CHAPTER 2
REVIEW OF LITERATURE

2.1 Need for novel thermal technologies

The food processing industry has focussed primarily on traditional thermal practices for product development, shelf-life enhancement and safety. As we know, foods are rich in nutrients, vitamins, minerals, and nutrients with functional properties such as pigments, antioxidants, enzymes and bioactive compounds. Due to the unstable composition of food constituents, they are highly susceptible to degradation under different storage temperatures, time, light, pH, and environmental conditions. Phenolic compounds, antioxidants, and vitamins are highly sensitive to heat. When thermal treatment is used for the processing of foods, the increase in temperature may lead to the deterioration of the compounds (Lima et al., 2014; Pereira and Vicente, 2010). Enzymatic and non-enzymatic spoilage are one of the major factors in the deterioration of the quality of food products. Non-enzymatic spoilage, mainly Maillard reaction and lipid oxidation, degrades the quality of the product. The enzymatic reaction occurs when the enzymes in the food product come in contact with the atmospheric air. Fruits and vegetables are primarily susceptible to enzymatic browning due to the presence of enzymes (Polyphenol oxidase (PPO), peroxidase (POD), and protease). Enzymatic browning leads to nutrition and colour loss and may degrade the overall quality of the food product. Due to the losses of nutrients during conventional thermal processing and to enhance the nutritional value and longevity of the food products, the inactivation of enzymes using low-temperature processing is required. There is a need for novel thermal processing to overcome the losses by minimally changing the original food quality. Alternative methods of modern novel thermal technologies are gaining attention in food processing due to their lower effect on food quality and nutritional value (Chakraborty et al., 2014; Shiferaw et al., 2010). These technologies provide higher nutritional qualities with better sensory properties of the processed food products. (Sunil et al., 2018). There is a great interest in the development of non-thermal technologies for food processing and preservation because of their better quality in retaining the nutritional properties and enhancing the shelf-life of the finished product by reducing microbial load and enzyme inactivation. They are often considered more energy efficient and maintain higher quality attributes than traditional thermally based technologies. In the food processing industry, novel thermal processes are in great demand for its potential to substitutes the conventional thermal and chemical unit operations (Zhang et al., 2019). Novel-thermal methods allow foods to be processed at temperatures lower than those used in thermal pasteurization, preserving flavours, essential nutrients and vitamins (Pivarnik and Worobo, 2014; Jan et al., 2017).

The application of novel thermal technologies improves the retention of colour, flavours or preservatives while maintaining its structure and preserving nutritional and other food properties. These technologies have been developed to increase the efficiency of heat production while ensuring food safety and removing adverse effects on food organoleptic and nutritional properties. The efficiency of these techniques is greatly dependent on the thermal and electrical conductivity, moisture, pH and rheological properties of the food products. The growing demand for minimally processed food drives the adoption of these novel technologies in food processing. As a result, food scientists are investigating and adopting alternatives to conventional food processing technologies, not only to better food preservation but also to improve product quality and sustainability without adversely affecting food safety (Pivarnik and Worobo, 2014).

2.2 Ohmic Heating

Ohmic heating (OH) is considered one of the novel thermal technologies in which food samples are placed between two electrodes, and current is passed through them. The food samples, which act as resistance, are heated up rapidly, uniformly and volumetrically by joule effect depending on the electrical conductivity (EC) of the materials and electrical field strength (EFS) applied (Kumar et al., 2021; Sastry and Barach, 2000). In ohmic heating, the processing time is gradually reduced because of the volumetric heating effect compared to conventional thermal processing, in which heat is transferred mainly by conduction and convection from the surface to the centre (Kumar et al., 2024; Saxena et al., 2016a). Because of rapid heating and an overall reduction in processing time, OH has several advantages in terms of lower damage to physicochemical properties, higher enzyme and microbial inactivation, higher retention of phytochemicals, and a highly energy-efficient process (Kumar and Srivastava, 2024).

2.2.1 Fundamental principle and processing parameters

OH works on the principle of Ohm's law that when electrical current flows through any conductor (here, food materials) between two points, it is directly proportional to the potential difference or voltage gradient applied, as shown in Fig. 2.1. The mathematical equation for Ohm's law is shown in Eq. 2.1.

$$I = \frac{V}{R} \text{ or } V = IR \quad \text{(Eq. 2.1)}$$

Where I is the electrical current (A) through the food materials, V is the voltage (V) across the food materials, and R is the electrical resistance (Ω) of the food samples. The motion of the charged particles when an alternating current flows through the food samples increases the internal heating, which ultimately raises the temperature of the food samples. The charged particles flow across the food samples towards the electrodes of opposite polarity, which include ions and charged proteins. Thus, the electrical energy gets converted into thermal energy depending on the resistivity of the food samples (Palaniappan and Sastry, 1991b). Since the heating takes place internally and volumetrically, there is a very high efficiency in energy conversion. Also, the heating takes place uniformly throughout the samples. Hence, it overcomes the problem of the temperature gradient across the samples and uneven heating, which commonly occurs during conventional thermal treatment (Kumar et al., 2024).

