects	Reference
Microbial inactivation	Sheep milk	Batch treatment; electric field: 8.33, 5.83, and 3.33 V/cm; frequency: 60 Hz	Increased energy efficiency by 73% when applying 8.33 V/cm. No difference in inactivation by OH or CH	[121]
Listeria monocytogenes inactivation	Vacuum packaged sausage	Batch treatment (water at 80 °C); voltage: 430 V; frequency: 50 Hz; time: 30 s and 2 min	OH allowed to reduce energy consumption by 50%. OH treatment inactivated 5 log; OH did not affect chemical composition, pH, lipid oxidation, cooking loss, or CRA. OH minimally affected color and texture	[122]
Molds and insect larvae inactivation	Chestnuts	Electric field: 9 V/cm; frequency: 25 kHz; temperatures: 35, 45, and 55 °C; time: 2.00, 2.83, 3.33 min	The application of OH (55 °C) resulted in a shelf life of 60 days without changes in the color and texture of the samples and lower losses of nutrients and vitamin C	[25]
Blanching	*Agaricus bisporus* mushroom	Electric field: 15 V/cm; frequency: 60 Hz; on/off cycle times; distilled water; water temperature: 67–90 °C	Faster heating by OH (15.6 vs 23.5 °C/min). OH allowed improving heating uniformity to increase the internal temperature and to favor the PPO inactivation. Both treatments caused browning reactions. No texture differences	[123]
Blanching	Pineapple	Pre-treatment before drying; temperature: 90 °C; frequency: 50 Hz; electric field:25–35 V/cm; holding time: 60–180 s; NaCl solution (0.1%)	Higher electric fields allowed higher drying speeds. Increased loss of TSS (total soluble solids) at higher electric fields. Best rehydration result with treatment at 25 V and 60 s	[124]
Pectinesterase inactivation	Orange juice	Batch treatment; electric field: 32–36 V/cm; frequency: 60 Hz; holding temperatures 60–90 °C Holding times 0–200 s	Higher inactivation at 60 °C in ohmic treatment than with conventional treatment, but this effect is reduced with increasing temperature	[125]
Enzyme inactivation	Coconut water	Batch treatment; electric field: 10 and 20 V/cm; frequency: 50 Hz; temperatures: 70, 80, and 90 °C; holding time: 3–15 min	Conventionally treated samples showed a pinkish discoloration while ohmic samples did not. Significantly lower PPO values when applying OH	[126]
Inactivation of PPO	Carrot juice	Batch treatment; variable electric field: < 120 V/cm; frequency: 60 kHz; 80 °C/ 7 min	Higher inactivation of PPO by OH than conventional treatment. OH juices presented better color, higher antioxidant capacity, and carotenoid content	[127]
Inactivation of PPO	Pineapple juice	Electric field: 16–36 V/cm; 80 °C/ 1 min	Exponential reduction of PPO activity with increasing voltage. Significant change of the L* value when applying 32 V/cm. HMF formation increased with the electric field. The total phenolic content decreased when applying fields higher than 15 V/cm	[24]

Table 2 (continued)

Process	Product	OH conditions	Effects	Reference
Inactivation of POD	Sugarcane juice	Electric field: 0–16.7 V/cm; frequency: 0–100 kHz; temperature: 60 and 80 °C	Higher inactivation of the POD enzyme with OH at 80 °C. No differences in POD enzyme inactivation between waveforms and voltages. The phenolic compounds were not affected by the applied electric field	[44]
Oxidative enzymes inactivation	Grape juice	Electric field: 82 and 87 V/cm; frequency: 60 Hz; Temperatures: 65 and 75 °C	Higher inactivation with FEM than with heat alone. Best results applying 87 V/cm y 75 °C	[104]
Extraction	Grape	Pre-treatment; electric field: 30 V/cm; frequency: 25 kHz; 100 °C / 13 s	Higher extraction yields of total polyphenols (3 times higher), ascorbic acid (2.8 times higher), anthocyanins (1.2 times higher) with OH treatment, and citric acid as a solvent	[46]
Extraction	Red eggplant	Continuous treatment; solvent: methanol, ethanol, and water; electric field: 10 V/cm; frequency: 20 kHz; 80 °C / 25 min	OH extraction improved the concentration of total phenols by 35%. OH increased the extraction yield by 27% with 50% ethanol as solvent. Extracts obtained by OH showed no toxicity	[47]
Extraction	*Gracilaria vermiculophylla* (macroalgae)	Solvent: 0–75% water:ethanol; electric field: 2–8 V/cm; frequency: 25 kHz; temperature: 82 °C	OH allowed a higher extraction yield by correctly adjusting the solvents according to the compound of interest. Higher extraction yields with OH after 1 h except for the solvent 100% water. The gelling capacity of the agar was not affected	[48]
Extraction of pectin	Grapefruit, lemon, orange wastes	Solvent: water:sulfuric acid (pH = 1); electric field: 9 V/cm; frequency: 50 Hz; holding temperature: 80 °C; holding time: 0–180 min	Longer times higher extraction yields	[128]
Extraction of betalain	Red Beetroot	Batch treatment; electric field: 11, 17, and 23 V/cm; frequency: 25, 100, and 400 Hz; 40 °C/ 1 h	Influence of solvent composition on ohmic treatment parameters. Best conditions: 17 V/cm, 400 Hz, and solvent water:ethanol. Energy efficiency of 37–67% for OH extraction while for conventional extraction it was 13–17%	[129]
Extraction of anthocyanins	Grape skins	Batch treatment; electric field: 16 and 70 V/cm; frequency: 25 kHz; solvent:water; 40 °C / 20 min or 40–100 °C/ 20 s	Extraction was not improved by applying 16 V/cm and 40 °C/ 20 min. When applying 80 V/cm and 100 °C, the extraction increased by 5%. Energy consumption was reduced by 6.7 times compared to CH	[42]
Drying	Potato	Hot air dryer; voltage: 75, 100, and 125 V; frequency: 50–60 Hz; temperatures: 50 and 60 °C; air velocity: 0.74–2.15 m/s	Drying time was reduced by 20–60% compared to the conventional method. As the humidity decreased, the ohmic heating became less effective	[130]

Table 2 (continued)

Process	Product	OH conditions	Effects	Reference
Drying	Litchi fruit	Intermittent ohmic heating; temperature: 70 °C; air velocity: 1.8 m/s; power: 2000 W	Energy consumption of the OH-dried samples was lower. OH reduced browning, improved the retention of vitamin C and phenolic compounds, did not affect hardness, and reduced methane and sulfur-organic odor	[131]
Concentration	Sour cherry juice	Electric field: 8.3–13.9 V/cm; frequency: 50 Hz; temperature: 95 °C	Heating rate is ten times higher in OH than CH. No differences were observed between the voltages in the final color and acidity of the samples	[132]
Concentration	Verjuice	Electric field: 13–19 V/cm; temperature: 102 °C; until 50% TSS	The higher the electric field, the shorter the processing times and the greater the energy efficiency. During evaporation, the conductivity increased by 32% (1.6 s/m) and then decreased	[133]
Concentration	Apple juice	Electric field: 13–17 V/cm; temperature: from 20 to 100 °C and then boiling process (atmospheric pressure)	Maximum reduction in processing time of 44% by applying 17 V/cm, which reduced energy consumption by 57.2%. Increasing the electric field improved the final TPC content and antioxidant activity	[134]
Concentration	Mulberry juice	Electric field: 15–30 V/cm; frequency: 50 Hz; temperature: 92 °C; final value of 2.39 kg water/kg dry matter	Processing time was reduced by 68.5% when applying an electric field strength of 30 V/cm. Total phenol content 3–4.5 times higher when OH was applied	[135]
Osmotic dehydration	Apples	Sucrose solutions of 40, 50, and 60%; electric field: 5.5 and 11 V/cm; frequency: 60 Hz	The application of MEF increased water loss and solid gain allowing for reduced processing time. The application of MEF caused the degradation of phenolic compounds and blackening of the samples	[67]
Thawing	Spinach puree	Electric field: 10 and 15 V/cm; hydrostatic pressure: 490 Pa; temperature: from − 18 to − 0.8; direct contact	Thawing times were reduced by 72.86% and 82.44% when applying 10 and 15 V/cm, respectively. Energy and exergy efficiency were improved	[136]
Thawing	Tuna fish	Voltages: 40–60 V; frequency: 50 Hz; NaCl solutions 0.3–0.5% (at 25 °C); temperature: from − 18 to − 7 °C	Maximum time reduction of 30% compared to using water at 27 °C when 50 V was applied employing 0.3% NaCl solution. Total losses after thawing were significantly reduced. There was no effect on color or CRA	[137]
Thawing	Minced beef meat	Electric field: 10 and 16 V/cm; temperature: from − 18 to − 1 °C; direct contact; fat content: 2–18%	From − 6 °C, the fat content affects the conductivity, the higher the fat content the lower the final conductivity. OH time was 64–87% lower than conventional thawing	[30, 138]

Table 2 (continued)

