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Review Article

Advances in Non-thermal Food Processing Technology: A Review

***Muzzammil Abdullahi Yunusa and Munir Abba Dandago**

Department of Food Science and Technology, Aliko Dangote University of Science and Technology, Wudil, PMB 3244, Kano State, Nigeria
****Corresponding Author's email***: neatn2@gmail.com; **Phone: +2348038870165**

ABSTRACT
Food processing and preservation methods play a vital role in extending shelf life and ensuring the quality of food for human consumption. Traditional methods, which involve high temperatures and pressures, have been widely employed for food safety and preservation. However, these methods often affect the sensory attributes of food and also the nutritional values. Moreover, the prolonged processing times associated with, lead to the generation of harmful components. Several research studies have been employed in recent years to find an alternative process to the conventional processing of food, which will be accomplished at low temperature, short processing time, ensuring microbial decontamination, enzyme inhibition, and yet retaining the nutritional values of food such as flavours, colours, textures and sensory attributes. Non-thermal food processing becomes the only viable option. These processes involve ultrasound (US), high hydrostatic pressure (HPP), ultraviolet light, pulsed electric fields (PEF), non-thermal /cold plasma (NTP), irradiation, ohmic heating, ozone, etc. The present study aims to review the application of non-thermal processing in food processing and preservation technology. A systematic approach was used in analysing papers obtained from different search engines.

Keywords: Food safety; Microbial decontamination; Non-thermal food processing; Preservation

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INTRODUCTION

Food processing is an essential link in the chain that connects agricultural production with consumer nutrition and safety. It is something everyone does in their everyday life, starting with breakfast (Karimov *et al.,* 2024). Processed food products are often the result of a series of purposeful actions on food raw materials. These purposes can include food preservation, combination of different food raw materials and improvement of food quality and safety. The connections from food processing to applied natural science disciplines such as chemistry, biology and microbiology provide good subject matter and learning objectives for practical laboratory work (Brandt *et al.,* 2021). Different types of natural science education and laboratory work have been analysed and their pedagogical value has been compared to each other (Doig *et al.,* 2022).

Food processing and preservation methods play a vital role in extending shelf life and ensuring the quality of food for human consumption. Traditional thermal methods, which involve high temperatures and pressures, have been widely employed to enhance storage life and safety. However, these methods often result in damage to sensory characteristics and nutritional value. Additionally, the prolonged processing times associated with thermal methods can lead to the generation of harmful components. In recent years, significant research has been dedicated to non-thermal extraction technologies. These innovative approaches utilize lower temperatures and shorter processing durations, thereby minimizing the negative effects on nutrients, flavours, colours and sensory attributes. Numerous experiments conducted over the past few decades have demonstrated that non-thermal extraction technologies cause minimal harm to these essential aspects of food quality. Comprehending the design, operation and impact of non-thermal extraction devices on food processing and quality is of utmost significance (Safwa *et al.,* 2024).

While food processing and preservation rely on extending shelf life by deactivating microorganisms, it is equally essential to maintain the quality of the food for human consumption. The traditional methods of thermal processing, including pasteurization, high-temperature sterilization, drying and evaporation, have been widely used in the food industry to achieve both preservation and sterilization. However, these conventional techniques subject food to high temperatures, which effectively reduce microbial contamination but also introduce undesirable changes in the food (Bigi *et al.,* 2023). Conventional thermal processing methods entail exposing food to heat for extended periods, leading to noticeable alterations in the food's properties and resulting in the production of lower-quality products. One of the key drawbacks is the formation of chemical toxicants in the food, some of which are carcinogenic and harmful to the human body. The type and quantity of these toxicants depend on the specific thermal method employed for cooking the food (Martín-Belloso *et al.,* 2023). Furthermore, few high heating processes can also destroy some of the food ingredients, especially the heat sensitive vitamins and polyphenols, which were related to the quality of the food (Allai *et al.,* 2023). Moreover, the evolving landscape of consumer demands in terms of food safety, coupled with an increasing desire for food products free from microorganisms while retaining high nutritional value and sensory qualities, has driven food professionals to seek better alternatives. Nonthermal treatments have emerged as a promising solution to address these concerns. Specifically, non-thermal technologies are gradually being introduced in various food industries due to their ability to cause minimal damage to nutrients, flavours, colours and other sensory attributes (Vignali *et al.,* 2022).

An over view of non-thermal Food Processing

The evolving landscape of consumer demands in terms of food safety, coupled with an increasing desire for food products free from microorganisms while retaining high nutritional value and sensory qualities, has driven food professionals to seek better alternatives. Non-thermal treatments have emerged as a promising solution to address these concerns. Specifically, non-thermal technologies are gradually being introduced in various food industries due to their ability to cause minimal damage to nutrients, flavours, colours and other sensory attributes (Vignali *et al.,* 2022). Numerous research studies have observed a notable retention rate of freshness quality after implementing non-thermal treatments. This phenomenon can be attributed to the fact that, specific food samples such as vegetables and dairy products are subjected to these non-thermal technologies for a minimal duration, which has insignificant effects on the nutrients and other attributes of the foods. However, these non-thermal technologies have proven to be effective against microorganisms and inactivating enzymes, thus safeguarding fruits and vegetables from spoilage. Non-thermal treatments result in the alteration of cell structures and damage to genetic materials in microorganisms, ultimately leading to the destruction of these microbes (Chiozzi *et al.,* 2022). These technologies can also be utilized in drying, extraction, freezing and other unit operations under appropriate conditions. Due to their advantageous properties, non-thermal technologies serve as suitable supplements to less efficient thermal technologies. In recent years, there has been a notable increase in the publication of review papers concerning the utilization of non-thermal technologies in the food processing industries. These review papers have predominantly focused on introducing the fundamental principles, the general treatment systems and the current applications of non-thermal technologies within the food industry. They have provided an overview of how these innovative approaches work and where they are currently being applied in the field of food processing (Safwa *et al.,* 2024).

The contamination of food and feed by fungi has become a global problem with a significant economic impact worldwide. Airborne fungal spores can easily infect, colonize and spoil plants and food. The rapid spread and adaptability of the spores in different areas negates all active disease control strategies. In addition, the morphology and stress tolerance of fungal spores, as well as their production process and dormant state, are highly variable. It is estimated that fungi are responsible for losing up to 10–23% of crop products due to disease and additionally, 10 to 20% in the postharvest processes (Stukenbrock and Gurr 2023) and climate change can exacerbate the situation by creating conditions that make the occurrence and spread of foodborne hazards more likely because they weaken the resistance of host plants making them more susceptible to fungal diseases. On the other hand, it is possible that there will be a shift in mycotoxin-producing fungi and a change in global patterns of mycotoxin incidence (Casu *et al.,* 2024). Nowadays, consumers are highly interested in food products that are safe, healthy, minimally processed and natural with a fresher taste. In order to attend to consumer demands, industries are trying to seek alternative technologies keeping in mind the freshness, safety, storage stability, nutritional profile, environment friendliness, appetizing qualities, affordability, personalization and therapeutic aspects of their processed products (Bulut *et al.,* 2021). This presents a significant challenge to the industry and demands for worldwide innovation and market competitiveness. These alternative technologies are usually considered "non-thermal" wherein, food is generally processed at ambient or slightly above ambient temperature and heat generation is minimal (Jadhav *et al.,* 2021). Milk, which is considered to be the most perishable commodity, contains several heat-sensitive flavourings, aroma compounds and vitamins that are often lost during heat treatments. Heat treatment also leads to certain undesirable changes in milk components like browning, off-flavouring and denaturation of proteins. The quality of the product is governed by the function of both temperature and process exposure time (Zadeike and Degutyte 2023). Traditional thermal energy-based methods are losing popularity as non-thermal technologies gain prominence in food processing (Bashir *et al.,* 2021; Rathod *et al.,* 2021). These innovative non-thermal techniques utilize electrical, electromagnetic forces, light and mechanical forces instead of heat energy (Cimmino *et al.,* 2023). Unlike heat treatment, which has significant consequences for the environment, high costs, energy consumption and water usage (Cimmino *et al.,* 2023), emerging non-thermal technologies are characterized by their low-temperature operation. Hence, these technologies offer the potential to minimize these consequences to a greater extent (Koutchma *et al.,* 2021). This shift towards non-thermal methods reflects a growing emphasis on energy-efficient and sustainable approaches to food processing.