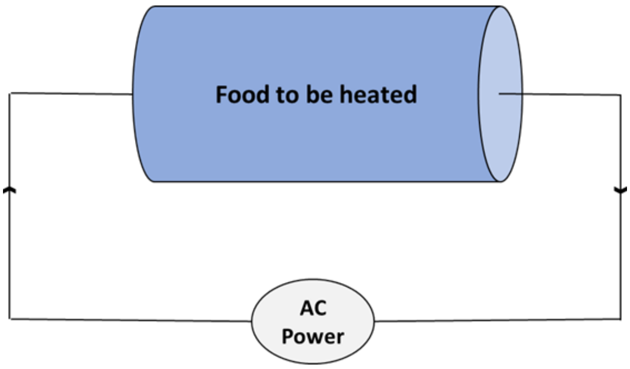

Fig. 2.1 The basic principle of ohmic heating

In OH, the EC of the food samples and EFS across the food are crucial factors that determine the heating rate (HR). Some of the mathematical equations that are important in designing the ohmic process are shown in Eq. 2.2, Eq. 2.3, and Eq. 2.4.

$$P = I\,V \qquad \text{(Eq. 2.2)}$$

$$P = \frac{V^2}{R} \qquad \text{(Eq. 2.3)}$$

$$q = \sigma\,E^2 \qquad \text{(Eq. 2.4)}$$

Where P is the electrical power (Watts), q is the rate of generation of heat (W/m^3), σ is the electrical conductivity of the food samples (S/m), and E is the electric field strength across the food materials (V/cm) (Gavahian and Farahnaky, 2018).

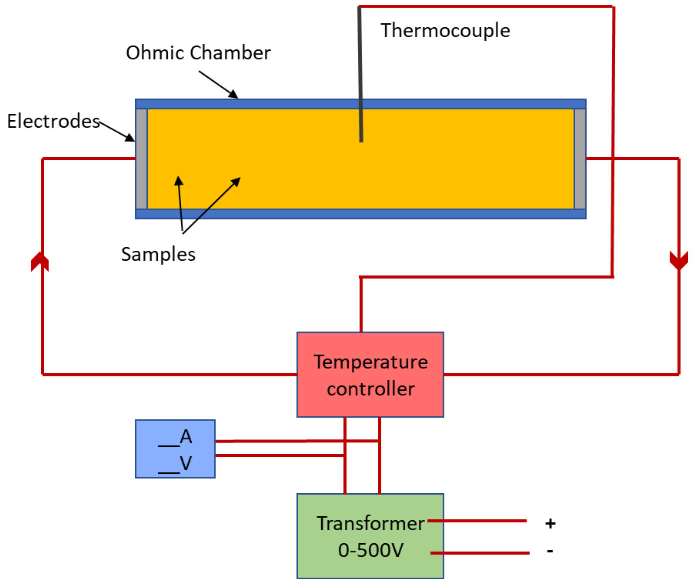

Fig. 2.2 Schematic diagram of the ohmic heating set-up

Eq. 2.4 shows that the HR is directly proportional to the EC and square of the EFS, which is essential in designing the OH process (Gavahian and Farahnaky, 2018; Kumar et al., 2024). The fabrication parts of any OH equipment consist of a power source, variac transformer, heating cell, electrodes, thermocouple and data logger, as shown in Fig. 2.2.

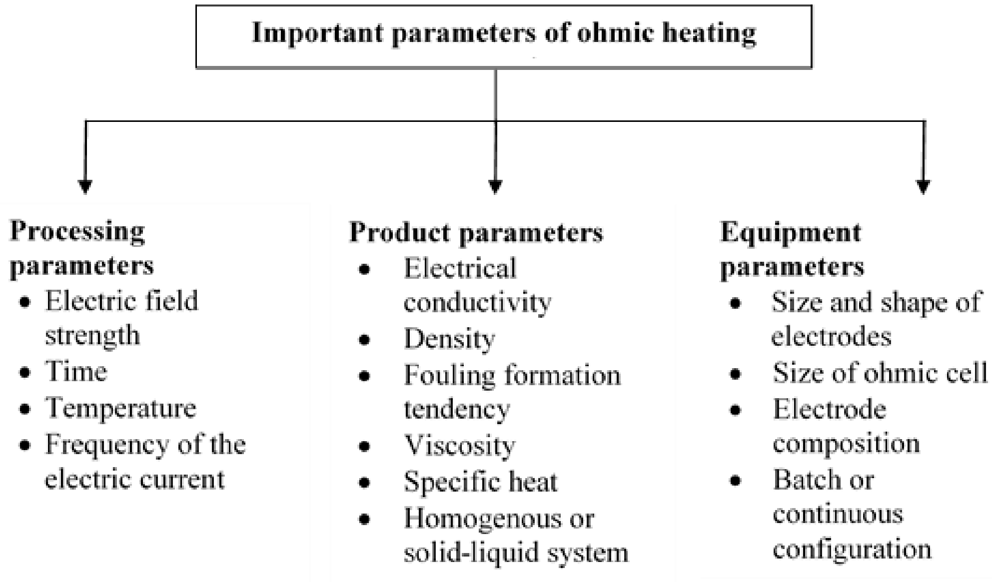

Fig. 2.3 Important parameters of ohmic heating in food processing

2.2.2 Factors affecting ohmic heating

Several factors that affect the OH rate of any food sample is shown in Fig. 2.3. The most important parameters include the EC of the food samples, EFS, ionic concentration (IC), particle size and concentration. Among these, the EC of the food samples plays a vital role in the OH of the food samples (Fryer and Li, 1993; Kumar et al., 2024). EC will influence the HR of different constituents of the mixture when the sample consists of multiple phases.