Process	Product	OH conditions	Effects	Reference
Peeling	Tomato	Electric field: 6.45–64.5 V/cm; NaCl/NaOH (%): 0.01–0.03 / 0.01–1; NaCl/KOH: 0.01 / 0.5–1.0; temperature: until 100 °C	Influence of the peeling composition on the chosen electric field. Better diffusivities for lye peeling with ohmic heating than without ohmic heating at both 50 and 65 C. Applying 20.20 V/cm and 0.01/0.5% NaCl/KOH best tomato quality, weight loss, and time was achieved. Post-ohmic heating improved firmness when applied 2% $CaCl_2$ at 4.03 V/cm dor 1 and 5 min and 4.84 C/cm for 5 min	[139, 140]
Peeling	Pear	Electric field: 426–638 V/cm; % NaOH: 0.5, 2, 3%; time: 30 and 60 s; temperature: 101 °C	Best result applying 532 V/cm and 2% NaOH with 97% yield while the control (18% NaOH) achieved 87%. Influence of the medium composition on the ohmic peeling: better yields with 2% NaOH than with 3%	[141]
Gel formation	Sodium caseinate (acidic gelification)	Electric field: 2–17 V/cm; time: 124, 50, and 69 s; temperature: 95 °C	Gels treated with OH had higher rupture strengths and lower water-holding capacity values	[142]
Gel formation	Whey protein isolates (osmotic gelification)	OH treatments: 20 kHz 10 V/cm, 20 kHz 20 V/cm, 50 Hz 10 V/cm, 50 Hz 20 V/cm; temperature: 90 °C	OH gels had a weaker and more elastic structure. Higher electric fields resulted in weaker gels	[143]
Gel formation	Egg white protein (thermal gelification)	Electric field: 6.7–17.2 V/cm, 4.3 and 7 V/cm; frequency: 10 kHz; temperature 85 °C; time: 0.5 and 15 min	Lower levels of ovalbumin denaturation and gelation. Gels with a more open and porous structure when applying OH	[144]

pectins from the peel of pomegranate, grapefruit, lemon, and oranges [46, 128], anthocyanins from grape peel [42], polyphenols from tomato peel and seeds [45], betalain from red beetroot [129], and phytochemical and steviol from *Stevia rebaudiana* leaves [32]. For instance, Pereira et al. [42] evaluated the application of two ohmic pre-treatments at 16 and 70 V/cm and 25 kHz (mild heating 40 °C/ 20 min and flash heating from 40 to 100 °C in 20 s) on grape peel to favor the extraction of anthocyanins in water. The results obtained with the mild treatment at 40 °C were not significantly different from the conventional heat treatment at the same temperature; meanwhile, the flash ohmic treatment allowed to increase the concentration to 20% total anthocyanins/TPC (total polyphenol content). This flash OH treatment that applies high temperature during short times allowed to minimize thermal degradation. In this sense, the application of MEF or ohmic-PEF that allows the application of higher electric fields resulting in an increased heating rate and higher electroporation capacity could be of interest for extraction processes. But it is something that requires more research.

At this point, it should be remarked that there are some factors that seem to highly influence the effect of ohmic extraction such as the solvent, applied electric field, and frequency. Cabas and Icier [129] studied the extraction (40 °C / 1 h) of betalain in water, ethanol–water, and acidified water–ethanol from beetroot at 11, 17, and 23 V/cm at 25, 100, and 400 Hz. The extraction medium had a significant effect on the total extraction yield for low gradients (11 V/cm at all frequencies) with the highest extraction being obtained when using acidified water–ethanol. However, at higher fields (23 V/cm) and frequencies (400 Hz), the extraction medium was not a significant factor. Furthermore, depending on the compound (betacyanins, betaxanthins, or betalain), the influence of frequency, extraction medium, and voltage was different. This suggests that OH is a potential technology to apply a sustainable extraction process but that optimization would be required before its industrial implementation.

Drying

Drying process is widely applied for food preservation, but it is a highly energy-consuming process, so any technology that accelerates mass transfer results is very interesting. Since OH has to be applied to the product in contact with the electrodes or immersed in a liquid medium, it has been evaluated as a pre-treatment for this drying application. Hosainpour et al. [151] applied an ohmic pre-treatment to tomato paste using a Teflon chamber with a hole in the center to insert the temperature probe and allow the water to evaporate until the moisture content was reduced to the desired level. Different electric fields (6–16 V/cm) were evaluated to reach a temperature of 95 °C which was maintained until the moisture content decreased from 90 to 70% (w.b.). Increasing the electric field from 6 to 16 V/cm allowed to reduce the processing time by 86.8% and up to 38 times when compared to air drying at 105 °C and 1 m/s. In another study, Soghani et al. [152] applied OH for the blanching process (8.18 V/cm, 15 min) before microwave (MW) drying (900 W) of white mushroom immersed in aqueous NaCl solution (1%). Blanching involved increasing the temperature from 20 to 80 °C in 15 min. No differences in drying rate were observed when applying MW after OH blanching.

There is a study in the literature where OH was applied during drying using needle-shaped electrodes. In that case, Turgut et al. [130] used stainless steel needle-shaped electrodes in which the potato sample was pricked at both ends so that current flowed from one electrode to the other inside the potato. This novel system was able to reduce the drying time by 20–60% compared to the conventional hot air system, but as the drying process progressed and the moisture of the product decreased, the efficiency of the ohmic heating was reduced. Any case, besides the potential of OH for drying, other electro-technologies for drying such as MW or radiofrequency are under research since no contact with the product is required, obtaining more efficient results [153].

Concentration

Concentration processes are highly used in the juice industry due to the restriction of the harvesting period, low cost of packaging, storage, transport, and distribution [132]. It has been observed that the rapid and uniform heating resulting from the application of ohmic technology reduces the fouling and therefore the cost of cleaning while maintaining the original quality of the sour cherry juice [132]. Additionally, the fast heating leads to reduced processing times and energy consumption. Thus, Karakavuk et al. [134] achieved a reduction of 44% in the time required for apple juice concentration; Darvishi et al. [135] reported a 68.5% diminution in mulberry juice concentration time. The higher the electric field, the better the results as higher heating rates were obtained [33, 132–134]. Moreover, better final results in terms of TPC and antioxidant activity were achieved. However, it must be noted that during water evaporation processes, the conductivity of the product will increase until it reaches boiling temperatures where the loss of moisture will reduce the electrical conductivity [134].

Thawing

Apart from being a high-cost and time-consuming process, thawing has to be done as quickly as possible in order to maintain the microbial and nutritional quality of the food.

Therefore, ohmic technology is an interesting alternative to conventional thawing systems as the heat applied is fast and uniform. There are several studies in the literature describing the thawing of food with OH [30, 136, 137, 154–158]. For instance, thawing time was reduced by 82.44% for pure spinach (15 V/cm) [136] and by 30% for tuna fish (50 V) [137]. In the latter study, a saline solution (0.3% NaCl) at 25 °C was used to immerse the fish during the treatment, although direct contact with the electrodes can also be used [154].

Achieving temperature uniformity is critical for all thermal processes but even more in ohmic thawing due to the large difference in electrical conductivities between a frozen and thawed product [159]. Frozen food is not a conductive material but, gradually, once part of the ice goes into a liquid state, its conductivity will increase, and it will be able to heat up due to the current flow. Liu et al. [158] conducted a study on different tuna pieces (dorsal, lateral, and ventral) using ohmic thawing to increase the temperature from − 30 to 20 °C. The thawing rates were different depending on the piece and the direction of the current to the muscle fibers. The configuration that presented the best uniformity of heating between the three pieces was in parallel with the current flow (the dorsal piece was the fastest, and no differences were observed between the lateral and ventral pieces). Moreover, the electrical conductivity hardly changed (0.00134 mS/cm) up to − 10 °C since water in solid state has very little mobility. But from − 7 °C onwards, an increase was observed, with the range from − 3 to − 1 °C showing the greatest change. This corresponds to the freezing temperature of the tuna (− 1.4 to − 5 °C) and therefore the amount of water in the liquid state begins to increase. The reached values increased to 2 mS/cm at 0 °C and 4 mS/cm at 20 °C. Similarly, Cevik and Icier [30] observed that thawing minced beef with a 2–18% fat content from − 6 °C onwards, the fat content had an impact on the final conductivity by reducing the value.

Furthermore, when OH is applied by direct contact with the electrodes, it is important that the frozen product is completely flat to ensure the perfect contact; otherwise, hot spots will be created, even though this is not very easy with frozen products unless those freeze with plate freezers.

Cooking

The purpose of cooking food is to bring changes in their texture and composition to make them edible, i.e., starch gelatinization (vegetables), softening the texture (pectins, collagen), boosting the flavor, color changes, and improving the digestibility of proteins. However, when the cooking temperature is not properly controlled, undesirable effects may occur, such as the generation of burning compounds on the surface of the cooked food or total loss of texture [160]. Therefore, applying ohmic cooking would aim to have a more uniform temperature evolution avoiding overtreatment in order to improve quality and shorten processing times.