The demand for more sustainable food production methods and the growing consumer interest in fresher and more nutritious food products in combination with the advancement of human knowledge and technology progress, have facilitated the development of new food pro cessing technologies for food preservation and safety, in replacement of the more classical food processing technologies like heating, (Chacha *et al.,* 2021; Nowosad *et al.,* 2021). The term, “non-thermal”, was coined to describe those alternative-to-temperature-based-pasteurization methods (Chacha *et al.,* 2021). “Non-thermal” technologies can utilize ultrasound (US), high hydrostatic pressure (HPP), ultraviolet light, pulsed electric fields (PEF), non-thermal /cold plasma (NTP), irradiation, ohmic heating, ozone etc.

Ultrasound

The Ultrasound consists of sound waves whose frequency exceeds the limit of human hearing (around ~20 kHz) and is classified into three groups: (i) power frequency (frequencies between 20 and 100 Hz), (ii) high-frequency US (frequencies between 20 kHz and 100 MHz) and (iii) diagnostic US (frequencies >1 MHz). On the other hand, the US, according to its application, is classified into low intensity (less than 1 W/cm^2) and high intensity (10–1,000 W/cm^2) Fig 1 gives general Schematic diagram of an ultrasound food decontamination set up (Gavahian *et al.,* 2021).

With high-intensity ultrasound, cavitation bubbles are created through generated pressure cycles, which grow irregularly during the compression/rarefaction cycles, absorbing energy until a maximum when implosively collapsing, releasing a large amount of energy and, in some instances, producing radicals and ROS. This released energy generates shear forces with very high temperature and pressure (5,000 K and 5,000 atm, respectively), capable of destroying any membrane or cell wall of microorganisms (Moosavi *et al.,* 2021). Three aspects influence the effectiveness of microbial inactivation: the cavitation threshold (intensity, frequency, amplitude, temperature and external pressure), the medium (viscosity, volume, pH and initial amount of microorganism) and therefore the properties of the microorganism (cell wall, size, shape, endospore or growth phase and growth phases) (Silva 2020).

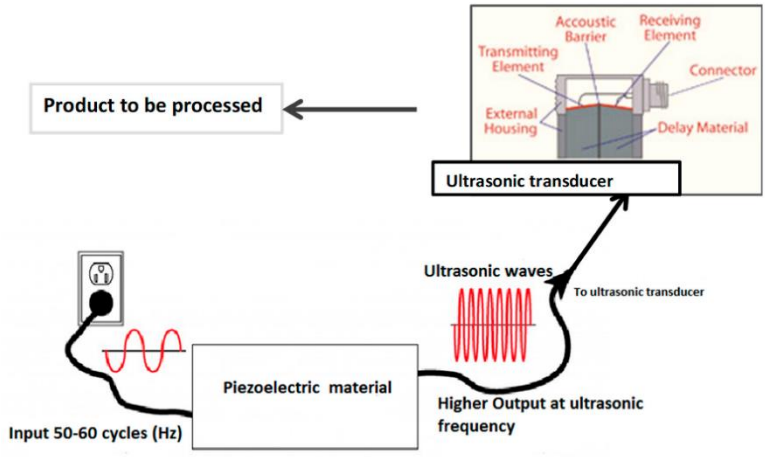

Fig 1; Schematic diagram of an ultrasound food decontamination set up (Chavan *et al.,* 2022)

Ultrasound is an emerging non-thermal food processing technology that has gained significant attention in recent years due to its potential to improve food safety and quality while maintaining the nutritional and sensory attributes of the product, (Ma *et al.,* 2023; Sireesha *et al.,* 2022). Ultrasound technology utilizes high-frequency sound waves (typically in the range of 20 kHz to 1 MHz) to induce mechanical effects in the food matrix, such as cavitation, which can disrupt microbial cells and enzymes, leading to their inactivation (Ma *et al.,* 2023; Sireesha *et al.,* 2022). The intensity and frequency of the ultrasound waves, as well as the duration of the treatment, can be adjusted to optimize the inactivation of specific microorganisms and enzymes, providing a high degree of control over the process (Hasan *et al.,* 2023; Ma *et al.,* 2023). Ultrasonication has been shown to improve the physiochemical properties such as texture and colour while also increasing the water-holding capacity (WHC). Additionally, it has been shown to increase omega-3 fatty acid content while reducing lipid oxidation (Sireesha *et al.,* 2022). Ultrasonication has also been shown to be effective in microbial inactivation, reducing the number of bacteria and viruses in seafood products (Ma *et al.,* 2023). Ultrasound treatments with a power of 20 kHz at amplitudes of 100 %, 50 % and 10 % were found to result in approximately 99 % inactivation of food pathogens, including *Brucella melitensis* type 3, *Salmonella Typhimirium*, *Escherichia coli, Listeria monocytogenes* and methicillin-resistant *Staphylococcus aureus*, inoculated in goat milk (Tavsanli *et al.,* 2022). Khanal *et al.* (2014) utilized ultrasound to deactivate spore-forming vegetative cells in milk, the results demonstrated complete inhibition of *B. coagulans* and *A. flavothermus* through ultrasonic treatment combined with heat. Scudino *et al.* (2023), reported significant reductions (up to 3.9 log cycles) in aerobic mesophilic heterotrophic bacteria, improved fat globule size, enhanced color and enhanced kinetic stability of whole milk following ultrasound application during storage**.**

High-pressure processing (HPP)

High-pressure processing (HPP) is a non-thermal food preservation technology that has gained significant attention in recent years due to its ability to maintain the sensory and nutritional quality of food products while ensuring their safety (Chen *et al.,* 2022; Khouryieh, 2021; Valø *et al.,* 2020). The mechanism of HPP involves the application of high hydrostatic pressure, typically between 100 and 800 MPa, to the food product for a certain period of time, usually a few minutes (Khouryieh 2021). This pressure is applied uniformly throughout the product, regardless of its size, shape, or composition, which is a distinct advantage over thermal processing methods, figure 2. One of the primary applications of HPP in the seafood industry is its use in microbial inactivation. HPP has been shown to effectively reduce the microbial load in seafood products, including pathogenic bacteria such as *Listeria monocytogenes* and *Vibrio parahaemolyticus*, which are commonly associated with seafood-borne illnesses (Roobab *et al.,* 2022). This contributes to an extended shelf life and improved safety of the product. The application of high pressure disrupts the cellular structures of microorganisms, including bacteria, yeasts and molds, leading to their inactivation (Khouryieh, 2021; Roobab *et al.,* 2022). Specifically, the high pressure affects the integrity of the microbial cell membrane and inhibits essential enzymatic activities, thereby preventing microbial growth and proliferation (Roobab *et al.,* 2022). In addition to its antimicrobial effects, HPP can also inactivate enzymes responsible for food spoilage, thereby further extending the shelf life of seafood products (Chen *et al.,* 2022; Kulawik *et al.,* 2022).

