**Food Processing and Preservation using Non-thermal Technologies**

 **Gousia Gani and Raies A Bhat**

*Department of Food Science and Technology, Sher-e-Kashmir University of Agricultural Sciences and Technology (SKUAST-K), Shalimar, India*

Food undergoes various thermal treatments during processing to extend its shelf life. However, these treatments can sometimes lead to a decline in the nutritional and sensory attributes of the food. As global lifestyles evolve, so do people's dietary preferences. Modern consumers now seek unadulterated and safe food options that don't compromise the food's nutritional and sensory qualities. This shift has prompted food experts to focus on developing non-thermal technologies that are ecologically sound, secure, and environmentally friendly.Non-thermal processing involves treating food at temperatures close to room temperature, ensuring that the heat-sensitive nutrients within the food remain undamaged. This stands in contrast to thermal food processing. These innovative non-thermal methods are versatile and applicable to a wide array of foods, including fruits, vegetables, pulses, spices, meat, fish, and more. The prominence of non-thermal technologies in the food sector has markedly grown in recent decades.

**Keywords:** food preservation, ultrasonication. cold plasma, supercritical technology,irradiation,pulsed electric field, high pressure processing, pulsed ultreaviolet technology, ozone, radio frequency and microwave technology, ohmic heating

**Introduction**

Maintaining food quality is a significant consideration during the preservation process. Traditional methods of preserving food involve subjecting it to high temperatures. While this effectively decreases contamination and microbial levels in food, it also leads to unfavorable alterations in the food's composition. These changes encompass the loss of temperature-sensitive nutritional elements, modifications in food texture due to heat, and shifts in the sensory attributes of the food (Hernández-Hernández *et al*., 2019). During thermal processing, edibles are subjected to extended periods of heat exposure, resulting in noticeable alterations in their composition. This, in turn, contributes to the creation of substandard food items (Iqbal *et al.,* 2019). The methods employed for thermal preservation lead to the emergence of harmful chemical agents within food, possessing carcinogenic properties that are detrimental to human health (Oz, 2020). The quantity and nature of these harmful agents are contingent upon the specific thermal technique employed for cooking. Techniques such as microwave cooking and deep fat frying instigate the development of heterocyclic aromatic amines, substances capable of inducing mutagenic transformations within the human body (Oz, 2020). Furthermore, the application of thermal treatment can give rise to moisture loss in food, oxidative changes in lipids, and modifications in the fatty acid composition. Grilling meat, for instance, results in the loss of meat juices containing predominantly saturated lipids stored in adipose tissue. This leads to a reduction in saturated fatty acids and an elevation in polyunsaturated fatty acids in the final product. The presence of polyunsaturated fatty acids renders the end product more susceptible to lipid oxidation, consequently diminishing product quality. This, in turn, imparts an undesirable flavor and diminishes the overall sensory experience (Oz, 2021).