2.2.2.1 Electrical conductivity

EC is defined as the ability of any material, such as food samples (juice, paste, puree, etc.), to conduct electrical current or charge. It is denoted by the Greek symbol σ (sigma) with S.I. unit S/m (siemens/meter). It is also defined as the reciprocal of the electrical resistivity of the food sample. The presence of electrolytic materials such as acids and salts in fruits and vegetables permits the flow of electricity within the materials, forming the basis for OH technology (Kumar et al., 2024). Depending on the resistivity or conductance of the materials, heating takes place internally, volumetrically, and uniformly. The heating of the food samples depends directly on the current, which is produced by EFS. Also, the current flow depends on the EC or resistance of the food samples in the system. So, EC plays a vital role in determining parameters in the OH process (De Alwis and Fryer, 1992; Palaniappan and Sastry, 1991a).

Food with high EC (for example, concentrated salt solution) or too low EC (for example, fats, alcohols, oils, etc.) are unsuitable for OH because high EC will allow easy flow of current and very low EC will be too resistive. In either of the cases, heating will not occur within the samples (De Alwis and Fryer, 1992). So, the knowledge of the EC conductivity of different food samples is essential for processing using OH.

2.2.2.2 Electric field strength

EC and HR increase when the EFS across the food samples increases. Due to the application of higher EFS, more significant membrane rupture takes place. It increases free water and higher motion of fluid in the food sample capillaries, ultimately increasing the EC (Halden et al., 1990). Higher EFS values results in greater microbial and enzyme inactivation and enhances the extraction process (Kaur and Singh, 2016).

2.2.2.3 Ionic concentration

Ionic concentration has a significant effect on the OH of any food sample. With the increase in the concentration of the ions, the HR of the samples also increases, i.e., the HR is directly proportional to the ionic concentration. EC increases with an increase in ionic mobility while heating food samples because of tissue softening and structural changes such as the breakdown of cell wall protopectin and the release of gas bubbles. Studies showed that the higher acid content of apricot puree was heated at a greater rate than peach puree, which had lower acid content (Icier and Ilicali, 2005). Similarly, it was also concluded that food samples with greater ionic concentration significantly affect the heating behaviour during OH (Sarang et al., 2008).

2.2.2.4 Particle size and concentration

The particle size and concentration of food samples are decisive product parameters in finding the HR during ohmic heating. HR was found to decrease as the particle size of the carrot increased, and thus, the time required to achieve the same temperature level also increased with the increase in particle size (Zareifard et al., 2003). It was also observed that EC is reduced with increased particle concentration in the strawberry pulp (Castro et al., 2003). Thus, higher heating time was required to attain the same temperature with increased solid concentration (Zareifard et al., 2003).

2.3 Equipment for ohmic heating system

There are two modes in which OH for food processing can be done, i.e., batch type and continuous type OH systems. The common requirements for both systems include a power supply, OH chamber, data logger, electrodes, thermocouples, temperature and voltage controller (Kumar et al., 2024; Kumar and Srivastava, 2024). Fig. 2.4 and Fig. 2.5 show a typical batch type and continuous type lab scale ohmic heating system. The ohmic chamber is made of Teflon material, which is resistant to heat and electrically insulating and has high anti-adhesion properties. A K-type thermocouple is used for temperature sensing and connected to the temperature controller.

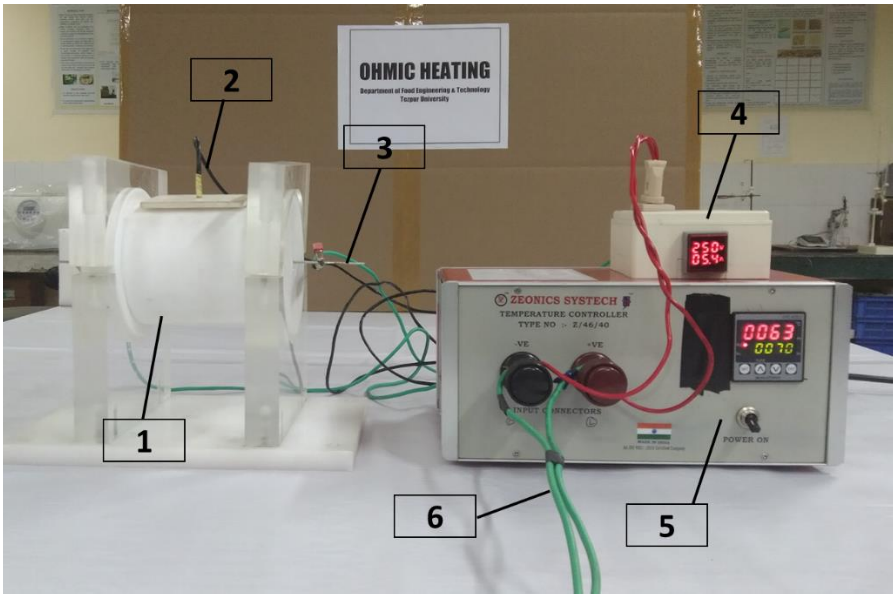

Fig. 2.4 Lab scale batch type ohmic heating system. 1-ohmic chamber, 2-K-type thermocouple, 3-electrodes, 4-current and voltage indicator, 5-temperature controller, 6-input power from variac transformer