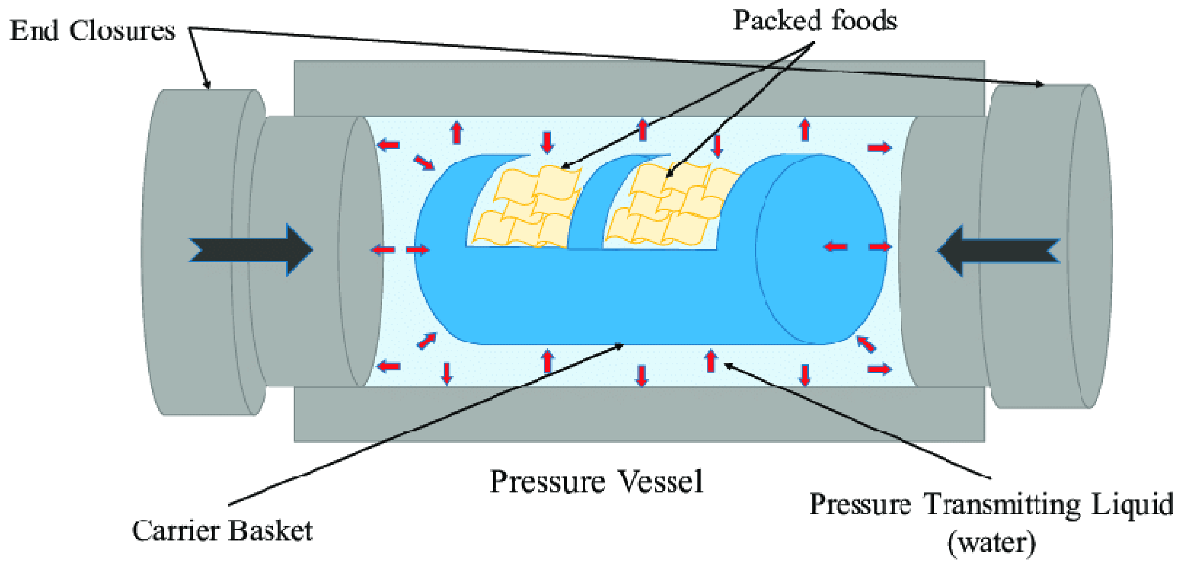

Figure 2: High hydrostatic pressure processing (Source: Kaushal *et al.,* 2020)

HPP is generally applied for food processing and shelf-life extension due to their inactivating effect on pathogenic and spoilage microorganisms. The determining factors are the types of microbes and their growth phases, duration of processing, pressure, food content, temperature, pH and water activity. Overall, HPP affects only non-covalent bonds as these are sensitive to pressure. HPP may be an effective post-harvest strategy to reduce microbial pathogens in fresh produce if plant tissue damage is minimal (Molina-Hernandez *et al.,* 2025). A study on smoothies preserved through high-pressure processing at 4 ^{0} C for 21 days shows that high-pressure processing at 350 and 450 MPa for 5 and 15 min, respectively, effectively reduces the native microflora without subsequent microbial activation during storage (Škegro et al., 2021). In another study, Sharma et al., (2008) significantly reduced titers of *feline calicivirus* using High-pressure processing in sausage microbial inactivation by 2.89 and 2.70 $\log_{10}$ median tissue culture infectious dose (TCID)50/ mL and *hepatitis* A virus by $\log_{10}$ 3.23 and 1.10, respectively using a pressure of 400 MPa, temperature 6 ◦C for 5 min, when compared to non-pressure-treated controls. A study by Petrus *et al.,* (2020) on Apple microbial inactivation reported that, *E. coli, Salmonella enterica* and *Listeria monocytogenes* were reduced by greater than 5 logs. Using a pressure of 100–600 MPa for 26–194 s.

Irradiation

Non-thermal processing technology has shown unparalleled advantages in improving food quality and safety, making it develop rapidly in recent years and become a new research hotspot in food processing. Food irradiation, a typical non-thermal food processing technology, has the advantages of rapid, efficient, low-cost and pollution-free, which has received extensive attention and gradually become one of the widely accepted modern food processing methods. Especially in recent years, with the deepening of related research, food irradiation has made remarkable research progress in food preservation, sterilization and degradation of harmful substances, showing a broad application prospect (Yang *et al.,* 2024).

The Ionizing radiation, such as the gamma rays, X-rays or the high-energy electrons, is used to irradiate the food. The Food irradiation is generally determined by the absorbed dose expressed in Gray (Gy) or kilo Gray (kGy), with 1 Gray being equivalent to 1 J/kg of product. The technique is considered a safe and effective way to decrease or eliminate hazardous microbes, prolong shelf life, as well as enhance the quality and safety of the food products Figure 3. The principles of food irradiation are determined by the ability to disrupt the genetic material of microorganisms, preventing them from reproducing or causing the illness. The irradiation affects the microorganisms' genetic material (the DNA or the RNA) directly and indirectly. The Direct irradiation can break the bonds between the base pairs in the genetic material, killing the cell's reproduction ability. Then, on the other hand, the damage to the water molecules creates the free radicals and the reactive oxygen species, which damage the genetic material indirectly (Oh *et al.,* 2023).

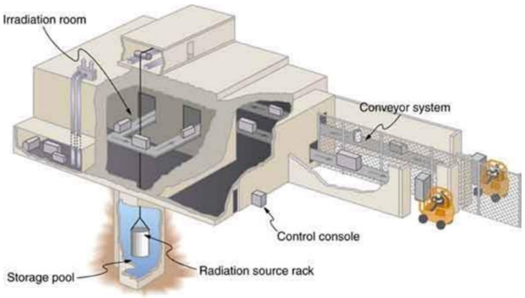

Figure 3: schematic diagram of a food irradiation procedure (Ibrahim 2020)

There are two main types of radiation: ionizing and non-ionizing. Radiations are widely distributed in the earth's crust with small amounts found in water, soil and rocks. Humans can also produce them through military, scientific and industrial activities. Ionizing and nonionizing radiations have a wide application in the food industry and medicine. γ-rays, X-rays and electron beams are the main sources of radiation used in the food industry for food processing (Danyo *et al.,* 2024).

Mishra *et al*. (2011) conducted a study on preserving sugarcane juice. In an ideal situation, fresh sugarcane juice changes its colour soon after withdrawal. Due to fermentation, it spoils within a few hours. Hence, a research study was conducted that applied gamma radiation along with preservatives and low temperature storage to make the juice last long. A study was conducted by Mahmoud *et al.,* (2015) where the effect of gamma radiation on millet grains was studied. The grains were subjected to gamma radiation at different doses: 0.25kGy, 0.5kGy, 0.75kGy, 1.0kGy and 2.0kGy. After the experiment, it was observed that a radiation level above 0.5kGy on the grain lowered the fungal incidence and free fatty acids content. At the same time, there was a reduction in anti-nutrients, such as, tannin and phytic acid. As a result, there was an increase in the vitro protein digestibility and protein solubility of the grain. This experiment proved gamma radiation was safe for shelf-life extension of millet grains.

Wang *et al.* (2017) conducted a study to examine the effect of e-beam processing on the structural and functional properties of albumin, globulin, glutenin and wheat germ protein isolate. The end results indicated that e-beam irradiation with optimal conditions was a very effective process to enhance water absorption, oil absorption and foaming properties of proteins. It was determined that the best results were obtained below 60kGy. It provided the optimal condition for oil absorption activity in albumin, globulin and glutenin. Whereas, 30kGy was best for water absorption as well as glutenin and wheat gram protein isolate. Therefore, it is essential to choose the right irradiation dose to meet the different prerequisites of protein functional properties. Some applications of radiation technology in the food industry are irradiation of spices and condiments (Singh and Singh 2020), control of sprouting in tubers and bulbs, insect disinfection in cereals, fruits and vegetables, fish and meat products (Zaki *et al.,* 2025) and application of irradiation in dairy products (Nyamakwere *et al.,* 2022).

Ohmic heating technology

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 (Astrain-Redin *et al.,* 2024).