In recent times, there has been a notable increase in consumer awareness concerning food safety. Consumers now have higher expectations for food products that are free from microorganisms, possess excellent nutritional qualities, and offer a satisfying mouthfeel. As a response, food industry experts have been actively seeking alternatives to traditional thermal treatments. The emergence of non-thermal processing methods has garnered attention. These methods involve subjecting food to ambient temperatures for brief periods, typically around 1 minute or less. This approach maintains the nutritional composition of the food, preserves its texture, and retains its desirable mouthfeel (Beyrer *et al.,* 2020).The growing consumer demand for fresh food with extended shelf life and superior sensory attributes has prompted extensive research into non-thermal food treatment (Frewer *et al.,*2011). Unlike thermal methods, which consume substantial energy and can result in lower quality products, non-thermal technologies for food processing and preservation offer advantages that are both consumer- and environmentally-friendly. These non-thermal approaches are also economically viable (Jadhav and Annapure, 2021). Over the past few decades, a range of non-thermal food processing techniques have gained prominence. These include methods such as pulsed electric field treatment, cold plasma treatment, ultrasonication, microwave treatment, supercritical technology, and more. By briefly exposing food to these non-thermal treatments, microbial loads can be significantly reduced, resulting in extended shelf life and improved sensory and textural characteristics (Thirumdas *et al.,* 2014).A significant benefit of non-thermal technologies lies in their superior preservation effects compared to thermal alternatives. The absence of elevated temperatures eliminates the risk of undesired product or by-product formation, both within the food itself and on its surface (Thirumdas *et al.,* 2020). Among the various non-thermal processing methods, pulsed electric field treatment stands out as a widely employed technique within the food industry. It finds particular utility in treating liquid foods such as fruit juices, alcoholic beverages, and nonalcoholic beverages. This method can be directly applied to whole fruits, where it disrupts the cell walls of microorganisms, leading to their deactivation and reduction in microbial load (Vorobiev and Lebovka, 2019). The effectiveness of pulsed electric field treatment depends on factors such as pulse intensity and pulse width, both of which influence the degree of microbial reduction (Niu *et al.,* 2020). Non-thermal processing also holds the capacity to arrest enzymatic activity, thereby preventing the spoilage of fruits and vegetables. Cold plasma technology has found extensive application in enhancing the physiological attributes of proteins and carbohydrates within food, making them suitable for a multitude of applications in food processing. The utilization of gaseous cold plasma processing has yielded improvements in the cooking and textural qualities of grains (Thirumdas *et al.,* 2017). Moreover, it serves to inactivate surface-level microbes on food products. The duration of cold plasma treatment significantly influences the achieved outcomes (Deng *et al.,* 2020).Ultrasonication stands out as an energy-efficient non-thermal method, often employed for the enhancement of processes such as synthesis, extraction, and preservation in the realm of food and related products. Parameters like ultrasonication duty cycle and exposure time yield positive impacts on food characteristics. Skillfully combining duty cycle and exposure time holds promise for crafting safe and nutritionally rich foods through ultrasonication (Bhargava *et al.,* 2021).Additional technologies, including ultra-pressure treatment and irradiation, are harnessed within the food processing domain to ensure food safety with minimal impact on nutritional, textural, and sensory attributes (Tsevdou *et al.,* 2019). These non-thermal treatments lead to a reduction in microbial load by altering bacterial cell membrane structures and destabilizing the helical DNA structure of microbial genetic material. This culminates in the swift demise of microbial cells. Beyond mitigating microbial loads, these non-thermal methods also find application in extracting bioactives from plant and animal sources, with a focus on nutraceutical food applications. These methods intensify nutraceutical component synthesis, facilitate dehydration, and enhance the physicochemical properties of food constituents (Mazzutti *et al.,* 2020).

Despite the manifold benefits offered by these non-thermal technologies in the food sector, their implementation remains largely confined to laboratory settings, with limited adoption within food industries. The comprehension of the mechanisms and functionality of these non-thermal technologies, as well as their effects on food, remains a crucial requirement. Although a substantial body of scientific literature exists on these technologies, it is imperative to concentrate on the current status of non-thermal techniques in the context of food processing industries. This involves assessing their impact on food quality, examining their effects on food components, evaluating the instrumentation integral to these techniques, and addressing the constraints associated with large-scale production, along with potential solutions. Furthermore, exploring the future prospects of these techniques within the realm of food processing industries is of paramount importance. This endeavor will undoubtedly prove invaluable for food scientists and technologists operating in the non-thermal technology domain, given the growing research interest in non-thermal treatment owing to its pronounced advantages over thermal methods.

**Non-thermal technologies**

**Ultrasonication**

Ultrasonication stands out as an emerging non-thermal technology within the food sector, while it already enjoys a well-established status in various other processing domains (Chemat *et al.,* 2011). In simplified terms, ultrasonication involves the propagation of sound waves at frequencies beyond the range of normal human hearing, specifically exceeding 20 kHz (Mason and Cintas, 2007). The passage of ultrasonic waves through a medium induces multiple cycles of expansion and compression within that medium. The presence of air leads to the formation of minuscule cavities, which grow to a predetermined size before collapsing. This collapse generates both substantial energy and localized hot spots, resulting in escalated rates of heat and mass transfer (Bhangu and Ashokkumar, 2016).Ultrasonication has proven effective in expediting chemical synthesis processes for organic compounds, leading to heightened reaction yields, primarily due to the amplified heat and mass transfer brought about by ultrasonication effects. This method utilizes various frequencies, categorized as low-frequency, medium-frequency, and high-frequency ultrasonication, spanning frequency ranges of 20 kHz–100 kHz, 100 kHz−1 MHz, and 1 MHz–100 MHz, respectively (Mason *et al.,* 2015). Low-frequency ultrasonication induces significant shear forces within the medium, while high-frequency ultrasonication generates comparatively milder shear forces. Medium-frequency ultrasonication induces the formation of radical species, rendering it optimal for several sonochemical-assisted processes. However, it's worth noting that the generation of chemical radicals might trigger undesired alterations in food products, such as oxidative changes in lipids and proteins (Delmas and Barthe, 2015).In practice, ultrasonication is executed using an ultrasonic horn, immersed within a liquid solution or juice and exposed to specific treatment frequencies. Alternatively, an ultrasonic bath can be employed, where the food material or packaged products are placed. Sound waves generated within the bath induce ultrasonic effects, yielding the desired alterations in the food matrix (Li *et al.,* 2021).