Regarding cooked meat, its major quality parameters are color, tenderness, and juiciness [161]. Bedane et al. [68] investigated the effect of ohmic cooking on beef by applying MEF (175 V/cm) and OH 57.5 V/cm for 2 min at 72 °C. No effect was observed on the tenderness and color of the samples compared to conventionally cooked samples, but quality was improved in terms of reducing cook-loss values (19–41%). Authors associated this improvement to the shortening of the processing time by 93.3% and 91.7% for reaching 72 °C in the center of the sample. Ángel-Rendón et al. [113] applied 21 V/cm for the cooking of marinated pork but instead of having the sample immersed in a salt solution, it was in direct contact with the electrodes. In this case, no improvement in cooking loss, color, or water-holding capacity was observed. These differences in the results may be related to the type of meat, e.g., the color in beef is strongly affected by heat (effect on myoglobin) while in pork, the impact is much lower. Therefore, further studies are needed to evaluate the effects of all critical parameters of OH processes.

Ohmic cooking has also been applied to vegetables found to promote softening of carrot, red beet, golden carrot [162], and potato samples [110] due to a greater damage of vegetable tissue. A relevant aspect of this application is the peel of the vegetables, which acts as an electrical insulator. Its presence generates a greater heterogeneity of temperatures as Gratz et al. [37] observed with potato tubers. They applied OH treatments (55.6–111 V/cm, 2 kW/kg) of potato samples immersed in aqueous NaCl solution with 2.5 mS/cm and after 200 s, the temperatures of the peeled and unpeeled potatoes were 80 and 30 °C for 12 kHz and 100 and 90 °C for 300 kHz, respectively.

Furthermore, a recent application with promising results is the baking of gluten-free bread by ohmic heating [49, 163, 164]. These products find it very difficult to retain CO_2 in their structure, resulting in dense and crumbly breads. However, applying ohmic baking (64.9 V/cm, 12 kHz) in gluten-free bread allowed to obtain a significant increase (up to twofold) in crumb volume compared to conventional baking [49]. They explained this result by the fact that as the heating process was much faster, the bread crumb was formed before the dissipation of CO_2. In addition, no differences were observed in the color of the crumb, but there were differences in the crust, as the heating process is volumetric, and the evaporation of water occurs in a similar way throughout the product.

Therefore, ohmic technology for food cooking is promising as it is easy to apply and highly reduces cooking times favoring the sensory and nutritional quality of the food. In fact, a domestic ohmic cooking device called Sevvy (https://www.sevvy.nl/) is already on the market.

Peeling

Conventional systems consist of using bleach in the treatment medium which, by diffusion, penetrates the inside of the peel and degrades the plant wall, in particular the pectins. The application of OH favors this diffusion process and reduces the percentage of bleach required, as was observed in the case of tomato peeling by Wongsa-Ngasri and Sastry [139]. They also observed that the electric field strength and the composition of the peeling medium affected the peeling time, i.e., for the same medium concentration, the higher the electric field, the shorter the peeling time. The peeling time was defined as the time needed until the peel cracking. Moreover, for the same electric field, the higher the NaOH concentration, the shorter the peeling time. This was to be expected, as the increase in the electric field favors electroporation and thus the diffusion process, and also the heating is much faster. Meanwhile, increasing the NaOH concentration not only increases the chemical effect but also increases the electrical conductivity of the solution, which makes the heating process faster. All things considered, the application of MEF and ohmic-PEF could have great potential for peeling as the electric fields are higher which would enhance the benefits of ohmic heating.

Protein Gels Formation

Apart from causing thermal denaturation of proteins, it has been observed that OH causes modifications to the structures (secondary and tertiary) of proteins due to exposure to an electric field [142, 165]. These ohmic effects may result in protein aggregates with different characteristics than those formed by conventional thermal systems, and the resulting gels may exhibit different properties, i.e., viscosity, water-holding capacity, solubility, or firmness. Most studies in the literature have evaluated the application of OH as a heat treatment of protein solutions, mainly as an initial heating step for a subsequent cold-set gelation process [142, 143, 166, 167]. Rodrigues et al. [143] evaluated OH (10–20 V/cm and 50 Hz, 20 kHz) for the formation of whey protein gelled by the addition of salts (NaCl). The gels were weaker and more elastic, with higher water retention and swelling capacity and lower solubility [143]. However, Wang et al. [166] applied OH (50 Hz and 200 V) to soymilk for protein thermal denaturation and found that gels were firmer and more resistant. When OH technology was applied during gel formation, it was not possible to induce an adequate elastic structure, resulting in gels with smaller aggregates and a fluid texture [168]. Joeres et al. [144] applied OH (7.7–17.2 V/cm and 4.3–7 V/cm; 10 kHz) during thermal gelification of white egg protein and reported that gels treated by OH showed lower water-holding capacity and lower firmness for longer heating times compared to CH, but the differences were not statistically significant.

The effect of OH on proteins and its impact on the characteristics and properties of gels are still unclear. However, OH can help to obtain gels with new textures and characteristics.

Impact on Food Allergenicity

One of the most current issues regarding novel food processing technologies is their impact on food allergenicity since it is strongly linked to consumer health. Allergenicity is an adverse reaction triggered by the immune system related to the ingestion of certain foods or specific component. The main food allergens are milk, soy, nuts, eggs, fish, shellfish, wheat, and peanuts, with several proteins involved such as β-lactoglobulin, casein, β-conglycinin, glycinin, ovalbumin, ovomucoids, among others. A growing number of studies are evaluating this aspect; however, there is little work on OH and allergenicity [6, 169, 170]. As in the previous section, both electrical and thermal effects must be considered for the assessment of allergenicity in OH-treated foods. Due to the wide variety of allergenic proteins, the effects of heat on them are heterogeneous, as some are more thermoresistant (caseins, β-lactoglobulin, ovomucoid, ovalbumin), and others are more thermolabile (bovine serum albumin, β-lactalbumin). OH would also be expected to behave similarly to heat due to its mainly thermal effect. The impact of ohmic heating is likely to depend on the specific food, the structure of the allergenic proteins, and the processing ohmic conditions since both electric field strength and frequency can have an effect on protein structure. Pereira et al. [171] evaluated the application of OH (4 V/cm and 25 kHz) on β-lactoglobulin immunoreactivity. They observed that OH decreased the immunoreactivity of the protein compared to conventional heating. However, when 4 V/cm at 25 kHz was applied during thermal treatment at 65 °C for 30 min, immunoreactivity was still increased as compared to the non-treated protein. In another study, Pereira et al. [172] evaluated the impact on trypsin inhibitor protein present in soybean, and it was observed that OH (10 V/cm) at low frequencies of 50 Hz produced higher conformational disturbances, but when two electric fields of 2 and 20 V/cm were evaluated, no effect was observed. This resulted in a 36% reduction in immunoreactivity at 50 Hz. Also, recently, Li et al. [173] applying 100 V at 50 Hz determined that OH at 50 °C required 19.2 × less time and 121.6 × less energy consumption to reduce by 70% eel collagen allergenicity than a heat treatment in a water bath at the same temperature. In a similar way and methodology, these authors observed a 65% reduction of the allergenicity of parvalbumin when using OH heating compared to water bath heating or thermostatic heating [174]. All these studies seem to indicate that OH may help to reduce the allergenicity of certain proteins;

however, the studies are too few to make solid conclusions, and more research is still required for this interesting possible application of OH in the food industry.

MEF and Ohmic-PEF Applications

Most studies in the literature focus on OH (E < 100 V/cm). In the case of MEF, some studies have been carried out but the applied electric fields ranging from 1 to 100 V/cm (similar to those of OH) [24, 69, 71, 104].

Considering the previous food applications, the use of higher electric fields would be interesting for those processes involving mass transfer, as it would be promoted by the electroporation phenomenon. Therefore, the application of MEF and ohmic-PEF would be very efficient to improve processes such as component extraction, drying, and concentration. Their application could reduce processing times by increasing the extraction of compounds and water removal, and moreover, the energy transfer could be increased. All of this could make it possible to work at lower temperatures in order to have less impact on food quality.

For other applications such as microbial and enzymatic inactivation, thawing, cooking, and peeling, the application of MEF and ohmic-PEF could improve energy transfer, increase heating speed, and reduce processing times, which could improve food quality by reducing thermal impact.

However, in the case of ohmic-PEF, literature studies are very recent, and current equipment is not optimized for it. Further studies are needed to assess the potential of this technology and its subsequent equipment development.

Future Trends

OH is a thermal technology applied in many processes in the food industry. Although its main effect is thermal, in some cases, such as spore and enzyme inactivation, a non-thermal effect can occur due to the application of an electric field, leading to higher inactivation than in traditional heating. These non-thermal effects are more pronounced at higher electric fields, which is why MEF and ohmic-PEF systems have been gaining interest in recent years. These systems allow higher electric fields to be applied than ohmic heating, which, on the one hand, favors non-thermal effects and, on the other hand, increases the heating rate. Moreover, in the case of eukaryotic cells, these systems induce higher degrees of electroporation, increasing the outflow of intracellular compounds and improving the homogeneity of the conductivity of the food and, consequently, the uniformity of the heating in the whole product. This approach would be very promising for the application of heating in large solids, where huge temperature gradients are generated when conventional heating is used.