Ohmic heating employs a pair of electrodes to generate a potential difference inside the food figure 4, resulting in the directional or reciprocal migration of free ions and charged macromolecules, thus generating an electric current (Cao *et al.,* 2020). According to Ohm's law, electrical energy is transformed into thermal energy, realizing food processing. When compared with conventional heating, OH is an energy-efficient method with minimal environmental impact (Ghnimi *et al.,* 2021).

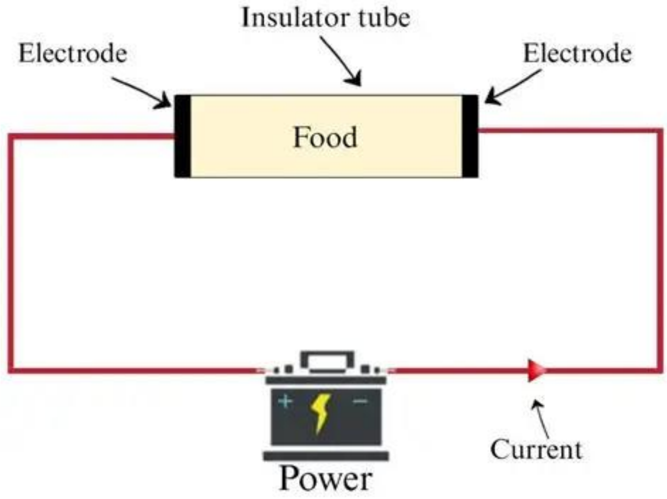

Figure 4: Schematic diagram of Ohmic heating food preservation technology (Dos Santos *et al.,* 2024)

It has been widely applied in food processing, including sterilization, enzyme inactivation, extraction, fermentation and other pre-treatments (Cao *et al*., 2020; Ríos-Ríos *et al.,* 2021). The heat is produced inside a food under the field, which depends upon its current density, then the food undergoes a temperature rise. Lee *et al.,* (2012) used a potential difference of 20, 15, 10 V/cm at 60 Hz for 90, 180, 480 s to achieve a 5-log reduction in E. coli O157:H7, *Salmonella typhimurium* and *Listeria monocytogenes.* In another study, Park *et al.* (2017) were able to achieve microbial decontamination of a concentrated tomato juice by 5-log reduction in bacteria population using a potential difference of 13.4 V/cm at a temperature of 60-63°C for 190-250 s. Moreover, using ohmic heating techniques, Bansode *et al.,* (2019) used 0.15V, 0.25V, 0.5 V, temperature of 24-25°C, 19-20°C, 21°C and 3, 5, 10 min respectively and Inactivated enzymes, reduced turbidity and quality of aloe vera juice maintained for 60 days.

The inactivation mechanism of OH treatment mainly relies on thermal effects. The process parameters that influence the efficiency of OH include electrical conductivity, applied voltage, frequency as well as input power. The conductivity range generally varies between 0.01 and 10 S/m (Shao *et al.,* 2021), but low-conductivity foods require relatively high electric field strength for the heating. The conductivity is not at a constant level but varies with temperature. Moreover, the food is generally a non-homogeneous system, with varying conductivity at different locations. Simultaneously, the heating process is also affected by initial temperature, viscosity, flow velocity, geometric shapes or other factors (Cao *et al*., 2020). Ohmic heating treatment has numerous microbial inactivation applications, all the cases have been commercialized since the 1990s and it consumes 4.6–5.3 times less energy than conventional pasteurization (Alkanan *et al.,* 2021).

Pulsed electric field (PEF)

Pulse Electric Field, a non-thermal processing technique, employs charged electrodes to produce high-intensity, short pulses voltage on the foods (Niu *et al.,* 2020). It has been commonly utilized for microbial and enzyme inactivation and enzyme inactivation due to high potential difference inside the food. The high-voltage and high-frequency pulses allow treated food to be maintained at a relatively low-temperature rise (Li *et al.,* 2023). When the PEF is applied, the electroporation effect causes the permanent destruction of cell membrane as well as the formation of membrane pores, eventually resulting in membrane lysis and spillage of the contents. The PEF process has minimal influence on food flavour and nutrients since there is no significant thermal effect. Although PEF avoids temperature rise during the process to some extent, a moderate temperature is beneficial in practical treatment for enhancing the non-thermal effect (Salehi 2020). The threshold of electric field strength causes the electroporation is mainly related to input power level. Meanwhile, the operations often require higher voltage.

Ordinarily, electric pulses are passed through a food material within a compartment at room temperature (figure 5) and food conducts electricity due to the presence of numerous ions, allowing the generation of a specific level of electrical conductivity. As a result, when an electrical field is applied, electrical current flows through the food, especially in liquids and agitation occurs at various points within the food due to the presence of charged particles (Wang *et al.,* 2022). Numerous non-thermal preservation methods have been considered in line with the overarching goal of conserving food at lower temperatures compared to traditional heat processing techniques. These methods aim to preserve the nutritional aspects of food, including vitamins, minerals and essential flavours, while using less energy than conventional high-temperature processing.

Šalaševičius *et al.* (2021) studied microbial inactivation of whey protein using pulse electric field. Electric field strength of 0.5–2.4 kV/cm, with frequency of 1 Hz for 25 µs. After treatment with pulsed electric field, a significant decrease in total bacterial viability of 2.43 log and coliforms of 0.9 log was achieved although undenatured whey protein content was not affected at 4.98 mg/mL. In another study, Clemente *et al.* (2020) sterilized chicken using electric field strength of 0.25–1 kV/cm, frequency of 1 Hz and 50 pulses for 20 µs. Application of 1 kV/cm in chicken followed by resuspension achieved a reduction close to 1.5 Log10 CFU/g and also showed synergistic behavior. Kantono *et al.* (2021) employed Pulsed electric field processing to increase the sensory properties of lamb. The energy of 88–109 kJ/kg, frequency of 90 Hz, electric field strength of 1–1.4 kV/cm with 964 pulses for 20 µs. The treatment contributed to more oxidized flavour in pulsed electric field treated frozen–thawed rib cut stored for 7 days.

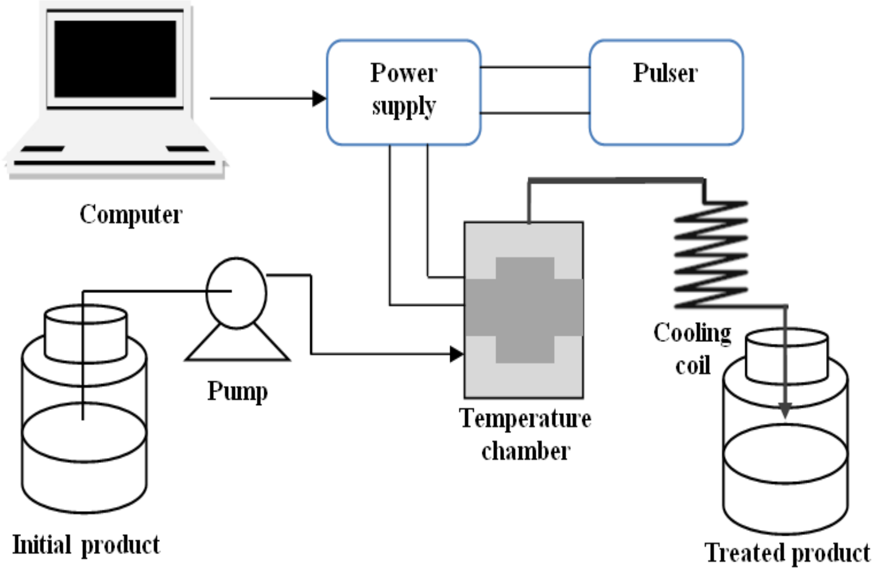

Figure 5: Schematic diagram of a pulsed electric fields technology (Mohamed and Eissa 2012)

The damage to cell membranes caused by pulsed electric field technology is irreversible, leading to the destruction of microorganisms. Pulsed electric field technology has found various applications, including electroporation in cell hybridization in genetic engineering and biotechnology, similar to other non-thermal processing technologies employed for maintaining food at lower temperatures in general applications during thermal processing. It preserves the nutritional characteristics of food, including vitamins, minerals and important flavours with minimal alteration to the final product's attributes compared to unprocessed foods. Electroporation, based on the strength of the electric field, can be categorized as reversible (cell membrane release) or irreversible (cell membrane collapse or lysis). These effects can be controlled based on the intended function. A typical pulsed electric field setup includes a high-energy pulse generator, a processing compartment with fluid control mechanisms and monitoring and control processes (Graybill, *et al.,* 2020).