**Applications**

Within the realm of food processing, the frequency range of 20 kHz–100 kHz finds application in diverse processes such as bioactive extraction, emulsification, cooking, debittering, and intensified synthesis. Jadhav *et al.* (2021) presented a notable example where sonication emerged as an excellent alternative for intensifying lipid synthesis, yielding up to 92% within a mere 6-hour reaction period. The heightened energy levels generated by ultrasonication result in the formation of high-energy regions, thereby expediting mass transfer rates and leading to shorter reaction times. Compared to traditional synthesis methods, ultrasonication-assisted synthesis is characterized by swifter completion (Jadhav and Annapure, 2021). Ultrasonication additionally facilitates interfacial molecule transfer, bolstering the efficiency of bioactive extraction from botanical and animal sources. This process not only augments extraction yields but also enhances the physical and chemical attributes of the extracted compounds. An illustrative study by Sun *et al.* (2020) revealed that ultrasonication-extracted proteins exhibited superior characteristics, including particle size, emulsification capacity, and structural attributes. Particles extracted through ultrasonication, particularly those treated for 30 minutes at 20 kHz, displayed improved emulsifying potential owing to their smaller size and more significant α helix structure. Notably, Cheila *et al.* (2020) designated ultrasonication as an environmentally conscious approach for extracting bioactives from velame leaves. Through indirect ultrasonication, this method enhanced bioactive extraction yield to 94% within a short span of 39.5 minutes. Ultrasonication has further demonstrated its efficacy in intensifying the extraction of oil from olive fruit, soybean, and flaxseed (Cavallo *et al.,* 2020). This technique is also harnessed for the extraction of bioactive compounds from various plant components, fruits, and vegetables (Qin *et al.,* 2021). Ultrasonic-assisted filtration stands out as a remarkably effective process with significant relevance to the dairy and beverage sectors. Notably, in cheese production, membrane filtration emerges as a pivotal technique for achieving complete milk protein separation from other milk solids (Saxena *et al.,* 2009). Ultrasonication also contributes to the optimization of freezing, drying, and thawing procedures applied to food products (Cheng *et al.,* 2014). Mothibe *et al.* (2014)) employed ultrasonication as an initial step prior to apple dehydration and observed a reduction in drying time along with improved texture and reduced water activity in the dried apples. Their findings highlighted favorable outcomes with treatment at 25 kHz for 15 minutes. Increasing treatment duration led to higher losses of soluble solids from the apples. This ultrasound-assisted process not only accelerates drying but also enhances and maintains texture post-rehydration. Rehydration refers to the reabsorption of moisture by dried foods (Tian *et al.,* 2016). Tao *et al.* (2019) demonstrated that ultrasound-assisted rehydration of white cabbage exhibited a notably quicker rehydration rate compared to untreated samples. Similar observations were documented for carrot and green pepper rehydration (Szadzinska *et al.,* 2017). Furthermore, ultrasonication serves as a beneficial pretreatment for convective drying and freeze drying (Rojas *et al.,* 2020).

Ultrasonication's applicability extends to the preservation of food products through brine solutions. Carcel *et al.* (2007) detailed the use of ultrasound to treat pork loin with a brine solution, leading to an augmented brine concentration, improved color, and enhanced texture of the pork loin pieces compared to untreated samples. This technology also proves valuable for degassing carbonated beverages and offers an alternative to pasteurization and sterilization for microbial load reduction in food and food products (Rojas *et al.,* 2020).Ultrasonication's prowess within the food sector is evident across multiple crucial domains, encompassing food preservation, extraction processes, intensified synthesis, and the refinement of food's physical and chemical attributes. The limited technical knowledge surrounding ultrasonication and the limited consumer awareness about ultrasonically-processed foods have posed challenges to its commercial adoption within the food industry. However, comprehensive assessments on bulk food are essential to comprehend the effects thoroughly and pave the way for industrial-scale implementation.