Regarding solid foods and due to their complexity, numerical simulation tools are useful to clarify how heat is distributed in the food depending on its components, the treatment chamber, the presence or not of a saline solution (immersion system), and the technological parameters applied. In this way, a more reliable and accurate optimization of the process could be achieved.

Finally, more studies on the application of MEF and ohmic-PEF are required, as these technologies have certain advantages over OH (mainly the electric field effect). Research should be focused on electrical effects, on a more in-depth evaluation of processing parameters on heating uniformity, on the design of new processing equipment for larger foods, and on the impact on the nutritional and sensory properties of the food. Moreover, the role of the electrical effect in this type of heating has not yet been clarified. For this reason, researchers need to make an effort to carry out studies focused on achieving a reliable and valid comparison between conventional and ohmic heating by developing a proper methodology.

Author Contribution Leire Astráin-Redín: conceptualization and writing—original draft, review, and editing. Sebastián Ospina: review. Guillermo Cebrián: conceptualization, review and editing, and Supervision. Ignacio Álvarez-Lanzarote: conceptualization, review and editing, and supervision.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. This research was supported by the Spanish Ministerio de Ciencia, Innovación y Universidades through the research grant FPU and the iNOBox Project (Project no. 281106) of the Research Council of Norway.

Availability of Data and Materials Not applicable.

Declarations

Conflict of Interest The authors declare no competing interests.

References

1. Alkanan ZT, Altemimi AB, Al-Hilphy ARS et al (2021) Ohmic heating in the food industry: Developments in concepts and

applications during 2013–2020. Appl Sci 11:2507. https://doi.org/10.3390/app11062507
2. Kaur N, Singh AK (2016) Ohmic heating: Concept and applications-a review. Crit Rev Food Sci Nutr 56:2338–2351. https://doi.org/10.1080/10408398.2013.835303
3. Smith PG (2011) Introduction to food process engineering. Springer, New York
4. Abea A, Gou P, Guàrdia MD et al (2022) Dielectric heating: A review of liquid foods processing applications. Food Rev Int. https://doi.org/10.1080/87559129.2022.2092746
5. Chizoba Ekezie F-G, Sun D-W, Han Z, Cheng J-H (2017) Microwave-assisted food processing technologies for enhancing product quality and process efficiency: A review of recent developments. Trends Food Sci Technol 67:58–69. https://doi.org/10.1016/j.tifs.2017.05.014
6. Jaeger H, Roth A, Toepfl S et al (2016) Opinion on the use of ohmic heating for the treatment of foods. Trends Food Sci Technol 55:84–97. https://doi.org/10.1016/j.tifs.2016.07.007
7. Sastry SK, Barach JT (2000) Ohmic and inductive heating. J Food Sci 65:42–46. https://doi.org/10.1111/j.1750-3841.2000.tb00617.x
8. Sastry SK, Heskitt BF, Sarang SS et al (2014) Why ohmic heating? Advantages, applications, technology, and limitations. In: Ramaswamy HS, Marcote M, Sastry SK, Abdelrahim K (eds) Ohmic heating in food processing. CRC Press, Boca Raton, pp 7–16
9. Tiravibulsin C, Lorjaroenphon Y, Udompijitkul P, Kamonpatana P (2021) Sterilization of coconut milk in flexible packages via ohmic-assisted thermal sterilizer. Food Sci Technol 147:111552. https://doi.org/10.1016/j.lwt.2021.111552
10. Ghnimi S, Nikkhah A, Dewulf J, Van Haute S (2021) Life cycle assessment and energy comparison of aseptic ohmic heating and appertization of chopped tomatoes with juice. Sci Rep 11:13041. https://doi.org/10.1038/s41598-021-92211-1
11. Samaranayake CP, Sastry SK (2005) Electrode and pH effects on electrochemical reactions during ohmic heating. J Electroanal 577:125–135. https://doi.org/10.1016/j.jelechem.2004.11.026
12. Pataro G, Barca GMJ, Pereira RN et al (2014) Quantification of metal release from stainless steel electrodes during conventional and pulsed ohmic heating. Innov Food Sci Emerg Technol 21:66–73. https://doi.org/10.1016/j.ifset.2013.11.009
13. Tzedakis T, Basseguy R, Comtat M (1999) Voltammetric and coulometric techniques to estimate the electrochemical reaction rate during ohmic sterilization. J Appl Electrochem 29:819–826. https://doi.org/10.1023/A:1003561208850
14. Jones F (1897) Apparatus for electrically treating liquids. D. W. a. T. Office, USA
15. Sastry SK (2005) Advances in ohmic heating and moderate electric field (MEF) processing. In: Barbosa-Cánovas GV, Tapia MS, Cano MP (eds) Novel food processing technologies, 1st edn. CRC Press, Boca Raton
16. Ariza-Gracia MÁ, Cabello MP, Cebrián G et al (2020) Experimental and computational analysis of microbial inactivation in a solid by ohmic heating using pulsed electric fields. Innov Food Sci Emerg Technol 65:102440. https://doi.org/10.1016/j.ifset.2020.102440
17. Astráin-Redín L, Moya J, Alejandre M et al (2022) Improving the microbial inactivation uniformity of pulsed electric field ohmic heating treatments of solid products. Food Sci Technol 154:112709. https://doi.org/10.1016/j.lwt.2021.112709
18. Astráin-Redín L, Raso J, Álvarez I et al (2023) New pulsed electric fields approach to improve the blanching of carrots. Food Sci Technol 189:115468. https://doi.org/10.1016/j.lwt.2023.115468
19. Müller WA, Ferreira Marczak LD, Sarkis JR (2020) Microbial inactivation by ohmic heating: Literature review and influence of different process variables. Trends Food Sci Technol 99: 650–659. https://doi.org/10.1016/j.tifs.2020.03.021
20. Sastry SK (2008) Ohmic heating and moderate electric field processing. FSTI 14:419–422. https://doi.org/10.1177/1082013208098813
21. Silva R, Rocha RS, Ramos GLPA et al (2022) What are the challenges for ohmic heating in the food industry? Insights of a bibliometric analysis. Food Res Int 157:111272. https://doi.org/10.1016/j.foodres.2022.111272
22. Fillaudeau L, Ghnimi S (2014) Energy efficiency and control of the ohmic heating process. In: Ramaswamy H, Marcotte M, Sastry S, Abdelrahim K (eds) Ohmic Heating in Food Processing. CRC Press, pp 157–176
23. Sastry SK, Li Q (1996) Modeling the ohmic heating of foods : Ohmic heating for thermal processing of foods : Government, industry, and academic perspectives. Food Technol 50:246–248
24. Makroo HA, Srivastava B, Jabeen A (2022) Influence of mild electric field (MEF) on polyphenol oxidase and quality attributes of pineapple juice during ohmic heating. Food Sci Technol 156:113021. https://doi.org/10.1016/j.lwt.2021.113021
25. Pino-Hernández E, Pereira RN, Ballesteros LF et al (2021) Effects of moderate electric fields on the post-harvest preservation of chestnuts. Food Bioprocess Technol 14:920–934. https://doi.org/10.1007/s11947-021-02612-3
26. Simpson R, Nuñez H, Jaques A et al (2018) Application of a moderate electric field for the potential acceleration of the salting process of Atlantic salmon (*Salmo salar*). J Food Process Eng 41:e12846. https://doi.org/10.1111/jfpe.12846
27. Kamonpatana P, Sastry SK (2022) Electrical conductivity of foods and food components: The influence of formulation processes. J Food Process Eng 45:e13992. https://doi.org/10.1111/jfpe.13992
28. Kusnadi C, Sastry SK (2012) Effect of moderate electric fields on salt diffusion into vegetable tissue. J Food Eng 110:329–336. https://doi.org/10.1016/j.jfoodeng.2012.01.004
29. Kim S-S, Jo Y, Kang D-H (2017) Combined inhibitory effect of milk fat and lactose for inactivation of foodborne pathogens by ohmic heating. Food Sci Technol 86:159–165. https://doi.org/10.1016/j.lwt.2017.07.043
30. Cevik M, Icier F (2018) Effects of voltage gradient and fat content on changes of electrical conductivity of frozen minced beef meat during ohmic thawing. J Food Process Eng 41:e12675. https://doi.org/10.1111/jfpe.12675
31. Kim S-S, Kang D-H (2015) Effect of milk fat content on the performance of ohmic heating for inactivation of *Escherichia coli* O157:H7, *Salmonella enterica* serovar Typhimurium and *Listeria monocytogenes*. J Appl Microbiol 119:475–486. https://doi.org/10.1111/jam.12867
32. Moongngarm A, Sriharboot N, Loypimai P, Moontree T (2022) Ohmic heating-assisted water extraction of steviol glycosides and phytochemicals from *Stevia rebaudiana* leaves. Food Sci Technol 154:112798. https://doi.org/10.1016/j.lwt.2021.112798
33. Darvishi H, Koushesh Saba M, Behroozi-Khazaei N, Nourbakhsh H (2020) Improving quality and quantity attributes of grape juice concentrate (molasses) using ohmic heating. J Food Sci Technol 57:1362–1370. https://doi.org/10.1007/s13197-019-04170-1
34. Amiali M, Ngadi MO, Raghavan VGS, Nguyen DH (2006) Electrical conductivities of liquid egg products and fruit juices exposed to high pulsed electric fields. Int J Food Prop 9:533–540. https://doi.org/10.1080/10942910600596456
35. Imai T, Uemura K, Ishida N et al (1995) Ohmic heating of Japanese white radish *Rhaphanus sativus* L. IFST 30:461–472. https://doi.org/10.1111/j.1365-2621.1995.tb01393.x
36. Shim J, Lee SH, Jun S (2010) Modeling of ohmic heating patterns of multiphase food products using computational fluid