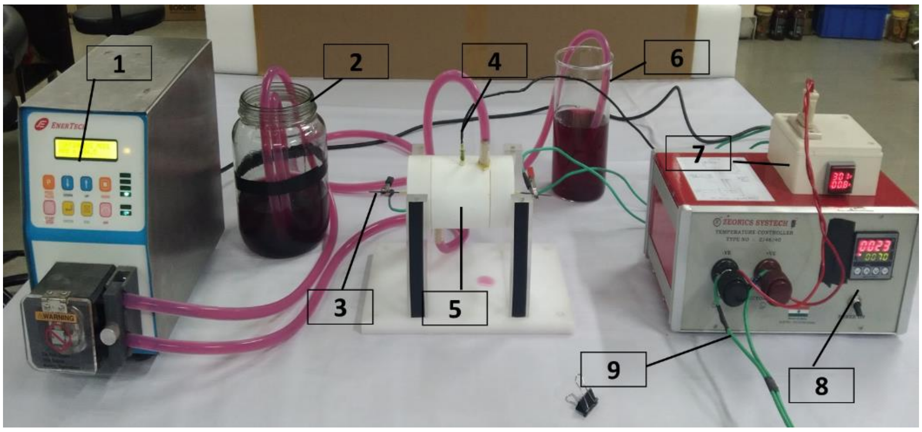

Fig. 2.5 Lab scale continuous type ohmic heating system. 1-pump, 2-inlet tank, 3-electrodes, 4-K-type thermocouple, 5-ohmic heating chamber, 6-outlet tank, 7-current and voltage indicator, 8-temperature controller, 9-input power from variac transformer

Two platinum-coated titanium electrodes are used, and the electrical circuit is completed by placing the food samples in between the space provided between these two electrodes. In a batch-type OH system, as shown in Fig. 2.4, food samples are kept in the ohmic chamber, and electric current is passed through it. Depending on the EC of the food samples, volumetric heating takes place. In batch-type, either fruit juice, pulp, or solid foods mixed in a conductive medium such as salt solutions can be heated.

However, in a continuous type of ohmic heating system, only pumpable food samples like fruits and vegetable juice and pulp up to a certain TSS value can be used for heating. A data logger can be used to continuously record the current, voltage, and temperature values to study the heating performance of the system. A variac transformer can provide the required voltage to the system, and depending on the gap between two electrodes, the desired EFs can be attained. For both systems, the optimum conditions must be obtained for every different sample as the electrical conductivity of each sample is different (Kumar et al., 2024; Kumar and Srivastava, 2024).

2.4 Applications of ohmic heating in food processing

Recent trends show the importance and broad applicability of OH in food processing as an alternative technology and also gained attention for its commercial applications. Extensive research has been carried out by several researchers on various food samples like fruit juices (orange, apple, watermelon, pomegranate, etc.), carrot, pineapple, potato, meat, egg, etc. The main aim of these experiments is to understand the heating properties and EC of the food samples under different EFS and the time required to attain the desired temperature (Kumar et al., 2024). Other parameters include physico-chemical properties, colour change, microbial inactivation, enzyme inactivation, rheological properties and nutritional properties. Various food processing in which OH finds its applicability include pasteurization, sterilisation, blanching, thawing, enzyme and microbial inactivation, peeling, dehydration, evaporation, extraction and many more, as shown in Fig. 2.6 (Makroo et al., 2020; Varghese et al., 2012).