**Cold Plasma Technology**

Plasma, constituting the fourth fundamental state of matter after solid, liquid, and gas, gained its nomenclature from Langmuir in 1925 (Irving, 1948). As the kinetic energy within solids intensifies, molecules experience elevated thermal states, transitioning from solid to liquid form. This progression continues, causing liquids to transition to gases. Subsequent to this energy increase, intermolecular structures start to disintegrate. Once the energy content of gases surpasses a critical threshold, gas molecules undergo ionization (Luo, 1998). This ionization phenomenon gives rise to plasma, thus earning its designation as the fourth state of matter.In essence, plasma treatment segregates into two primary categories: thermal plasma and cold plasma (nonthermal). Thermal plasma harnesses high temperatures to yield substantial energy. Conversely, cold plasma, also referred to as nonthermal plasma, operates within the temperature range of 25–65°C (Niemira, 2012). The ionization of gas precipitates the formation of free radicals, including ions and electrons. The composition of reactive species in plasma is significantly influenced by the composition of the ionized gas itself (Alves Filho *et al.,* 2019). Commonly employed gases in plasma generation encompass argon, helium, oxygen, nitrogen, and air (Keener and Misra, 2016). These gases are subjected to varying forms of energy input, including thermal, electrical, and magnetic fields, culminating in the formation of plasma replete with positive ions, negative ions, and reactive species such as ozone and singlet oxygen (O) (Misra and Roopesh, 2019).Diverse fields, including chemistry, chemical engineering, textiles, electronics, surface coatings, pharmaceuticals, and food sectors, have harnessed plasma's versatile nature for various applications (Roth *et al.,* 2007). Within the domain of food, cold plasma presents opportunities for reducing microbial loads on food and food surfaces, enhancing the attributes of food constituents like lipids and proteins, sterilizing food processing equipment, deactivating enzymes responsible for food spoilage, treating food packaging materials, and addressing wastewater concerns (Chizoba Ekezie *et al.,* 2017). Cold plasma operates at nearly ambient temperatures and achieves microbial inactivation without the reliance on elevated temperatures. This temperature proximity ensures the prevention of thermal damage to heat-sensitive food materials (Chizoba Ekezie *et al.,* 2017).

**Applications**

The efficacy of microbial inactivation within cold plasma is attributed to the impact of reactive species on microbial cells. These reactive species inflict damage upon the DNA of cells, induce protein oxidation, and compromise the structural integrity of microbial components, culminating in cell death (Phan *et al.,* 2017). Lin *et al.* (2020) noted the inhibitory effect of cold nitrogen plasma on *Salmonella enterica* serovar *Typhimurium* biofilms situated on the outer surface of eggshells. Their study found that a treatment duration of 2 minutes at 600 W reduced the catabolic and anabolic activities of *S. enterica* serovar *Typhimurium* by 82.2%. Similarly, Devi *et al.* (2017) demonstrated significant reductions of 97.9% and 99.3% in the growth of fungal species, including *Aspergillus parasiticus* and *Aspergillus flavus*, respectively, on groundnut surfaces when treated with 60 W plasma power.

Within the food sector, atmospheric pressure cold plasma is frequently utilized in conjunction with other gases like helium and argon. Notably, Bang *et al.* (2020) recently explored the combination of antimicrobial washing and in-package cold plasma treatment for mandarin oranges, resulting in microbial load reduction. Treatment involving 26 to 27 kV for 1 to 4 minutes led to the inactivation of *Penicillium digitatum.* The synergistic effect of antimicrobial solution washing and cold plasma treatment successfully decreased the *P. digitatum* load within the packaging while preserving the texture, sensory attributes, and nutritional qualities of the oranges. Furthermore, the treated oranges exhibited reduced ripening damage in comparison to untreated counterparts. Liao *et al.*(2018) detailed the utilization of cold atmospheric pressure-activated water and plasma-activated ice as innovative mediums for seafood cold storage. Shrimps stored in plasma-activated water exhibited extended shelf life attributed to bacterial inactivation, with no discernible alterations in texture. Shrimp samples stored in plasma-treated ice showcased a total volatile base nitrogen value lower than 20 mg/100 g on the ninth day, contrasting with the 30 mg/100 g for samples stored in untreated water or ice.Cold plasma treatment also proves effective in combating pathogenic microorganisms present in both raw and processed food items. A recent study conducted by Gan *et al.* (2021) illustrated the prowess of cold plasma against *Escherichia coli* and *Saccharomyces cerevisiae* within chokeberry juice. In this research, a 4-minute treatment led to reductions of 2.27 and 1.23 log CFU/ml for E. coli and *S. cerevisiae,* respectively. This treatment showcased a higher efficacy against *E. coli* inactivation compared to *S. cerevisiae.* Similar efforts targeting *E. coli* inactivation were also documented by Shah *et al.* (2019).Further applications of cold plasma encompass the disinfection of food processing equipment surfaces to eliminate microbial loads before food processing. Hou *et al.* (2019) delved into the impact of atmospheric pressure cold plasma on bacterial inactivation and the quality of blueberry juice. In this research, a 6-minute cold plasma exposure resulted in a substantial 7.2 log CFU/ml reduction in *Bacillus spp.* within the juice.These studies collectively underscore the multifaceted potential of cold plasma technology in preserving food quality, enhancing safety, and extending shelf life. Brief exposure times have exhibited a positive correlation with color retention and the preservation of bioactive components in juices. Analogous outcomes have been observed in studies involving fresh tomato juice (Starek *et al.,* 2019), cloudy apple juice (Illera *et al.,* 2019), nectars from apple, tomato, orange, sour cherry, and whey grape (Amaral *et al.,* 2018). Cold plasma has also made strides in the realm of meat preservation by curbing microbial loads. Roh *et al.* (2020) explored the impact of a 3.5-minute cold plasma treatment on pathogenic microbes within chicken breast, yielding reductions of 3.9 log CFU/g for E. coli, 3.5 log CFU/g for *Listeria monocytogenes,* and 2.2 log CFU/g for Tulane virus. Similar results were documented for Salmonella inactivation in chicken breast (Moutiq *et al.,* 2020), as well as the microbial load within sea snail (Lin *et al.,* 2020).