dynamics codes. J Food Eng 136–141. https://doi.org/10.1016/j.jfoodeng.2010.02.009
37. Gratz M, Schottroff F, Gall L et al (2021) Advantages of ohmic cooking in the kilohertz-range - part I: Impact of conductivity and frequency on the heating uniformity of potatoes. Innov Food Sci Emerg Technol 67:102595. https://doi.org/10.1016/j.ifset.2020.102595
38. Angersbach A, Heinz V, Knorr D (1999) Electrophysiological model of intact and processed plant tissues: Cell disintegration criteria. Biotechnol Prog 15:753–762. https://doi.org/10.1021/bp990079f
39. Doan NK, Lai QD, Le TKP, Le NT (2021) Influences of AC frequency and electric field strength on changes in bioactive compounds in ohmic heating of pomelo juice. Innov Food Sci Emerg Technol 72:102754. https://doi.org/10.1016/j.ifset.2021.102754
40. Rascón L, Cruz M, Rodríguez-Jasso RM et al (2020) Effect of ohmic heating on sensory, physicochemical, and microbiological properties of "Aguamiel" of *Agave salmiana*. Foods 9:1834. https://doi.org/10.3390/foods9121834
41. Lebovka NI, Praporscic I, Ghnimi S, Vorobiev E (2005) Temperature enhanced electroporation under the pulsed electric field treatment of food tissue. J Food Eng 69:177–184. https://doi.org/10.1016/j.jfoodeng.2004.08.037
42. Pereira RN, Coelho MI, Genisheva Z et al (2020) Using ohmic heating effect on grape skins as a pretreatment for anthocyanins extraction. Food Bioprocess Technol 124:320–328. https://doi.org/10.1016/j.fbp.2020.09.009
43. Casaburi O, Petrosino F, Marra F (2021) Modeling aspects in simulation of MEF processing of solid behaving foods. Chem Eng Trans 87:223–228. https://doi.org/10.3303/CET2187038
44. Brochier B, Hertz PF, Marczak LDF, Mercali GD (2020) Influence of ohmic heating on commercial peroxidase and sugarcane juice peroxidase inactivation. J Food Eng 284:110066. https://doi.org/10.1016/j.jfoodeng.2020.110066
45. Coelho M, Pereira R, Rodrigues AS et al (2019) Extraction of tomato by-products' bioactive compounds using ohmic technology. Food Bioprod Process 117:329–339. https://doi.org/10.1016/j.fbp.2019.08.005
46. Coelho M, Silva S, Costa E et al (2021) Anthocyanin recovery from grape by-products by combining ohmic heating with food-grade solvents: Phenolic composition, antioxidant, and antimicrobial properties. Molecules 26:3838. https://doi.org/10.3390/molecules26133838
47. Ferreira-Santos P, Duca AB, Genisheva Z et al (2021) Extracts from red eggplant: Impact of ohmic heating and different extraction solvents on the chemical profile and bioactivity. Front Sustain Food Syst. 17 December 2021. Sec. Sustainable Food Processing, vol 5. https://doi.org/10.3389/fsufs.2021.804004
48. Pereira SG, Teixeira-Guedes C, Souza-Matos G et al (2021) Influence of ohmic heating in the composition of extracts from *Gracilaria vermiculophylla*. Algal Res 58:102360. https://doi.org/10.1016/j.algal.2021.102360
49. Waziiroh E, Bender D, Jäger H, Schönlechner R (2022) Ohmic baking of gluten-free bread: Role of non-gluten protein on GF bread structure and properties. Int J Food Sci Technol. https://doi.org/10.1111/ijfs.16206
50. Moya J, Astráin-Redín L, Grasa J et al (2022) A numerical approach to analyze the performance of a PEF-ohmic heating system in microbial inactivation of solid food. Front Food Sci Technol. https://doi.org/10.3389/frfst.2022.880688
51. Schottroff F, Pyatkovskyy T, Reineke K et al (2019) Mechanisms of enhanced bacterial endospore inactivation during sterilization by ohmic heating. Bioelectrochemistry 130:107338. https://doi.org/10.1016/j.bioelechem.2019.107338
52. Ghnimi S, Fillaudeau L (2014) Tubular and fluid jet units. In: Ramaswamy H, Marcotte M, Sastry S, Abdelrahim K (eds) Tubular and Fluid Jet Units. CRC Press, pp 183–199
53. De Alwis A, a. p., Fryer P j. (1990) A finite-element analysis of heat generation and transfer during ohmic heating of food. Chem Eng Sci 45:1547–1559. https://doi.org/10.1016/0009-2509(90)80006-Z
54. Gally T, Rouaud O, Jury V, Le-Bail A (2016) Bread baking using ohmic heating technology; a comprehensive study based on experiments and modelling. J Food Eng 190:176–184. https://doi.org/10.1016/j.jfoodeng.2016.06.029
55. Ito R, Fukuoka M, Hamada-Sato N (2014) Innovative food processing technology using ohmic heating and aseptic packaging for meat. Meat Sci 96:675–681. https://doi.org/10.1016/j.meatsci.2013.10.012
56. Marra F (2014) Mathematical model of solid food pasteurization by ohmic heating: Influence of process parameters. Sci World J 2014:236437. https://doi.org/10.1155/2014/236437
57. Zell M, Lyng JG, Morgan DJ, Cronin DA (2011) Minimising heat losses during batch ohmic heating of solid food. Food Bioprod Process 89:128–134. https://doi.org/10.1016/j.fbp.2010.04.003
58. Gratz M, Sevenich R, Hoppe T et al (2021) Gentle sterilization of carrot-based purees by high-pressure thermal sterilization and ohmic heating and influence on food processing contaminants and quality attributes. Front Nutr 8:643837. https://doi.org/10.3389/fnut.2021.643837
59. Mok JH, Pyatkovskyy T, Yousef A, Sastry SK (2020) Synergistic effects of shear stress, moderate electric field, and nisin for the inactivation of *Escherichia coli* K12 and *Listeria innocua* in clear apple juice. Food Control 113:107209. https://doi.org/10.1016/j.foodcont.2020.107209
60. Mok JH, Pyatkovskyy T, Yousef A, Sastry SK (2019) Combined effect of shear stress and moderate electric field on the inactivation of *Escherichia coli* K12 in apple juice. J Food Eng 262:121–130. https://doi.org/10.1016/j.jfoodeng.2019.05.019
61. Anderson AK, Finkelstein R (1919) A study of the electro-pure process of treating milk. JDS 2:374–406. https://doi.org/10.3168/jds.S0022-0302(19)94338-4
62. Monfort S, Gayán E, Saldaña G et al (2010) Inactivation of *Salmonella* Typhimurium and *Staphylococcus aureus* by pulsed electric fields in liquid whole egg. Innov Food Sci Emerg Technol 11:306–313. https://doi.org/10.1016/j.ifset.2009.11.007
63. Saldaña G, Álvarez I, Condón S, Raso J (2014) Microbiological aspects related to the feasibility of PEF technology for food pasteurization. Crit Rev Food Sci Nutr 54:1415–1426. https://doi.org/10.1080/10408398.2011.638995
64. Toepfl S, Heinz V, Knorr D (2006) Applications of pulsed electric fields technology for the food industry. In: Raso J, Heinz V (eds) Pulsed electric fields technology for the food industry, 1st edn. Springer, New York, pp 197–217
65. Sastry SK, Yousef A, Cho HY et al (2002) Ohmic heating and moderate electric field (MEF) processing. In: Welti-Chanes J, Aguilera JM (eds) Engineering and Food for the 21st Century. CRC Press, Boca Raton
66. Núñez H, Cavada G, Ramírez C et al (2020) Effect of a moderate electric field on the salting of Atlantic Salmon (*Salmo salar*): An experimental study and phenomenological understanding. Food Res Int 137:109475. https://doi.org/10.1016/j.foodres.2020.109475
67. Fronza A, Marczak LDF, Mercali GD (2021) Increase of mass transfer rates during osmotic dehydration of apples by application of moderate electric field. Int J Food Eng 17:199–208. https://doi.org/10.1515/ijfe-2020-0061
68. Bedane TF, Pedrós-Garrido S, Quinn G, Lyng JG (2021) The impact of emerging domestic and commercial electro-heating technologies on energy consumption and quality parameters of