Pulsed Light

One of the key advantages of pulsed light (PL) over other non-thermal technologies is its emission of highly concentrated, short-duration light bursts. These intense energy pulses can inactivate microorganisms within milliseconds to seconds, making PL a highly time-efficient method for surface treatments. Its broad-spectrum light, which includes UV, visible and infrared wavelengths, enhances its ability to target and eliminate a wide range of pathogens effectively (Santamera *et al.,* 2020).

A typical PL system consists of a high-voltage power supply, a storage capacitor, a pulse-forming network that determines the pulse shape and spectrum characteristics, a gas-discharge flash lamp and a trigger that initiates the discharging of the electrical energy to the flash lamp, figure 6. Electrical pulses are applied to excite inert gases, such as xenon in flashlamps and cause gaseous molecules to collide, producing light pulses. After that, the light energy is emitted in extremely concentrated short-duration light bursts (lasting for a few hundred microseconds, usually 1 to 1,000 µs). The resulting light has an electromagnetic spectrum ranging from ultraviolet (UV) to near infrared (IR). This range of electromagnetic radiation includes UV rays (λ = 100–400 nm), visible light (λ = 400–700 nm) and infrared (λ = 700–1,100 nm). In order to satisfy the unique process requirements, the PL system can deliver light as a single pulse, a burst of pulses (timed mode) at a frequency of 1–20 Hz with a pulse width of 300 ns to 1 ms, or a continuous array of pulses in random sequences. Optical sensors measure the fluence of the PL irradiation on the sample. Numerous variables, such as the number of flashes, the pulsed energy level, the distance between the sample and the lamps and the type of sample treated, affect the inhibitory effect of PL (Filho *et al.,* 2020).

Suwandy *et al.,* (2015) reported tenderization of beef using an electric field strength of 0.50–0.58 kV/cm, Voltage of 10 kV, Frequency of 90 Hz for 20 µs. The use of repeated pulsed electric field had a positive impact on the beef muscles (19.5 % reduction in the shear force) without increasing off-flavor or off-odor. Telfser and Galindo (2019) conducted research using a Basil leaf to reduce the drying time of the leaves. They used an electric field strength of 650 V/cm, 65 pulses for 150 µs. Drying times reduced 57 % for air drying, 33 % for vacuum drying and 25 % for freeze drying. Wu *et al.,* (2015) determined protein aggregation of an egg white using an electric field strength of 25 kV/cm, Pulse width of 200–800 s, Energy of 681.3–2726.3 kJ/L and Frequency of 100 Hz. The SDS–PAGE patterns showed that lysozyme (34.4 %), ovalbumin (36.2 %) and ovo-transferrin (24.1 %) existed in the aggregates formed in Ova 1 solution (the content of ovalbumin was 87.2 %) after pulsed electric field treatment.

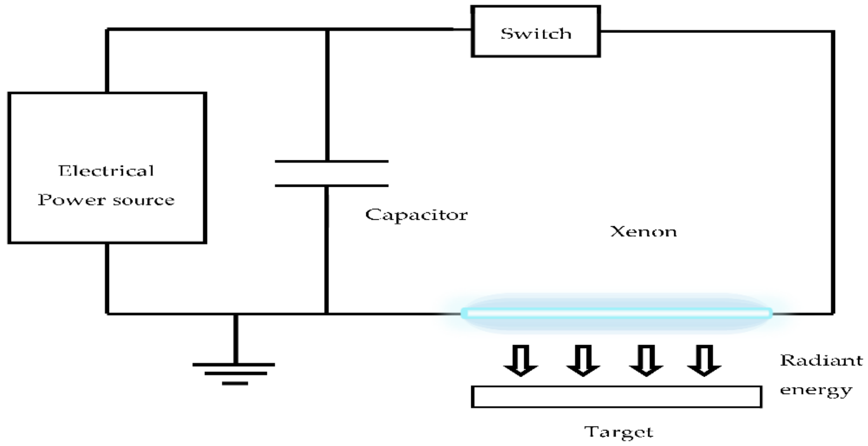

Figure 6: Schematic diagram of a typical Light pulse technology (Mandal *et al.,* 2020)

The effects of PL on microbial cells are divided into three categories:

(i) The photochemical effect, caused by PL UV component that can be absorbed by DNA and other cell components, refers to the water vapor-induced damages like disruption in the cell wall, shrinkage in the cytoplasmic membrane and mesosome rupture, followed by leakage of cell content and genetic material (Contigiani *et al.,* 2021), the absorption of UV fraction initiates the DNA or RNA damage by forming pyrimidine dimers, resulting in mutations, inhibition of DNA and thus prevents the microorganisms' ability to replicate.

(ii) The photothermal effect caused by the visible and near-infrared regions, which only generate heat high enough to kill microorganisms on the surface of the treated substrate (a few µm thick) and

(iii) The photophysical effect caused by the high-power pulsing effect, which is constantly disturbing structure damages.

Many factors influence microbial inactivation, such as;

(i) food surface, in this case, non-uniform exposure of the sample reducing the inactivation efficiency.

(ii) Food shape, spherical shape is the most suitable shape.

(iii) Distance of exposure of light.

(iv) Food colour media.

(v) Degree of heat dissipation and its absorption by the food matrix.

(vi) Turbidity that may be caused by the presence of particles that have a high UV absorbance, which could lower overall PL efficiency.

In addition, after PL treatment, temperature, moisture content and lighting are considered significant environmental variables that can influence microbial activation and inhibition. However, the intrinsic properties of the microbial cells—that is, the kind of microorganism, the growth stage and the size of the inoculum—also influence PL lethality (Molina-Hernandez *et al.,* 2025).

One of the technique's key limitations is its limited penetrating power; hence, opacity, topography and matrix composition all significantly impact process effectiveness. If the treated surface has a rough texture or a pored structure, a shadow effect occurs, allowing microorganisms to survive the treatment. The large-scale implementation of PL systems in production environments presents significant challenges. The effectiveness of PL depends on several factors, such as the wavelength of the emitted light (generally between 200 and 300 nm for maximum germicidal action), the fluence (energy per unit area) and the pulse duration. These parameters must be carefully adjusted for each application since excessive fluence can damage materials and insufficient fluence may not guarantee the complete inactivation of microorganisms. In addition, the generation of ozone as a by-product of the interaction of UV light with atmospheric oxygen can sometimes limit its application. The costs associated with the acquisition and operation of PL equipment and the need for trained personnel to operate it constitute another obstacle to its widespread adoption (Molina-Hernandez *et al.,* 2025).

Oscillating Magnetic Field

Oscillating Magnetic Field (OMF), is an environmentally responsible way to extend the shelf life of milk and dairy products is through the use of magnetic fields in dairy manufacturing operations. Milk can get contaminated by a variety of bacteria both during and after milking, even though the udder is sterilized. For example, mastitis can be caused by *staphylococcus aureus*, *streptococcus uberis* and *coliform spp*., (Ghoshal 2023).