The potential of this technology extends to enhancing the physical and chemical attributes of food constituents (Bulbul *et al.,* 2019). This includes augmenting the functionality and applicability of carbohydrates and proteins within the food context. In a recent study by Jahromi *et al.* (2020), granulated sodium caseinate underwent treatment at 10 kHz for durations of 0, 2.5, 5, and 10 minutes. Increasing treatment durations resulted in improved physical and chemical properties. Notably, protein structure unfolding led to heightened protein hydrophilicity, increasing water solubility from 20.6% to 30.28%. Tensile strength witnessed an increment from 5.04 MPa to 7.17 MPa for the 10-minute treatment, slightly decreasing to 4.73 MPa at 15 minutes.The impact of cold plasma on milk protein, among other compounds, is detailed by Sharma *et al.* (2020). While cold plasma harbors various reactive species, it is noteworthy that these reactive species may contribute to lipid oxidation processes during storage. Despite its numerous advantages, this technology's influence on lipid oxidation serves as a point of consideration. Gao *et al*. (2019) emphasized that cold plasma treatment at 70 kV for a duration of 180 seconds may trigger lipid oxidation during storage. This phenomenon was evidenced by the rise in thiobarbituric acid-reactive substances (TBARS) values, which increased from 1.43 mg MDA/kg to 2.48 mg MDA/kg when refrigerated for 5 days. For context, the control sample of chicken patties exhibited a TBARS value of 0.37 mg MDA/kg. In the TBARS assay, malondialdehyde (MDA) is quantified. MDA emerges as a byproduct arising from lipid peroxidation processes. The reaction of MDA with thiobarbituric acid produces a pink chromogen recognized as TBARS. The oxidative deterioration of lipids in food can be regulated by modifying treatment conditions. This might involve exposing food to plasma for shorter durations or incorporating antioxidants to mitigate the detrimental effects of cold plasma on lipid content in food. Notably, foods containing higher lipid levels can be subjected to briefer cold plasma exposure times compared to foods with lower lipid content (Gavahian *et al.,* 2018). This strategy helps in addressing the potential lipid oxidation concerns associated with cold plasma treatment in food processing.

**Plasma for packaging treatment**

Cold plasma induces a variety of physical and chemical transformations at the interface between the plasma and polymers, which can be harnessed to modify the surface properties of packaging materials. This modification includes the impartation of selective and adjustable surface energies to polymers utilized in packaging, leading to enhancements in various properties. These improvements encompass barrier and migration attributes, adhesion/anti-adhesion characteristics, hydrophobicity, sealability, printability, and the polymer's ability to withstand mechanical stress (Pankaj*et al.,* 2013). Microorganisms adhering to polymer surfaces can undergo inactivation through reactions induced by gas plasma. However, treated materials can experience a decline in these properties, referred to as 'aging' over time. This aging process is attributed to the inward diffusion, agglomeration, or sublimation of low molecular weight organic molecules, the repetition or reorientation of polymer chains, and the migration of additives from the bulk to the surface (Pankaj*et al.,* 2013). This phenomenon can be mitigated by utilizing gases like methane and oxygen, or other suitable gas mixtures, for cold plasma treatment.