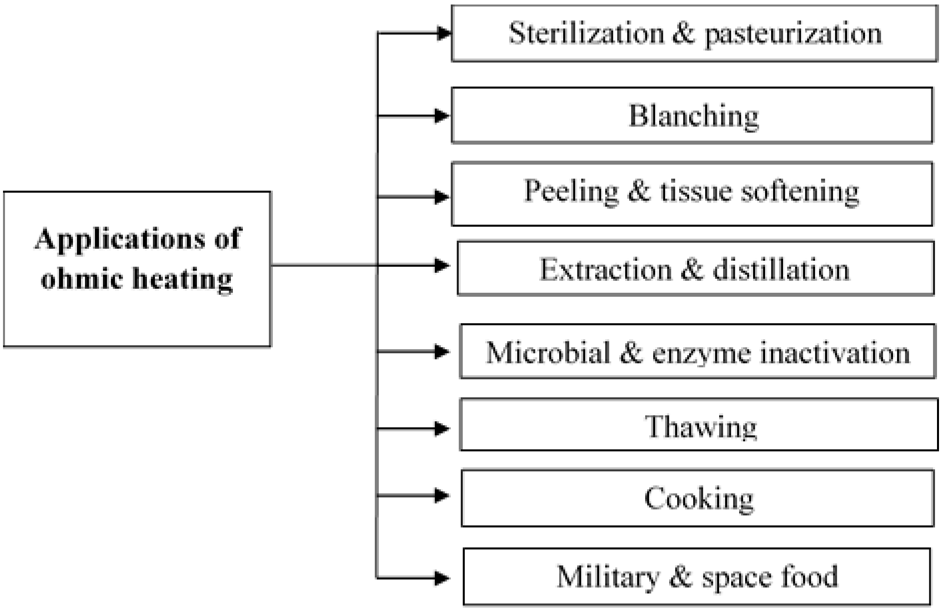

Fig. 2.6 Various applications of ohmic heating in food processing

Kumar et al. (2021) studied the effect of OH on pineapple cubes as pre-treatment (blanching) prior to drying, and they observed an enhanced rate of drying at greater EFS along with a reduction in the drying time. Also, a colour change was observed less with OH treated samples than with conventional treatment. The higher electric field might have resulted in the electroporation and electro-permeabilization effect, which caused an increased rate of mass transfer. OH has a positive effect on mass and heat transfer, with higher solid retention and uniformity when heating fruits and vegetables throughout the samples. Also, the requirements for water for blanching are comparatively reduced compared to conventional treatment, which makes OH blanching a better alternative.

OH can be used as the best alternative method for pasteurization and sterilization of fruit juices, pulp and purees as products are heated uniformly and rapidly, saving time and energy (Makroo et al., 2020). OH treatment showed better product quality as compared to conventional processing. Achir et al. (2016) studied the OH pasteurization of citrus juices and observed 70% and 40% losses in epoxy xanthophylls and hydroxy xanthophylls, respectively, with conventional treatment, but the losses were under 30% and 20%, respectively, when the samples were treated with OH. The authors also observed stability in the carotene viz. lycopene and β-carotene under both treatments and concluded OH was a better alternative for preserving the vital carotenoid pigments during processing.

Extraction and distillation are important operations for separating essential oils, flavour components, phytochemicals and other vital compounds. Ohmic-assisted hydrodistillation can overcome the limitations of conventional distillation and extraction as this technology utilises the benefits of volumetric heating and saves process time and overall energy (Gavahian and Farahnaky, 2018). Gavahian et al. (2013) extracted essential oils from Ajwain and found that the ohmic-assisted hydrodistillation method was much faster than hydrodistillation alone. They also observed similarities in antioxidant activity and sensory attributes among the processes used. Hamzah et al. (2013) mentioned higher extraction yield from citronella grass than conventional methods and observed swelling of cell walls during hydrodistillation but microfractures during ohmic-assisted hydrodistillation. Similarly, Al-Hilphy (2014) quoted a reduction in the extraction time and overall energy consumption during ohmic-assisted hydrodistillation.

The most important objective of any processing technologies, either traditional or novel methods, is to inactivate spoilage microorganisms and quality deteriorating enzymes to ensure the safety and prolong the shelf life of the processed products. OH can be efficiently used to achieve a higher rate of enzyme inactivation and lesser decimal reduction time. At higher EFS, enzyme inactivation was higher. And because of non-thermal effects at higher EFS, higher electroporation and electropermeabilization occur, resulting in higher microbial inactivation (Makroo et al., 2020). The above discussion shows the broad applicability of OH and potentially the best alternative for conventional thermal processing with higher efficiency in terms of processing and come-up time for a desired temperature, energy consumption, microbial and enzyme inactivation and many more.

2.5 Effect of ohmic heating on enzyme inactivation

OH inactivates food enzymes primarily through the process of thermal denaturation. In addition to the thermal effect, the non-thermal effect of the electric field also provides additional inactivation of enzymes (Kumar and Srivastava, 2024). Thermal denaturation refers to the disruption of the three-dimensional structure of proteins, including enzymes, due to the application of heat. OH achieves this by passing an electrical current through the food product, which generates heat uniformly throughout the material. As the temperature increases, the kinetic energy of the molecules within the food matrix also increases. Enzymes are proteins with specific three-dimensional structures that are essential for their function. However, these structures are sensitive to changes in temperature. As the temperature of the food product increases, the thermal energy disrupts the bonds, stabilizing the enzyme's native conformation, including hydrogen bonds, disulfide bonds, and hydrophobic interactions. The disruption of the enzyme's three-dimensional structure through thermal denaturation leads to the loss of its catalytic activity. The enzyme's active site, where the substrate binds, and the catalytic reaction occurs, becomes distorted or destroyed, rendering the enzyme incapable of performing its function (Makroo et al., 2020). In many cases, the denaturation of enzymes by OH is irreversible. Once the enzyme's structure is sufficiently altered by heat, it cannot return to its native conformation and regain its catalytic activity. This irreversibility ensures that the enzymes remain inactive even after the food product has cooled down. Non-thermal effects of OH on enzyme inactivation refer to the influence of electrical properties and other factors besides temperature that can affect enzyme activity. While the primary mechanism of enzyme inactivation during OH is thermal denaturation, several non-thermal factors can also contribute to enzyme inactivation or modulation. An electric field within the food product can potentially affect the conformation and activity of enzymes, influence biochemical reactions, and alter surface charge by ionizing the solution. Electric fields can induce changes in protein structure, alter protein-protein interactions, and modify enzyme-substrate binding kinetics (Kumar and Srivastava, 2024).