Because bacteria that cause food to spoil are inhibited by magnetic fields, they have lately been used to eradicate pathogens. Microorganisms in non-conductive environments may be killed or rendered inactive by applying high-intensity magnetic fields at a reasonable frequency. Bacteria in milk and food are eliminated by an oscillating magnetic field. In non-conductive environments, high-intensity magnetic fields with a reasonable frequency can be used to either kill or inactivate microorganisms. Bacteria in milk and food are eliminated by relatively brief treatments in the form of pulses when subjected to an oscillating magnetic field; this prevents a discernible temperature rise in the finished goods (Ying *et al.,* 2024).

Meals, whether solid or liquid, can be stabilized with oscillating magnetic fields. Liquid meals can be pushed through a conduit figure 7, while solid meals are stored with OMF by being sealed in a plastic bag. The product is exposed to 1 to 100 pulses in an OMF at frequencies between 5 and 500 kHz, at 0 to 50 °C, for a total exposure time between 25 and 100 ms (Sawale *et al.,* 2024).

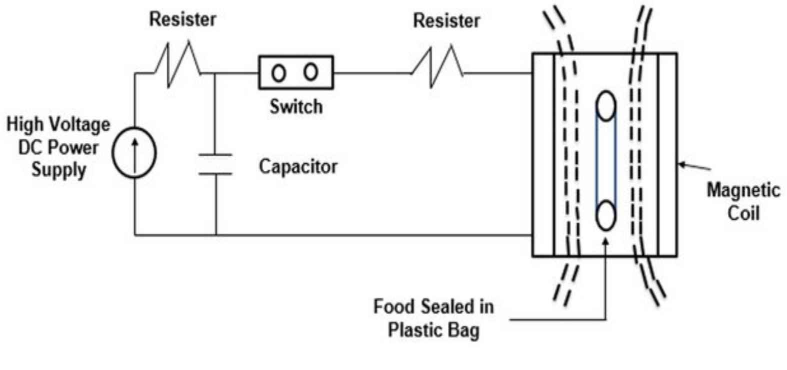

Figure 7: Electrical circuit for generation of OMF (Kardile *et al.,* 2022)

Milk and milk products can be pasteurized or treated in other ways. At a field intensity of 12 tesla, the treatment of milk reduced the number of bacteria from 25000 to 970 cfu/ml (Ying et al., 2024). Additionally, magnetic milk gives tired individuals energy and strength (Ying *et al.,* 2024). Milk can be steadily magnetized by immersing a magnetic device in a container of milk and leaving it there for four to six hours. The resulting magnified milk has several uses, including improving milk quality, promoting sexuality, healing ailments and preserving food quality by minimizing heat damage.

It has been demonstrated that food microorganisms inactivate when exposed to OMFs at intensities greater than 2 t, the number of microorganisms was reduced by two log cycles by a single 5-50 t pulse at a frequency of 5-500 kHz (Zhang *et al.,* 2023).

James *et al.,* (2015) conducted a study to investigate how garlic bulbs would react when subjected to oscillating magnetic fields, as compared to freezing them under normal conditions. The results of this study showed substantial cooling in the garlic bulbs, during some of the freezing trials. However, the oscillating magnetic fields had a significant effect on the garlic bulbs over the normal freezing method. Also, the researchers concluded super-cooling was more effective with garlic bulbs if they were frozen at an initial ambient 21 ± 1℃ rather than 4 ± 5 ºC. Lipiec *et al.,* (2005) Studied the effect of oscillating magnetic field pulses on selected oats used for food purposes. The sprouts of the naked oat were submitted to the oscillating magnetic field pulses treatment. The treatment significantly reduced the number of microorganism (bacteria and fungi) colonies. At the same time, the level of polyphenols slightly increased and therefore the antioxidant activity.

Kang *et al.,* (2021) determined the effect of oscillating magnetic field on the inhibition of ice nucleation and its application for supercooling preservation of fresh-cut mango slices. Supercooling probability results indicated that OMF intensities of 50 mT inhibited ice nucleation in supercooled water when stored at the temperature of −11 °C, whereas OMF intensities exceeding 100 mT induced freezing. In this respect, the OMF at the field strength of 50 mT was applied for the supercooling preservation of fresh-cut mango slices, which were preserved in a supercooled state at −5 °C for up to 7 days. Foods with low electrical conductivity need to be oscillated 10-100 times in order to achieve complete disinfection. Effective liquid and powder separation of iron and stainless-steel particles. Compared to powders, smaller quantities can be removed from liquids like milk, butter or whey. A metal detector cannot pick up on the little metal particles found in milk powder (Le *et al.,* 2023).

Membrane Technology

In the modern era, membrane processing plays a vital role in the dairy industry for clarification, concentration, along with separation of particular milk ingredients from milk and milk by products. There are four distinct kinds of membrane filtration processes with different properties commonly used in the dairy industry i.e. microfiltration (MF), nanofiltration (NF), ultrafiltration (UF) and reverse osmosis (RO), Chen *et al.,* (2022). Fractionation of milk can be done by membrane separation technology based on milk components size. By lowering production costs and establishing new sources of income, membrane technology contributes in the improvement of economies of the dairy. The dairy sector has used membrane technologies in a variety of areas including the cheese industry, shelf-life extension of milk, whey and milk protein processing and separation of milk fat and desalting or demineralization of milk by products (Ji *et al.,* 2022).

Reverse osmosis is a membrane filtration process that uses an extremely dense membrane and is powered by high pressure. It concentrates the total solids by allowing only water to pass through the membrane film. Reverse osmosis is usually used in the dairy sector to preconcentrate, concentrate or reduce the volume of milk and whey, recover milk solids and recycle water. Monovalent ions can flow through the membrane structure of nanofiltration, a moderate to high-pressure operated membrane filtration process. The membrane is mostly responsible for the retention of divalent ions (Kwon *et al.,* 2022). The key uses of nanofiltration in the dairy sector include the volume decrement of whey, partial demineralization of whey and whey powders, lactose-free milk and the purification of CIP solutions. A membrane having a medium open structure is used in the moderate pressure-driven ultrafiltration process. The majority of dissolved and some non-dissolved components can pass through it, but the membrane retains bigger components like protein and fat (Mangel *et al.,* 2022).

Katayon *et al.* (2004) achieved a higher removal rate of suspended solids (99.2%) and turbidity (99.73%) in a food wastewater treatment at a lower concentration of Mixed liquor suspended solid (MLSS). Zielińska *et al.,* (2017) conducted an experimental study with microfiltration (MF) and ultrafiltration (UF) alone and with UF/MF combined to treat dairy wastewater. Results showed that MF alone could remove 89 ± 2% chemical oxygen demand (COD) while using the UF process, the removal efficiency of COD increased to 95 ± 1%. Zulaikha *et al.,* (2014) treated restaurant wastewater effluent through sequential filtration from UF to NF and obtained similar removal percentages of COD (97.8%) and turbidity (9.9%). Whey protein concentration (WPC), milk protein concentration, standardization and to enhance the yield of fermented milk products are all common uses of UF in the dairy sector. A membrane filtering method termed microfiltration uses an open-structured membrane and low pressure. While the majority of non-dissolved components are retained by the membrane, it permits dissolved components to pass. Microfiltration is frequently used in the dairy sector to reduce bacteria and spores, lactose reduction, remove fat from milk and whey and to standardize casein and protein (Molina-Hernandez *et al.,* 2025).