Cold plasma treatment is applied for sterilizing packaging materials and decontaminating materials within packages. This includes materials such as PET foils, polystyrene, polyethylene (LDPE, HDPE), polypropylene, and multi-layer packaging like PET/PVDC/LDPE. Additionally, cold plasma treatment is employed for immobilizing antimicrobial substances like chitosan, silver, and triclosan onto films (Keener et al., 2012). Research has demonstrated its effectiveness against microorganisms such as *E. coli,L. monocytogenes*, *S. aureus*, and *P. aeruginosa*(Pankaj*et al.,* 2013).

**Supercritical Technology**

Supercritical technology harnesses supercritical fluids, which offer a viable alternative to organic solvents utilized in various processes (Temelli *et al.,* 2012). When a fluid surpasses its critical temperature and pressure, it enters a supercritical state, becoming a supercritical fluid. This state blends characteristics of both gas and liquid: it possesses liquid-like density and gas-like diffusivity and viscosity (Brunner, 2004). Supercritical fluids exhibit improved properties akin to liquids, making them effective solvents that facilitate accelerated mass transfer during the extraction of bioactive compounds from diverse plant and animal sources.The attributes of these fluids can be modified by altering temperature and pressure conditions. While multiple fluids serve in supercritical processes, carbon dioxide stands out due to its suitability as an excellent supercritical fluid in food processing. This is attributed to its ability to achieve a supercritical state at relatively moderate temperature and pressure values (31.1°C and 7.4 MPa, respectively). Across the food industry, supercritical fluids find widespread employment in diverse applications such as extraction, microbial inactivation, and enhancement of mass transfer in synthesis. Notably, the foremost application of supercritical technology lies in extraction processes.

**Applications**

Supercritical carbon dioxide is a preferred choice for extraction due to its non-toxic nature and ease of separation from the final product (Deotale *et al.,* 2021). Natural bioactive compounds, often sensitive to temperature and oxygen, can be extracted with enhanced quality using supercritical carbon dioxide. This is attributed to the inherently low temperature of supercritical extraction in the presence of carbon dioxide, which eliminates the possibility of oxygen presence. As a result, the extracted material attains a high level of quality and can serve as a functional ingredient in various nutraceutical formulations.Recent studies conducted by Lefebvre *et al.* (2020) highlight supercritical carbon dioxide as a powerful tool for selectively extracting antioxidants from rosemary. Operating at a temperature of 25°C and a pressure of 20 MPa, the conditions proved ideal, ensuring the purity of the extracted products remained intact. Another study by Santos *et al.* (2020) delved into the extraction of bioactives from feijoa leaves, employing both supercritical and pressurized liquid extraction methods. The authors found that while pressurized extraction yielded a higher amount of antioxidant and antibacterial components, these components lacked effectiveness in their function. In contrast, supercritical extraction of antioxidant and antibacterial components at 55°C and 30 MPa exhibited greater efficacy against pathogenic bacteria, including *E. coli.* his technique finds application in extracting functional and nutraceutical ingredients from various sources, including microalgae (Molino *et al.,* 2020), fruit seed oils (Ferrentino *et al.,* 2020), olive oil (Al-Otoom *et al*., 2014), ginger oil (Salea *et al.,* 2017), corn germ oil, green coffee oil (De Oliveira *et al.,* 2014), essential oils (Priyanka and Khanam, 2018), as well as bioactives like carotenoids, lycopene, astaxanthin, anthocyanins, and quercetin (Pinto *et al.,* 2020). These extracted components serve as valuable constituents for nutraceutical formulations. The use of supercritical carbon dioxide for extraction has been prevalent in the food processing industry for several years.

In addition, supercritical technology is applied for mitigating microbial loads in food products. The original attributes and sensory qualities of food are preserved by using low operating temperatures of supercritical treatments(Koubaa *et al.,* 2018). The treatment lowers the pH within bacterial cells, causing cell rupture or bursting. This, in turn, deactivates bacterial enzymes responsible for both catabolism and anabolism. Consequently, bacterial cells perish, leading to a reduction in microbial populations within food and related products (Spilimbergo and Bertucco, 2003). Supercritical technology finds extensive use in preserving fresh agricultural products, including fruits, vegetables, and their juices (Silva *et al.,* 2020). In a study by Bertolini *et al.* (2020), the impact of supercritical carbon dioxide on microbial reduction in pomegranate juice was examined, and results were compared to traditional pasteurization and high-pressure processing. The researchers noted that pomegranate juice treated with supercritical carbon dioxide exhibited bacterial growth below detectable levels even after 28 days of storage. During this treatment, the total phenolic content increased by 22%, in contrast to a 15% decrease observed in traditional pasteurization. Moreover, the antioxidant activity of phenolic components was higher in the supercritical-treated juice compared to high-pressure processing and traditional pasteurization. Similar positive outcomes were observed for preserving coconut water (Cappelletti *et al.,* 2014), sports drinks (Cappelletti *et al.,* 2015), and liquid food (Smigic *et al*., 2019).The application of supercritical fluids extends to the preservation of ground meat as well. (Yu and Iwahashi, 2019) treated ground beef with high-pressure carbon dioxide at 1 MPa pressure for 26 hours and noted a reduction in microbial load.A comprehensive analysis of the literature underscores the promising potential of supercritical technology within the food processing domain. Its utility extends beyond extraction, encompassing the preservation and enhancement of physiological properties in food constituents. This, in turn, positions them as valuable functional ingredients for use in functional and nutraceutical formulations.