The effect of OH on various enzymes like polyphenol oxidase (PPO), peroxidase (POD), pectinase, pectin methylesterase, urease, lipoxygenase, etc. has been carried out. PPO and POD are the two oxidoreductase enzymes mainly responsible for enzymatic browning in fruits and vegetables and their juices. These enzymes affect their colour, texture, aroma, flavour, and organoleptic properties. PPO and POD are used interchangeably as marker enzymes for testing the completion of blanching and pasteurization, depending on their thermal stability (Kumar and Srivastava, 2024).

PPO is a copper-containing enzyme majorly responsible for forming a brown pigment called melanin in the presence of oxygen whenever fruits and vegetable tissues are damaged or exposed to open air and, thus, results in enzymatic browning. To inactivate this enzyme, blanching becomes essential after peeling and cutting of fresh fruits and vegetables and pasteurization of juices. It was reported that the exposure of PPO to a temperature of 70-90 °C destroys the catalytic activity and, thus, inactivates the PPO enzymes (Makroo et al., 2020). In one study, PPO inactivation effectiveness in watermelon juice was conducted using OH and compared with the conventional hot water bath thermal treatment. Results showed that both the treatment methods had significantly reduced the enzyme activity, but the inactivation was faster with OH because of the additional effect of the electric field along with the thermal effect (Makroo et al., 2016). Similarly, Saxena et al. (2016a) also studied the effect of OH parameters like EFS, treatment time and temperature on PPO inactivation in sugarcane juice and observed a maximum inactivation of 97.8% with a treatment time of 5 min at 90 °C in the presence of 32 V/cm electric field. POD, a heme-containing enzyme, catalyzes the oxidation of various compounds, including amines, phenols, ascorbic acid, and indole, in the presence of hydrogen peroxide. This enzyme is also responsible for the discolouration of various plant products and black-heart development in pineapple (Kumar and Srivastava, 2024). PPO and POD are the two main enzymes used in process optimization and are used as biological indicators of the blanching process of fruits and vegetables and juice pasteurization (Pipliya et al., 2022). Icier et al. (2006) studied the peroxidase inactivation during OH blanching and, compared with hot water blanching, observed that voltage gradient significantly affected the POD inactivation. Further, they observed that the ohmic blanching was significantly different from water blanching, indicating the additional contribution of non-thermal effects of ohmic heating. The non-thermal effect might have altered the surface charge and/or the enzyme's environment because of the ionization of the solution components in the presence of the electric field. A detailed study of PPO and POD enzyme inactivation in pineapple juice using continuous ohmic heating (COH) and their kinetic modelling was recently conducted by Kumar and Srivastava (2024). They have reported that a partial enzyme inactivation of around 20% of polyphenol oxidase and 30% of peroxidase was observed during the come-up time to achieve a desired temperature of 90 °C at 40 V/cm. The juice was then passed to an isothermal holding section where a maximum inactivation of 68.2% PPO and 82.2% POD were observed at 90 °C when treated for 60 s. Time and temperature significantly affected PPO and POD inactivation during the isothermal treatment. The authors also noted the higher thermal stability of PPO than that of POD enzymes. The Weibull distribution model was the best-fit kinetic model for both PPO and POD inactivation with $R^2 > 0.980$ and RMSE < 0.050 and can be used as a valuable tool to predict enzyme inactivation during COH. Pectin methylesterase (PME) is an enzyme responsible for catalyzing the de-esterification of pectin in various fruits and vegetables. Sometimes, PME is thermally more stable than several vegetative microorganisms, and thus, the destruction characteristics of this enzyme become essential to the process design of PME-containing food, for example, orange juice (Makroo et al., 2020). Several studies suggested that OH with moderate treatment temperature can effectively inactivate the PME enzyme at a faster rate with lesser treatment time as compared to the conventional heat treatment method