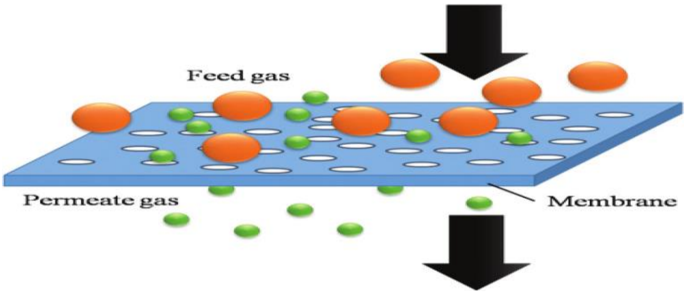

Figure 8: schematic diagram of membrane separation technology (Ji and Zhao2017)

Membrane filtration has already been shown to be useful in the manufacture of ESL milk (Rathnakumar *et al.,* 2023) as well as in the separation of dairy proteins, which yield helpful peptides when hydrolysed. This mechanism has the potential to diminish enzymatic activity. Despite these advances, increased fractionation efficiency and higher throughput are still required (Sawale *et al.,* 2024).

Ozone (O_3) treatment

During the production and storage of agricultural products, mold frequently occur as contaminants that can produce a wide range of secondary metabolites, the most important of which are mycotoxins. To solve these problems, the industry uses various methods, products and processes. One of the latest advances in novel non-thermal technologies for post-harvest inactivation of filamentous fungi and reduction of mycotoxins is ozone treatment figure 9, the effectiveness of these technologies is highly dependent on the fungal species and the structural characteristics of the mycotoxins. New findings related to the inactivation of fungi and mycotoxins underline that for a successful application it is essential to carefully determine and optimize certain key parameters in order to achieve satisfactory results (Molina-Hernandez *et al.,* 2025).

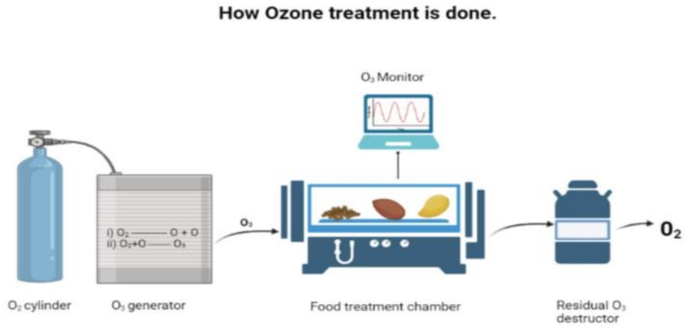

Figure 9: Schematic diagram of ozone treatment technology. (Pandiselvam *et al.,* 2019)

Ozone treatment is considered a safe method for food because it decomposes into oxygen and does not form residues that affect consumers' health. The most common gaseous ozone generators work through Corona Discharge (CD), with 600 to 2 kHz frequencies. Ozone in the aqueous phase (ozonated water) can be used in fresh foods; however, its effect on fungal inactivation is lower due to its low stability in this medium (Davies *et al*., 2021).

In its mechanism of action, Ozone can diffuse through the cell wall of filamentous fungi, reach the cytoplasm and change cell activity (Deng *et al.,* 2020). In the fungal cell envelope, polyunsaturated fatty acids are affected by ozone, whereby the membrane permeability enables electrolytes and the contents of cells to leak out (Ouf and Ali, 2021). One aspect of ozone toxicity is its ability to form reactive oxygen species (ROS), which oxidatively destroy biological components, causing cellular dysfunction or cell death. Additionally, ozone inhibits the expression of genes involved in ergosterol synthesis (Li *et al.,* 2022) and decreases the quantity of −1,3-glucan rather than chitin in the inner layer of the cell wall (Ali and Abdallah, 2024); in addition, O_3 oxidizes sulfhydryl and amino acid groups of enzymes, resulting in a reduction of spore development, germination and causing rapid cell death (Afsah-Hejri *et al.,* 2020). Fungal spores differ in sensitivity to ozone and it seems to be directly linked to spore surface (Pagès *et al.,* 2020) and to differences in their component content, which might accelerate or decrease the toxic action of ozone (Ali and Abdallah, 2024).

Karaca *et al.* (2014) treated lettuce, spinach and parsley with aqueous ozone (12 mg L^{-1}), gaseous ozone (950 µL L^{-1}, 20 min) and chlorinated water (100 mg L^{-1}) to inactivate the inoculated *Escherichia coli* and *Listeria innocua*. Chlorine and ozone washes resulted in average log reductions of 2.9±0.1 and 2.0±0.3 for *E. coli*, while the efficiency of ozone (2.2±0.1 log) was very close to that of chlorine (2.3±0.1 log) on *L. innocua.* Venta *et al.,* (2010) evaluated the impact of gaseous ozone on some physical-chemical parameters and loss during the postharvest period in unripe tomatoes in Cuba. Exposure of green tomatoes to 25 mg m^{-3} ozone for 2 h day^{-1} for 16 days gave the best results in terms of firmness, loss of weight and spoilage, but in this case, the tomatoes had a lower lycopene and ascorbic acid content than the control. Moreover, Chaidez *et al.* (2007) analyzed the impact of immersion or spraying on fresh ripe tomatoes surface-inoculated with S. Typhimurium. Contact times of about 30 and 120 s with 1 and 2 mg L^{-1} ozonated water at 25 ◦C and pH of 7.0 were efficient for reducing S. Typhimurium.

The drawback in non-thermal food processing using ozone treatments is that, Ozone is an unstable gas and decomposes rapidly, so specialized equipment is required to generate it *in situ*, which increases investment and operating costs. In addition, the adaptation of existing production lines, the corrosiveness of ozone towards certain materials and the health risks for operators require rigorous safety and control measures. Accurate ozone dosing is critical to prevent adverse product and environment effects. Excessive ozone exposure can lead to the degradation of proteins, vitamins and lipids, resulting in undesirable compounds and altered sensory properties. Moreover, ozone's limited selectivity can generate undesirable by-products, underscoring the importance of precise dosing and control in ozone applications. On the other hand, batch or semi-continuous operation limits the scalability of ozonation processes or limits them to bulk product storage operations (Molina-Hernandez *et al.,* 2025).

Plasma technology

Cereal and legume proteins, pivotal for human health, significantly influence the quality and stability of processed foods. Despite their importance, the inherent limited functional properties of these natural proteins constrain their utility across various sectors, including the food, packaging and pharmaceutical industries. Enhancing functional attributes of cereal and legume proteins through scientific and technological interventions is essential to broadening their application. Cold plasma (CP) technology, characterized by its non-toxic and non-thermal nature, presents numerous benefits such as low operational temperatures, lack of external chemical reagents and cost-effectiveness. It holds the promise of improving proteins' functionality while maximally retaining their nutritional content (Li *et al.,* 2024).

Grains and legumes are valuable sources of plant proteins, featuring a diverse array of proteins such as gluten, zein, legumin, β-conglycinin, glycinin and prolamins, among others. These proteins significantly contribute to the functional characteristics that are essential for maintaining quality during food processing (Wen *et al.,* 2020). However, these natural proteins may exhibit limitations, such as poor solubility and allergenicity, which restrict their use in the food industry (Huang *et al.,* 2022). To overcome these limitations, food processing commonly employs enzymes and chemical and physical methods to enhance the functional characteristics of proteins. These include solubility, gelation, emulsification and foaming, which are critical to meeting production requirements (Wang *et al.,* 2023). Consequently, there is a growing interest in employing eco-friendly non-thermal methods to modify protein structures and improve their functional characteristics, which has become a research hotspot in food science (Li *et al.,* 2024).

Numerous non-thermal techniques have been developed for protein modification, including high pressure (Wang *et al.,* 2022), ultrasound (Qayum *et al.,* 2023), pulsed electric fields (Osae *et al.,* 2020) and supercritical fluids (Zhang *et al.,* 2020). These methods, which preserve nutritional and sensory qualities by avoiding thermal degradation, have their unique benefits and drawbacks. High pressure, ultrasound and pulsed electric fields are noted for efficiently altering protein conformation while maintaining food quality. However, methods like irradiation and supercritical fluids often require high energy inputs and specialized equipment, making them costly and less accessible. Additionally, certain techniques might induce undesirable changes in protein structures, affecting functional properties and face regulatory and consumer acceptance challenges (Li *et al.,* 2024).