**Irradiation**

Irradiation is a technique employed to sterilize or extend the shelf life of various food products by subjecting them to controlled exposure of low doses of radiation. This physical process utilizes sources of gamma rays, X-rays, or high-speed electrons to treat prepackaged or bulk food items. Gamma rays of high energy, X-rays, and accelerated high-speed electrons are approved forms of radiation for use in the food processing industry. These rays penetrate the food and can be utilized to preserve the food and enhance its quality.Commonly, foods are exposed to gamma radiation using a radioisotope source, high-speed electrons generated by an electron accelerator, or X-rays. This method allows for preservation and quality enhancement due to the significant penetration capability of these rays. The quantity of ionizing radiation absorbed by food during exposure is termed the "radiation absorbed dose" (rad) and is measured in rads or Grays (Liu *et al.,* 2011). For instance, radionuclides like Cobalt-60 and Cesium-137 are employed to generate gamma rays with high energy. Cobalt-60, being a radioactive element, serves as a primary source of these high-energy gamma rays that are used for food irradiation purposes. Gamma rays, which are electromagnetic waves or photons, are emitted from the nucleus of an atom. These gamma rays possess sufficient energy to dislodge electrons from molecules within food, resulting in the conversion of these molecules into electrically charged ions. It's important to note that these rays cannot induce radioactivity in treated food because their energy isn't sufficient to dislodge neutrons from the nuclei of molecules. The intensity of radiation dose varies based on factors such as the thickness of the food, its moisture content, and other relevant factors.External variables, including temperature, the presence or absence of oxygen, and storage conditions subsequent to irradiation, can impact the efficiency of radiation treatment (Barbosa-Canovas and Bermudez-Aguirre, 2016). X-rays with energies up to 5 MeV are utilized in the food processing sector, while high-speed electrons with an energy of 10 MeV find applications in various aspects of food industries (Farkas, 2005). An advantage of irradiation is that it doesn't raise the temperature of the food being treated, which ensures that components sensitive to heat in the food remain undamaged (Bashir *et al.,*2021).The penetration capacity of high-speed 10-MeV electrons can extend up to 39 mm in foods with high moisture content, offering effective treatment. Both X-rays and gamma rays have the ability to deeply penetrate food materials (Bashir *et al.,*2021). The resultant impact of these radiations includes the unwinding of DNA, damage to nucleic acids, and ionization of water molecules, leading to oxidative damage in microbial cells. This cumulative effect contributes to a reduction in the microbial load of the food (Castell-Perez and Moreira, 2021).

**Effect of Irradiation on food**

Irradiation of food has limited impact on the quality of proteins, lipids, and carbohydrates present. Importantly, the process does not notably affect minerals within the food. Overall, irradiation induces only minor chemical changes in food, which have negligible effects on its nutritional value. When moist food is irradiated while frozen and in the absence of oxygen, the resulting chemical alterations are significantly reduced by about 80%. This means that irradiating food to a cumulative dose of 50 kGy at 30°C is roughly equivalent to irradiating it to a dose of 10 kGy at or below room temperature.Irradiation proves effective in controlling foodborne parasites that cause trichinosis, with doses ranging from 1 to 10 kGy. Similarly, a minimum dose of 0.15 kGy can prevent insect infestations in dried fish. In some cases, irradiation is a necessary phytosanitary requirement for agricultural products destined for export. An advantageous characteristic of radiation decontamination is its ability to treat packaged foods even when they are frozen (Robichaud *et al.,* 2020). This feature underscores the versatility and utility of irradiation in food safety and preservation.