(Abedelmaksoud et al., 2018; Saxena et al., 2016b; Demirdoven and Baysal, 2015). Abedelmaksoud et al. (2018) investigated the effect of OH on PPO and PME inactivation in undiluted mango juice and optimized the process parameters. No residual activity of PPO was observed under optimized conditions of 40 V/cm and 80 °C when treated for 60 s, while 95.7% of the PME activity was inactivated under the same treatment conditions. On the other hand, the conventional heat treatment resulted in 89.9% PME inactivation under similar treatment conditions. However, the time taken by OH was less than that of the conventional method, and thus, a conclusion was drawn that the combined effect of temperature and electric field enhances enzyme inactivation and shortens the overall time requirement. A study on pectinase enzyme inactivation was conducted using both OH and conventional heating, and the results were compared. Results showed that similar D and Z values were obtained for both the treatment methods, and there was statistically no difference observed between the two methods on the pectinase inactivation (Castro et al., 2004). The reason was the absence of any metallic prosthetic group in the pectinase enzyme, which resulted only in thermal inactivation of the enzyme, and no additional non-thermal effect was observed due to the presence of an electric field during OH. The findings were in agreement with the hypothesis, which states that the presence of an electric field during the OH has an influence on the enzymes with the metallic prosthetic group, for example, copper in PPO, iron in lipoxygenase, etc. (Castro et al., 2004). Lipoxygenases are a family of non-heme iron-containing enzymes classified as oxidoreductases. It plays a crucial role in the oxidation of polyunsaturated fatty acids, specifically those containing a cis,cis-1,4-pentadiene structure, including linoleic and arachidonic acid. They insert oxygen molecules into these fatty acids at specific carbon atoms, forming hydroperoxides. In fruits and vegetables, lipoxygenases can catalyze the oxidation of fatty acids, leading to the formation of off-flavours and off-aromas. They can promote enzymatic browning reactions that negatively impact food products' sensory quality. The ohmic heating resulted in a lower decimal reduction time of lipoxygenase enzyme compared to conventional thermal treatment (Casto et al., 2004). Similarly, Li et al. (2015) also reported higher urease enzyme inactivation during ohmic heating than similar thermal profiles of conventional thermal treatment. Since the urease is a metallo-enzyme that contains one or more nickel ions (Ni^{2+}) in its active site. Therefore, the presence of the alternating electric field during ohmic heating may have removed the metallic prosthetic groups of the urease enzyme, leading to greater inactivation.

OH is particularly effective for enzyme inactivation because it provides rapid and uniform heating throughout the food product. This ensures that enzymes in all parts of the food matrix are exposed to the elevated temperatures required for denaturation. Additionally, the ability to precisely control the heating process allows for targeted inactivation of enzymes while minimizing damage to the overall quality of the food product. In summary, OH inactivates food enzymes by raising the temperature of the food product and causing thermal denaturation of the enzymes' three-dimensional structures. In addition to thermal denaturation, a non-thermal effect due to the presence of an electric field also enhances the enzyme inactivation compared to conventional thermal treatment. This disrupts the enzymes' catalytic activity, rendering them inactive and ensuring the preservation of the food product.

2.6 Effect of ohmic heating on microbial inactivation

OH inactivates microorganisms primarily through thermal effects. The non-thermal effects on microbial inactivation have an additional advantage during OH. The application of heat is the primary mechanism of microbial inactivation during OH. OH works by passing an electric current through a food product, which has resistance, resulting in the uniform generation of heat throughout the material. This heat raises the temperature of the food product, effectively killing the microorganisms present. The high temperatures denature proteins, disrupt cell membranes, and generally destabilize cellular structures within microorganisms (Makroo et al., 2020). Like all living organisms, microorganisms contain proteins crucial for their structure, function, and metabolism. When exposed to elevated temperatures during OH, the proteins within microbial cells undergo denaturation. Denaturation involves the disruption of the protein's native structure, leading to the loss of its functional properties. This process affects enzymes, structural proteins, and other vital components within the microorganism, ultimately leading to its inactivation. Heat also affects the integrity of microbial cell membranes. Microbial cell membranes are primarily composed of lipids and proteins, forming a selectively permeable barrier that regulates the movement of molecules in and out of the cell. Elevated temperatures caused by OH can disrupt the lipid bilayer structure of cell membranes, making them more fluid and permeable. This disruption leads to leakage of cellular contents, loss of cellular homeostasis, and, ultimately, cell death. Microbial enzymes play crucial roles in various metabolic processes essential for microbial growth and survival. However, these enzymes are also sensitive to heat. The high temperatures generated during ohmic heating lead to the denaturation of microbial enzymes, rendering them inactive. Loss of enzyme activity disrupts essential metabolic pathways within the microorganism, further contributing to its inactivation (Kaur et al., 2024).

While thermal effects are the primary mechanism of microbial inactivation during OH, some additional non-thermal mechanisms may contribute to microbial inactivation. The passage of electric current through microbial cells during OH can induce electroporation, a process in which transient pores or openings form in the cell membrane. Electroporation increases the permeability of the cell membrane, allowing ions, molecules, and even larger particles to enter or exit the cell. This disruption of membrane integrity can lead to cellular dysfunction and cell death. The flow of electric current through the food product may also lead to electrochemical reactions at the surface of microbial cells. These reactions can generate reactive oxygen species (ROS), such as hydrogen peroxide and hydroxyl radicals, which have antimicrobial properties and contribute to microbial inactivation.