cooked beef. Meat Sci 179:108550. https://doi.org/10.1016/j.meatsci.2021.108550

69. Turgay-İzzetoğlu G, Çokgezme ÖF, Döner D et al (2022) Cooking the chicken meat with moderate electric field: Rheological properties and image processing of microstructure. Food Bioprocess Technol 15:1082–1100. https://doi.org/10.1007/s11947-022-02800-9
70. Wang L-H, Pyatkovskyy T, Yousef A et al (2020) Mechanism of *Bacillus subtilis* spore inactivation induced by moderate electric fields. Innov Food Sci Emerg Technol 62:102349. https://doi.org/10.1016/j.ifset.2020.102349
71. Al-Hilphy AR, Abdulstar AR, Gavahian M (2021) Moderate electric field pasteurization of milk in a continuous flow unit: Effects of process parameters, energy consumption, and shelf-life determination. Innov Food Sci Emerg Technol 67:102568. https://doi.org/10.1016/j.ifset.2020.102568
72. Barrón-García OY, Morales-Sánchez E, Gaytán-Martínez M (2019) Inactivation kinetics of *Agaricus bisporus* tyrosinase treated by ohmic heating: Influence of moderate electric field. Innov Food Sci Emerg Technol 56:102179. https://doi.org/10.1016/j.ifset.2019.102179
73. Gavahian M, Tiwari BK (2020) Moderate electric fields and ohmic heating as promising fermentation tools. Innov Food Sci Emerg Technol 64:102422. https://doi.org/10.1016/j.ifset.2020.102422
74. Raso J, Heinz V, Álvarez I, Toepfl S (2022) Pulsed electric fields technology for the food industry, 2nd edn. Springer, Switzerland
75. Donsì F, Ferrari G, Pataro G (2010) Applications of pulsed electric field treatments for the enhancement of mass transfer from vegetable tissue. Food Eng Rev 2:109–130. https://doi.org/10.1007/s12393-010-9015-3
76. Palaniappan S, Sastry SK, Richter ER (1992) Effects of electroconductive heat treatment and electrical pretreatment on thermal death kinetics of selected microorganisms. Biotechnol Bioeng 39:225–232. https://doi.org/10.1002/bit.260390215
77. Somavat R, Mohamed HMH, Chung Y-K et al (2012) Accelerated inactivation of *Geobacillus stearothermophilus* spores by ohmic heating. J Food Eng 108:69–76. https://doi.org/10.1016/j.jfoodeng.2011.07.028
78. Schwan HP (1957) Electrical properties of tissue and cell suspensions. Adv Biol Med Phys 5:147–209. https://doi.org/10.1016/b978-1-4832-3111-2.50008-0
79. Heinz V, Alvarez I, Angersbach A, Knorr D (2001) Preservation of liquid foods by high intensity pulsed electric fields—basic concepts for process design. Trends Food Sci Technol 12:103–111. https://doi.org/10.1016/S0924-2244(01)00064-4
80. Ben Ammar J, Lanoisellé J-L, Lebovka NI et al (2011) Impact of a pulsed electric field on damage of plant tissues: Effects of cell size and tissue electrical conductivity. J Food Sci 76:E90-97. https://doi.org/10.1111/j.1750-3841.2010.01893.x
81. Asavasanti S, Ersus S, Ristenpart W et al (2010) Critical electric field strengths of onion tissues treated by pulsed electric fields. J Food Sci 75:E433–E443. https://doi.org/10.1111/j.1750-3841.2010.01768.x
82. Gavahian M, Chu Y-H, Sastry S (2018) Extraction from food and natural products by moderate electric field: Mechanisms, benefits, and potential industrial applications. CRFSFS 17:1040–1052. https://doi.org/10.1111/1541-4337.12362
83. Lebovka NI, Shynkaryk M, Vorobiev E (2007) Moderate electric field treatment of sugarbeet tissues. Biosyst Eng 96:47–56. https://doi.org/10.1016/j.biosystemseng.2006.09.005
84. Cebrián G, Condón S, Mañas P (2017) Physiology of the inactivation of vegetative bacteria by thermal treatments: Mode of action, influence of environmental factors and inactivation kinetics. Foods 6:107. https://doi.org/10.3390/foods6120107
85. Weaver JC, Chizmadzhev YuA (1996) Theory of electroporation: A review. Bioelectrochem Bioenerg 41:135–160. https://doi.org/10.1016/S0302-4598(96)05062-3
86. Khue DN, Tiep HT, Dat LQ et al (2020) Influence of frequency and temperature on the inactivation of *Salmonella enterica* serovar enteritidis in ohmic heating of pomelo juice. Food Sci Technol 129:109528. https://doi.org/10.1016/j.lwt.2020.109528
87. Park IK, Kang DH (2013) Effect of Electropermeabilization by ohmic heating for inactivation of *Escherichia coli* O157:H7, *Salmonella enterica* Serovar Typhimurium, and Listeria monocytogenes in Buffered Peptone Water and Apple Juice. Appl Environ Microbiol 7122–7129. https://doi.org/10.1128/AEM.01818-13. Epub 2013 Aug 30
88. Pereira MO, Guimarães JT, Ramos GLPA et al (2020) Inactivation kinetics of *Listeria monocytogenes* in whey dairy beverage processed with ohmic heating. Food Sci Technol 127:109420. https://doi.org/10.1016/j.lwt.2020.109420
89. Jia L, Shao L, Zhao Y et al (2023) Inactivation effects and mechanism of ohmic heating on *Bacillus cereus*. Int J Food Microbiol 390:110125. https://doi.org/10.1016/j.ijfoodmicro.2023.110125
90. Song J, Joshi RP, Schoenbach KH (2011) Synergistic effects of local temperature enhancements on cellular responses in the context of high-intensity, ultrashort electric pulses. Med Biol Eng Comput 49:713–718. https://doi.org/10.1007/s11517-011-0745-z
91. Saldaña G, Puértolas E, Álvarez I et al (2010) Evaluation of a static treatment chamber to investigate kinetics of microbial inactivation by pulsed electric fields at different temperatures at quasi-isothermal conditions. J Food Eng 100:349–356. https://doi.org/10.1016/j.jfoodeng.2010.04.021
92. Schottroff F, Biebl D, Gruber M et al (2020) Inactivation of vegetative microorganisms by ohmic heating in the kilohertz range – evaluation of experimental setups and non-thermal effects. Innov Food Sci Emerg Technol 63:102372. https://doi.org/10.1016/j.ifset.2020.102372
93. Ruan R, Ye X, Chen P et al (2001) Ohmic heating. Woodhead Publishing, Cambridge
94. Pataro G, Ferrari G (2020) Limitations of pulsed electric field utilization in food industry. In: Barba FJ, Parniakov O, Wiktor A (eds) Pulsed electric fields to obtain healthier and sustainable food for tomorrow. Academic Press, pp 283–310
95. Setlow P (2006) Spores of *Bacillus subtilis*: Their resistance to and killing by radiation, heat and chemicals. J Appl Microbiol 101:514–525. https://doi.org/10.1111/j.1365-2672.2005.02736.x
96. Setlow P (2014) Spore resistance properties. Microbiol Spectr 2(5). https://doi.org/10.1128/microbiolspec.TBS-0003-2012
97. Setlow B, Atluri S, Kitchel R et al (2006) Role of dipicolinic acid in resistance and stability of spores of *Bacillus subtilis* with or without DNA-protective α/β-type small acid-soluble proteins. J Bacteriol 188:3740–3747. https://doi.org/10.1128/JB.00212-06
98. Setlow P (1994) Mechanisms which contribute to the long-term survival of spores of Bacillus species. Soc Appl Bacteriol Symp Ser 23:49S–60S. https://doi.org/10.1111/j.1365-2672.1994.tb04357.x
99. Pereira R, Martins J, Mateus C et al (2007) Death kinetics of *Escherichia coli* in goat milk and *Bacillus licheniformis* in cloudberry jam treated by ohmic heating. Chem Pap 6(2):121–126. https://doi.org/10.2478/s11696-007-0008-5
100. Cho H-Y, Yousef AE, Sastry SK (1999) Kinetics of inactivation of Bacillus subtilis spores by continuous or intermittent ohmic and conventional heating. Biotechnol Bioeng 62:368–372. https://doi.org/10.1002/(SICI)1097-0290(19990205)62:3%3c368::AID-BIT14%3e3.0.CO;2-0
101. Murashita S, Kawamura S, Koseki S (2017) Effects of ohmic heating, including electric field intensity and frequency, on thermal inactivation of Bacillus subtilis spores. J Food Prot 80:164–168. https://doi.org/10.4315/0362-028X.JFP-16-300