In contrast, cold plasma technology is gaining attention for its low-temperature operation, energy efficiency and ability to preserve heat-sensitive compounds, (Cheng *et al.,* 2021; Akharume *et al.,* 2021). Cold plasma treatment is an innovative technology in the food processing and preservation sectors is primarily employed to deactivate microorganisms and enzymes without heat and chemical additives; hence, it is often termed a "clean and green" technology. However, food quality and safety challenges may arise during cold plasma processing due to potential chemical interactions between the plasma reactive species and food components (Bayati *et al.,* (2024).

Plasma is a collection of various excited atomic, molecular, ionic and radical species that coexist with a variety of other particles, such as electrons, ions, free radicals, reactive oxygen/nitrogen species (RONS), gas atoms, molecules in ground or excited state and electromagnetic radiation (UV photons and visible light) which have a potent oxidizing effect (Laurita *et al.,* 2021). The production of a variety of components is necessary for the antifungal activity and mycotoxin degradation process, including ultraviolet radiation, reactive oxygen species (ROS) like ozone (O3), hydrogen peroxide (H2O2), singlet oxygen (1 O2), peroxyl (ROO•) and hydroxyl radicals (•OH), reactive nitrogen species (RNS) like nitric oxide (NO•), peroxynitrite (ONOO-) or peroxynitrous acid (OON). Although each of these species can act on its own, it has been noted a synergistic interaction of the plasma's constituent (Laurita *et al.,* 2021).

Cold plasma processing has recently attracted increasing interest in the food industries, particularly for heat-sensitive foods (Mollakhalili-Meybodi *et al.,* 2021). The appeal of this technology lies in its nonthermal, multipurpose and environmentally friendly nature (Kopuk *et al.,* 2022). In the food and agriculture sectors, it is mainly used in packaging modification, seed germination enhancement, microbial inactivation, pesticide and mycotoxin degradation (Mehta and Yadav, 2022). Recent studies have also shown that cold plasma treatment can activate antioxidant, enzymes and inactivate undesirable oxidative enzymes, depending on the treatment properties of cold plasma, which can thereby improve the shelf life of foodstuffs. Furthermore, major food pathogens like *Staphylococcus aureus, Salmonella typhimurium and Escherichia coli* have been found to be sensitive to cold plasma treatment (Bangar *et al.,* 2022). The antimicrobial activity can be attributed to the oxidative degradation of cellular lipids, proteins and DNA by reactive oxygen/nitrogen species (ROS and RNS) associated with the cold plasma treatment. However, these reactive species produced through the cold plasma can also interact with macronutrients (proteins, lipids and carbohydrates) and other bioactive molecules in food, leading to various chemical reactions, namely, nitration, nitrosation, hydroxylation, oxidation, sulfoxidation, deamidation, dehydrogenation or hydrogenation and dimerization (Feizollahi *et al.,* 2020). Although most of the current literatures provide the application of plasma technologies on various foods, the chemistry of cold plasma on the quality and structural changes of food components has not been critically reviewed (Sruthi *et al.,* 2022).

Coutinho *et al.,* (2019) increase the consistency of Chocolate milk using cold plasma technology. The plasma flow rates were 10, 20 and 30 mL/min at a temperature of 21–25 ◦C, for 5 min. Cold plasma treatment for 5 min at 20 mL/min gas flow increased particle size (18.29 ±0.81) and consistency (744.39 ±24.19) compared to pasteurized sample (11.51 ±0.42 and 14.83 ±0.08, respectively). Ali *et al.* (2021) reported a reduction of pesticide residues in tomato. Using voltage of 220 V, Treatment time of 15 min, Frequency of 50 kHz and 3 mm distance between the two electrodes. Plasma-activated water provided a valuable solution for reducing chlorothalonil (85 %) and thiram (79 %) pesticide residues on tomato fruit. Korachi *et al.* (2015) studied the milk biological changes using cold plasma technology. Voltage of 9 kV, power supply of 90 mA at a temperature <35 ^{0}C for 20 min. the cold plasma treatment of raw milk for 20 min resulted in a marked increase in total aldehydes (20.8 ±5.1 mg) and a minor effect on the fatty acid composition of raw milk, with a decrease in saturated fatty acids from 64.4 % to 63.6 % initially, followed by an increase to 65.8 %. Polyunsaturated fatty acids decreased from 3.0 % to 2.5 %.

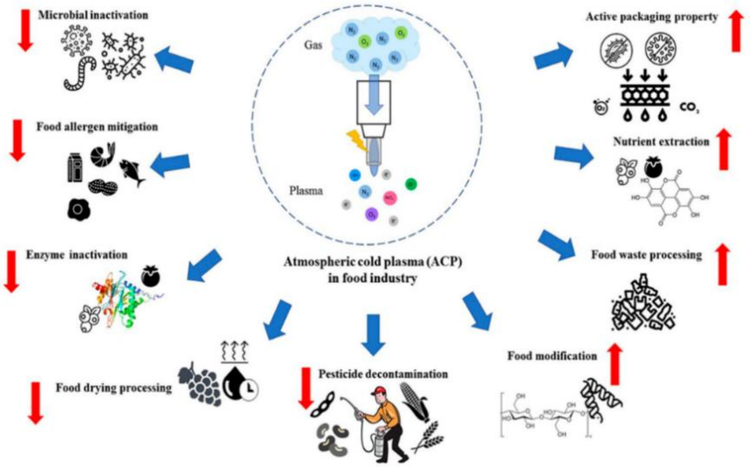

Figure 10: Cold plasma (CP) treatment advancements in food processing (Li *et al.,* 2024)

Plasma, as a unique state of matter, mainly contains a complex mixture of electrons, positively and negatively charged ions, ground or excited states of molecules, free radicals, neutral atoms, heavy particles, UV–visible light photons, heat and electromagnetic radiations (Holubová *et al.,* 2020). In High Temperature Plasma, ions, neutral particles and electrons will be under a thermodynamic equilibrium, which is achieved by heating a gas to sufficiently high temperatures to ionize it. The Low Temperature Plasma (LTP), is typically characterized by having plasma species at low temperatures, which is further categorized as equilibrium and nonequilibrium plasma. Equilibrium plasma is characterized by the presence of local thermodynamic equilibrium among the plasma species and collision processes (Saremnezhad *et al.,* 2021). In equilibrium plasma, heavy particles and electrons will be at almost identical temperatures. Nonequilibrium plasma (well-known as cold plasma) involves a thermodynamic imbalance among electrons and heavy particles (Holubová *et al.,* 2020) and the temperature of the heavy particles is much lower than that of electrons (Saremnezhad *et al.,* 2021).

CONCLUSION

In conclusion, the applications of these new advances in non-thermal food processing such as cold plasma technologies, pulsed electric field, high-pressure processing and ultrasound extraction have demonstrated their colossal potential in various sectors of the food industry. These technologies have paved ways in a new era of food processing, offering a multiple of advantages, such as enhanced nutritional value, increased food safety, improved product quality and extend shelf-life of food products. Moreover, they overtook the traditional heat treatments which is characterized by inherent disadvantages which include nutrient loss and detrimental impacts on sensory attributes. In the dairy industry, these technologies have brought significant improvements. Ultrasound extraction technology has been instrumental in enhancing the texture, stability and functionality of dairy products. The future of non-thermal food processing is wide and promising. There is therefore, the need for researchers to do more work in establishing more accurate operating parameters for each process. Integrating these technologies with artificial intelligence (AI) will also improve their operations in terms of speed, consistency and overall efficiency.

Conflict of interest. The authors declare that they have no conflict of interest.

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