Numerous studies have been conducted on the application of OH treatment for microbial inactivation. For instance, Baysal and Icier (2010) compared the effectiveness of OH and conventional thermal treatment for inactivating *Alicyclobacillus acidoterrestris* spores in orange juice under various treatment conditions. A maximum of 5-log reduction of the spore was observed with ohmic heating at 90 °C and 30 V/cm, while the conventional treatment observed only a 3.5-log reduction. Thus, the OH was more efficient in *Alicyclobacillus acidoterrestris* spore inactivation than the conventional treatment, as the Oh gave significantly lower D-values at all treatment temperatures than the conventional treatment. Similarly, several studies were conducted on *Escherichia coli* inactivation, a major food-borne pathogen, using ohmic heating and compared it with conventional thermal treatment. One such study was carried out by Park and Kang (2013) in buffered peptone water, and it was observed that *E. coli* was inactivated significantly more by OH than by conventional heat treatment. OH resulted in 4.0 and 5.6 log reduction of *E. coli* at 58 and 60 °C, respectively, when treated for 30 s. On the other hand, conventional heat treatment resulted in only 1.6 and 2.3 log reduction under the same treatment conditions. This result showed the additional non-thermal effects of OH, like the electroporation effect, causing damage to cell morphology and structure microorganisms. Similarly, OH reduced the *E. coli* from 6.73 to less than 1 log CFU/mL in skim milk when treated for 1 min at 70 °C, which was significantly different from the conventional heating. Similarly, the study on *Salmonella typhimurium* inactivation using OH has been carried out on several food samples like orange, tomato, and apple juice (Lee et al., 2012; Park and Kang, 2013) and skim milk (Kim and Kang, 2015). It was reported that a 1.32 log CFU/mL reduction of *Salmonella typhimurium* was observed when the orange juice was treated in COH for 60 s. The reduction was observed at more than 6.52 log CFU/mL when the treatment was done for 90 s, while it reached to an undetectable limit when the treatment was done for 180 s at 30

V/cm (Lee et al., 2012). On the other hand, *Salmonella typhimurium* in tomato juice reached an undetectable limit (< 1CFU/mL) when the sample was treated ohmically for 55 s. Thus, the processing time may differ depending on the type of food samples and microorganisms. Kim and Kang (2015) studied the inactivation of *Salmonella typhimurium* in skim milk and cream using OH and conventional heating. It was observed that in skim milk from an initial load of 6.69 log CFU/mL, the *Salmonella typhimurium* inactivated below detection level when treated with OH at 65 °C while it reached to 1.2 log CFU/mL when it was conventionally heat treated. On the other hand, for cream, no significant difference was observed between ohmic and conventional heat treatment of *Salmonella typhimurium* inactivation. *Listeria monocytogenes* can be found over a range of temperatures and are reported to be more thermally resistant than *E. coli* and *S. typhimurium*. A 3.6 log reduction of *L. monocytogenes* was observed in apple juice when the sample was treated with OH for 30 s at 55 °C with an EFS of 60 V/cm, while only a 1.2 log reduction was observed with conventional heat treatment. It was also observed that the *L. monocytogenes* can be inactivated to an undetectable limit by OH at 58 °C within 30 s of treatment time. On the other hand, conventional heat treatment was insufficient to attain the same level of inactivation under similar treatment conditions (Makroo et al., 2020). Similarly, in skim milk, *L. monocytogenes* inactivated below the detection limit (< 1 log CFU/mL) from an initial load of 5.6 log CFU/mL when treated with OH for 1 min, whereas only 3.6 log CFU/mL reduction of *L. monocytogenes* was observed under similar conventional heat treatment (Kim and Kang, 2015). Apart from these specific food-related pathogens, several studies have been conducted to investigate the effect of OH on total plate count to analyse microbial stability on various food samples like fruit juices, milk, etc. (Makroo et al., 2020). For instance, when sugarcane juice was treated with OH for 15 min at 90 °C, the total plate count was reduced to 3.47 log CFU/mL from an initial microbial load of 6.3 log CFU/mL. Thus, OH inactivates microorganisms primarily through thermal effects, including protein denaturation, membrane disruption, and enzymatic inactivation. Additional mechanisms such as electroporation and electrochemical reactions may also contribute to microbial control during OH. Overall, OH is an effective method for microbial inactivation in food products, offering rapid and uniform heating to ensure food safety and quality.

2.7 Advantages and limitations

2.7.1 Advantages

The various advantages of OH are as follows:

- Uniformity of heating of the entire food sample

- Higher HR as the heat is generated within the food matrix than conventional heat treatment.
- The HR can be controlled by varying electric field supplied and EC of the food samples.
- Highly energy-efficient process
- Allows the use of high-temperature short time (HTST) and ultra-high temperature (UHT) techniques processing.
- Volumetric heating
- It is applicable equally in batch and continuous flow mode of operations.
- High throughput and reduced processing time.
- Non-thermal effects of electric field on enzyme and microbial inactivation.
- A wide variety of ohmic heater sizes and designs can be made available depending on the type of requirements.
- Online monitoring is possible.

2.7.2 Limitations

The various limitations of the OH are as follows:

- Electrode corrosion (at certain frequencies)
- Strong dependence on electrical conductivity
- Sufficient water and electrolytes are required for the material to be treated.
- Not suitable for dry solid food.
- Not suitable to electrically resistive food products like fats, oils, alcohol, etc.
- Not suitable to electrically very conductive materials.
- More knowledge is required on the effects and mechanism of electric field, current, and frequency on different microorganisms.
- Identification and measurement of cold-spot during complex food processing is tedious.
- Heating patterns and modelling of complex food are required.