102. Makroo HA, Rastogi NK, Srivastava B (2020) Ohmic heating assisted inactivation of enzymes and microorganisms in foods: A review. Trends Food Sci Technol 97:451–465. https://doi.org/10.1016/j.tifs.2020.01.015
103. Leite TS, Samaranayake CP, Sastry SK, Cristianini M (2019) Polyphenol oxidase inactivation in viscous fluids by ohmic heating and conventional thermal processing. J Food Process Eng 42:e13133. https://doi.org/10.1111/jfpe.13133
104. Samaranayake CP, Mok JH, Heskitt BF, Sastry SK (2023) Nonthermal inactivation effects on oxidative enzymes in grape juice influenced by moderate electric fields: Effect of constant exposure electrical treatments combined with temperature. J Food Eng 340:111288. https://doi.org/10.1016/j.jfoodeng.2022.111288
105. Samaranayake CP, Mok JH, Heskitt BF, Sastry SK (2022) Nonthermal inactivation of polyphenol oxidase in apple juice influenced by moderate electric fields: Effects of periodic on-off and constant exposure electrical treatments. Innov Food Sci Emerg Technol 77:102955. https://doi.org/10.1016/j.ifset.2022.102955
106. Samaranayake CP, Sastry SK (2016) Effect of moderate electric fields on inactivation kinetics of pectin methylesterase in tomatoes: The roles of electric field strength and temperature. J Food Eng 186:17–26. https://doi.org/10.1016/j.jfoodeng.2016.04.006
107. Samaranayake CP, Sastry SK (2016) Effects of controlled-frequency moderate electric fields on pectin methylesterase and polygalacturonase activities in tomato homogenate. Food Chem 199:265–272. https://doi.org/10.1016/j.foodchem.2015.12.010
108. Samaranayake CP, Sastry SK (2021) Molecular dynamics evidence for nonthermal effects of electric fields on pectin methylesterase activity. PCCP 23:14422–14432. https://doi.org/10.1039/d0cp05950a
109. Alamprese C, Cigarini M, Brutti A (2019) Effects of ohmic heating on technological properties of whole egg. Innov Food Sci Emerg Technol 58:102244. https://doi.org/10.1016/j.ifset.2019.102244
110. Gratz M, Schottroff F, Gall L et al (2021) Advantages of ohmic cooking in the kilohertz range – Part II: Impact on textural changes and approaches to improve heating uniformity. Innov Food Sci Emerg Technol 67:102594. https://doi.org/10.1016/j.ifset.2020.102594
111. Gavahian M, Chu Y-H, Farahnaky A (2019) Effects of ohmic and microwave cooking on textural softening and physical properties of rice. J Food Eng 243:114–124. https://doi.org/10.1016/j.jfoodeng.2018.09.010
112. Jo Y-J, Park SH (2019) Evaluation of energy efficacy and texture of ohmically cooked noodles. J Food Eng 248:71–79. https://doi.org/10.1016/j.jfoodeng.2019.01.002
113. Ángel-Rendón SV, Filomena-Ambrosio A, Cordon-Díaz S et al (2019) Ohmic cooking: Application of a novel technology in pork and influences on water holding capacity, cooking loss and colour. Int J Gastron Food Sci 17:100164. https://doi.org/10.1016/j.ijgfs.2019.100164
114. Casaburi O, Brondi C, Romano A, Marra F (2021) Ohmic heating of basil-based sauces: Influence of the electric field strength on the electrical conductivity. Chem Eng Trans 87:343–348. https://doi.org/10.3303/CET2187058
115. Khodeir M, Rouaud O, Ogé A et al (2021) Study of continuous cake pre-baking in a rectangular channel using ohmic heating. Innov Food Sci Emerg Technol 67:102580. https://doi.org/10.1016/j.ifset.2020.102580
116. Debbarma T, Thangalakshmi S, Tadakod M et al (2021) Comparative analysis of ohmic and conventional heat-treated carrot juice. J Food Process Preserv 45:e15687. https://doi.org/10.1111/jfpp.15687
117. Giuliangeli VC, Ströher GR, Shirai MA (2022) Comparison of energy consumption, color, ascorbic acid and carotenoid degradation in guava (*Psidium guajava*) pulp during conventional and ohmic heating. J Food Sci Technol. https://doi.org/10.1007/s13197-022-05607-w
118. Müller WA, Pasin MVA, Sarkis JR, Marczak LDF (2021) Effect of pasteurization on *Aspergillus fumigatus* in apple juice: Analysis of the thermal and electric effects. Int J Food Microbiol 338:108993. https://doi.org/10.1016/j.ijfoodmicro.2020.108993
119. Dhenge R, Langialonga P, Alinovi M, Lolli V, Aldini A., Rinaldi M. et al (2022) Evaluation of quality parameters of orange juice stabilized by two thermal treatments (helical heat exchanger and ohmic heating) and non-thermal (high-pressure processing). Food Control 141(11):109150. https://doi.org/10.1016/j.foodcont.2022.109150
120. Rinaldi M, Littardi P, Paciulli M et al (2020) Impact of ohmic heating and high pressure processing on qualitative attributes of ohmic treated peach cubes in syrup. Foods 9:1093. https://doi.org/10.3390/foods9081093
121. Balthazar CF, Cabral L, Guimarães JT et al (2022) Conventional and ohmic heating pasteurization of fresh and thawed sheep milk: Energy consumption and assessment of bacterial microbiota during refrigerated storage. Innov Food Sci Emerg Technol 76:102947. https://doi.org/10.1016/j.ifset.2022.102947
122. Inmanee P, Kamonpatana P, Pirak T (2019) Ohmic heating effects on *Listeria monocytogenes* inactivation, and chemical, physical, and sensory characteristic alterations for vacuum packaged sausage during post pasteurization. Food Sci Technol 108:183–189. https://doi.org/10.1016/j.lwt.2019.03.027
123. Barrón-García OY, Nava-Álvarez B, Gaytán-Martínez M et al (2022) Ohmic heating blanching of Agaricus bisporus mushroom: Effects on polyphenoloxidase inactivation kinetics, color, and texture. Innov Food Sci Emerg Technol 80:103105. https://doi.org/10.1016/j.ifset.2022.103105
124. Kumar A, Begum A, Hoque M et al (2021) Textural degradation, drying and rehydration behaviour of ohmically treated pineapple cubes. Food Sci Technol. https://doi.org/10.1016/j.lwt.2021.110988
125. Funcia ES, Gut JAW, Sastry SK (2020) Effect of electric field on pectinesterase inactivation during orange juice pasteurization by ohmic heating. Food Bioprocess Technol 13:1206–1214. https://doi.org/10.1007/s11947-020-02478-x
126. Kanjanapongkul K, Baibua V (2021) Effects of ohmic pasteurization of coconut water on polyphenol oxidase and peroxidase inactivation and pink discoloration prevention. J Food Eng 292:110268. https://doi.org/10.1016/j.jfoodeng.2020.110268
127. Negri Rodríguez LM, Arias R, Soteras T et al (2021) Comparison of the quality attributes of carrot juice pasteurized by ohmic heating and conventional heat treatment. Food Sci Technol 145:111255. https://doi.org/10.1016/j.lwt.2021.111255
128. Sabanci S, Çevik M, Göksu A (2021) Investigation of time effect on pectin production from citrus wastes with ohmic heating assisted extraction process. J Food Process Eng 44:e13689. https://doi.org/10.1111/jfpe.13689
129. Cabas BM, Icier F (2021) Ohmic heating–assisted extraction of natural color matters from red beetroot. Food Bioprocess Technol 14:2062–2077. https://doi.org/10.1007/s11947-021-02698-9
130. Turgut SS, Küçüköner E, Feyissa AH, Karacabey E (2021) A novel drying system – simultaneous use of ohmic heating with convectional air drying: System design and detailed examination using CFD. Innov Food Sci Emerg Technol 72:102727. https://doi.org/10.1016/j.ifset.2021.102727
131. Cao X, Islam MN, Xu W et al (2020) Energy consumption, colour, texture, antioxidants, odours, and taste qualities of litchi fruit dried by intermittent ohmic heating. Foods 9:425. https://doi.org/10.3390/foods9040425

132. Norouzi S, Fadavi A, Darvishi H (2021) The ohmic and conventional heating methods in concentration of sour cherry juice: Quality and engineering factors. J Food Eng 291:110242. https://doi.org/10.1016/j.jfoodeng.2020.110242
133. Cevik M (2021) Electrical conductivity and performance evaluation of verjuice concentration process using ohmic heating method. J Food Process Eng 44:e13672. https://doi.org/10.1111/jfpe.13672
134. Karakavuk E, Goksu A, Sabanci S (2022) Investigation of electrical conductivity and bioactive quality during ohmic evaporation process of apple juice. J Food Process Preserv. https://doi.org/10.1111/jfpp.17036
135. Darvishi H, Salami P, Fadavi A, Saba MK (2020) Processing kinetics, quality and thermodynamic evaluation of mulberry juice concentration process using ohmic heating. Food Bioprod Process 123:102–110. https://doi.org/10.1016/j.fbp.2020.06.003
136. Çabas BM, Azazi I, Döner D et al (2022) Comparative performance analysis of ohmic thawing and conventional thawing of spinach puree. J Food Process Eng 45:e14015. https://doi.org/10.1111/jfpe.14015
137. Fattahi S, Zamindar N (2020) Effect of immersion ohmic heating on thawing rate and properties of frozen tuna fish. Food Sci Technol Int 26:453–461. https://doi.org/10.1177/1082013219895884
138. Cevik M, Icier F (2021) Comparison of quality attributes of minced beef samples thawed by ohmic and conventional methods. J Food Process Preserv 45:e15122. https://doi.org/10.1111/jfpp.15122
139. Wongsa-Ngasri P, Sastry SK (2016) Tomato peeling by ohmic heating with lye-salt combinations: Effects of operational parameters on peeling time and skin diffusivity. J Food Eng 186:10–16. https://doi.org/10.1016/j.jfoodeng.2016.04.005
140. Wongsa-Ngasri P, Sastry SK (2016) Tomato peeling by ohmic heating: Effects of lye-salt combinations and post-treatments on weight loss, peeling quality and firmness. Innov Food Sci Emerg Technol 34:148–153. https://doi.org/10.1016/j.ifset.2016.01.013
141. Gupta S, Sastry SK (2018) Ohmic heating assisted lye peeling of pears. J Food Sci 83:1292–1298. https://doi.org/10.1111/1750-3841.14116
142. Moreira TCP, Pereira RN, Vicente AA, da Cunha RL (2019) Effect of ohmic heating on functionality of sodium caseinate – a relationship with protein gelation. Food Res Int 116:628–636. https://doi.org/10.1016/j.foodres.2018.08.087
143. Rodrigues RM, Fasolin LH, Avelar Z et al (2020) Effects of moderate electric fields on cold-set gelation of whey proteins – from molecular interactions to functional properties. Food Hydrocoll 101:105505. https://doi.org/10.1016/j.foodhyd.2019.105505
144. Joeres E, Schölzel H, Drusch S et al (2022) Oventional heating: Influence of moderate electric fields on properties of egg white protein gels. Food Hydrocoll 127:107519. https://doi.org/10.1016/j.foodhyd.2022.107519
145. Kuriya SP, Silva R, Rocha RS et al (2020) Impact assessment of different electric fields on the quality parameters of blueberry flavored dairy desserts processed by Ohmic Heating. Food Res Int 134:109235. https://doi.org/10.1016/j.foodres.2020.109235
146. Silva R, Rocha RS, Guimarães JT et al (2020) Ohmic heating technology in dulce de leche: Physical and thermal profile, microstructure, and modeling of crystal size growth. Food Bioprod Process 124:278–286. https://doi.org/10.1016/j.fbp.2020.09.001
147. Dhua S, Kumar K, Sharanagat VS, Nema PK (2022) Bioactive compounds and its optimization from food waste: Review on novel extraction techniques. Nutr Food Sci 52:1270–1288. https://doi.org/10.1108/NFS-12-2021-0373
148. Petkowicz CLO, Vriesmann LC, Williams PA (2017) Pectins from food waste: Extraction, characterization and properties of watermelon rind pectin. Food Hydrocoll 65:57–67. https://doi.org/10.1016/j.foodhyd.2016.10.040
149. Doble M, Kumar A (2007) Green chemistry and engineering. Academic Press, USA
150. Coelho MC, Pereira RN, Rodrigues AS et al (2020) The use of emergent technologies to extract added value compounds from grape by-products. Trends Food Sci Technol 106:182–197. https://doi.org/10.1016/j.tifs.2020.09.028
151. Hosainpour A, Darvishi H, Nargesi F, Fadavi A (2014) Ohmic pre-drying of tomato paste. Food Sci Technol Int 20:193–204. https://doi.org/10.1177/1082013213480360
152. Soghani BN, Azadbakht M, Darvishi H (2018) Ohmic blanching of white mushroom and its pretreatment during microwave drying. Heat Mass Transfer 54:3715–3725. https://doi.org/10.1007/s00231-018-2393-4
153. Wray D, Ramaswamy HS (2015) Novel concepts in microwave drying of foods. Dry Technol 33:769–783. https://doi.org/10.1080/07373937.2014.985793
154. Bozkurt H, İçier F (2012) Ohmic thawing of frozen beef cuts. J Food Process Eng 35:16–36. https://doi.org/10.1111/j.1745-4530.2009.00569.x
155. Döner D, Çokgezme ÖF, Çevik M et al (2020) Thermal image processing technique for determination of temperature distributions of minced beef thawed by ohmic and conventional methods. Food Bioprocess Technol 13:1878–1892. https://doi.org/10.1007/s11947-020-02530-w
156. Duygu B, Ümit G (2015) Application of ohmic heating system in meat thawing. Procedia Soc 195:2822–2828. https://doi.org/10.1016/j.sbspro.2015.06.400
157. Icier F, Izzetoglu GT, Bozkurt H, Ober A (2010) Effects of ohmic thawing on histological and textural properties of beef cuts. J Food Eng 99:360–365. https://doi.org/10.1016/j.jfoodeng.2010.03.018
158. Liu L, Llave Y, Jin Y et al (2017) Electrical conductivity and ohmic thawing of frozen tuna at high frequencies. J Food Eng 197:68–77. https://doi.org/10.1016/j.jfoodeng.2016.11.002
159. Luzuriaga DA, Balaban MO (1996) Electrical conductivity of frozen shrimp and flounder at different temperatures and voltage levels. J Aquat Food Prod 5:41–63. https://doi.org/10.1300/J030v05n03_06
160. Fellows PJ (2017) Front-matter. In: Food Processing Technology (Fourth Edition). Woodhead Publishing, pp i–iii
161. Kim K-I, Lee S-Y, Hwang I-G et al (2015) Quality characteristics of beef by different cooking methods for frozen home meal replacements. Korean J Food Sci Anim Resour 35:441–448. https://doi.org/10.5851/kosfa.2015.35.4.441
162. Farahnaky A, Azizi R, Gavahian M (2012) Accelerated texture softening of some root vegetables by ohmic heating. J Food Eng 113:275–280. https://doi.org/10.1016/j.jfoodeng.2012.05.039
163. Bender D, Gratz M, Vogt S et al (2019) Ohmic heating—a novel approach for gluten-free bread baking. Food Bioprocess Technol 12:1603–1613. https://doi.org/10.1007/s11947-019-02324-9
164. Waziiroh E, Bender D, Saric A et al (2021) Ohmic baking of gluten-free bread: Role of starch and flour on batter properties. Appl Sci 11:6567. https://doi.org/10.3390/app11146567
165. Bekard I, Dunstan DE (2013) Electric field induced changes in protein conformation. Soft Matter 10:431–437. https://doi.org/10.1039/C3SM52653D
166. Wang L-J, Li D, Tatsumi E et al (2007) Application of two-stage ohmic heating to tofu processing. Chem Eng Process 46:486–490. https://doi.org/10.1016/j.cep.2006.06.017
167. Shimoyamada M, Itabashi Y, Sugimoto I et al (2015) Characterization of soymilk prepared by ohmic heating and the effects of

voltage applied. Food Sci Technol Res 21:439–444. https://doi.org/10.3136/fstr.21.439

168. Rodrigues RM, Martins AJ, Ramos OL et al (2015) Influence of moderate electric fields on gelation of whey protein isolate. Food Hydrocoll 43:329–339. https://doi.org/10.1016/j.foodhyd.2014.06.002
169. Cappato LP, Ferreira MVS, Guimaraes JT et al (2017) Ohmic heating in dairy processing: Relevant aspects for safety and quality. Trends Food Sci Technol 62:104–112. https://doi.org/10.1016/j.tifs.2017.01.010
170. Pereira RN, Rodrigues RM, Ramos ÓL et al (2018) Electric field processing: Novel perspectives on allergenicity of milk proteins. J Agric Food Chem 66:11227–11233. https://doi.org/10.1021/acs.jafc.8b03689
171. Pereira RN, Costa J, Rodrigues RM et al (2020) Effects of ohmic heating on the immunoreactivity of β-lactoglobulin – a relationship towards structural aspects. Food Funct 11:4002–4013. https://doi.org/10.1039/C9FO02834J
172. Pereira RN, Rodrigues RM, Machado L et al (2021) Influence of ohmic heating on the structural and immunoreactive properties of soybean proteins. Food Sci Technol 148:111710. https://doi.org/10.1016/j.lwt.2021.111710
173. Li X, Deng Y, Qiu W et al (2022) Alteration of collagen thermal denaturation, structural and the abrogation of allergenicity in eel skin induced by ohmic heating. Food Chem 391:133272. https://doi.org/10.1016/j.foodchem.2022.133272
174. Li X, Deng Y, Qiu W et al (2024) Effects of different ohmic heating treatments on parvalbumin structure and reduction of allergenicity in Japanese eel (*Anguilla japonica*). Food Chem 432:137257. https://doi.org/10.1016/j.foodchem.2023.137257