**Applications**

Irradiation holds the potential to enhance the safety of meat and meat products by effectively eliminating various pathogens and parasites. In addition to this pathogen reduction, irradiation contributes to better preservation of the nutritional quality of food, thereby extending its storage life. This technique is often referred to as "cold sterilization" or "electronic pasteurization". Using lower doses of irradiation, it's possible to deactivate over 90% of bacteria and extend the shelf life of meat products. This is particularly effective with low dose rates around 10 Gy. In the range of 20 to 150 Gy, irradiation can prevent the sprouting of plants like potatoes, onions, garlic, shallots, and yams. The biological alterations induced by radiation significantly reduce or entirely prevent sprouting in these products. Similarly, the ripening of fruits can be delayed in the dose range of 0.11 kGy due to enzymatic changes in plant tissues.

Irradiation primarily finds application in the food processing sector for the preservation of various food products. It demonstrates effectiveness against pathogenic microorganisms such as *E. coli*, *Staphylococcus*, and *Salmonella* (Robichaud *et al.,* 2020). The overall effect of irradiation on food safety, preservation, and shelf life extension makes it a valuable tool in the food industry. Modifying the intensity of irradiation demonstrates more potent effects on the inactivation of microbes in food. Irradiation is also a technique used in the preservation of meat, enabling its storage for extended periods. For example, ready-to-cook chicken subjected to gamma radiation intensities of 0, 1.5, 3, and 4.5 kGy exhibited noteworthy outcomes in terms of *L*. *monocytogenes*, *E. coli*, and *Salmonella typhimurium* inactivation. The D10 values for these pathogens were 0.680, 0.397, and 0.601, respectively. Additionally, ready-to-eat chicken maintained favorable sensory and textural characteristics even after 15 days of storage (Fallah *et al.,* 2010).Irradiation technology contributes to enhancing the shelf life and freshness of food by deactivating microbes responsible for foodborne illnesses (Shalaby *et al.,* 2016). However, it's important to note that irradiation at high doses can lead to undesirable changes in certain foods, particularly those where color and lipids are defining factors. These changes can lead to consumer rejection, as observed in foods like meat and cereals (Li *et al.,* 2017). To strike a balance between microbial inactivation and maintaining food quality, irradiation is often conducted at low doses, complemented by the use of antimicrobial agents (Ghabraie *et al.,* 2016).Irradiation has been effectively employed for microbial inactivation, as seen in cases such as reducing microbial load in fresh pasta (Cassares *et al.,* 2020), as well as enhancing the physical and chemical attributes of various foods, including wheat (Bhat *et al*., 2020), garlic bulbs (Sharma *et al.,* 2020), grape juice (Carvalho Mesquita *et al.,* 2020), mangosteen fruit (Syauqi *et al.,* 2020), and apple juice (Lim*et al.,* 2021). This underscores the versatility of irradiation in improving food safety, preservation, and quality. Indeed, despite the numerous advantages of irradiation technology, particularly in food preservation, low consumer acceptance remains a significant obstacle. This reluctance is often rooted in misconceptions associated with the term "irradiation." For many who aren't familiar with food technology, the term may evoke concerns about the generation of carcinogens in food due to its similarity to "radiation therapy" (Carvalho Mesquita *et al.,* 2020). This misperception contributes to the reluctance of consumers to embrace irradiation-processed food. This consumer hesitancy poses a considerable challenge to the widespread adoption of this technology within the food industry. Overcoming this obstacle requires efforts to shift consumer perspectives and encourage them to consider irradiated food as a viable option. This might involve educational campaigns to dispel myths about irradiation and provide accurate information about its benefits and safety.Furthermore, simplifying and making irradiation technology more accessible through reliable instrumentation could play a crucial role in improving consumer acceptance. By addressing consumer concerns and increasing their understanding of the technology's benefits, the market for irradiated food has the potential to grow in the coming years.

**Pulsed Electric Field**

Pulsed electric field (PEF) processing is a non-thermal method employed for food preservation, primarily focusing on the inactivation of microorganisms. This technique involves applying brief bursts of high electric fields to food products. These bursts have durations ranging from microseconds to milliseconds, and the electric field intensities fall within the range of 10-80 kV/cm. The processing time is determined by multiplying the number of pulses with the effective pulsation duration.The food product is positioned between a pair of electrodes, and the process revolves around delivering pulsed electrical currents through the product. The gap between the electrodes in the PEF chamber is referred to as the treatment gap. The high voltage used generates an electric field that effectively deactivates microorganisms (Garriga *et al.,* 2004). The palpitated electric field leads to the poration of cell membranes, resulting in permeability changes in microorganisms, industrial materials, or animal tissues.The electroporation technique, encompassing PEF, can be utilized across a wide array of food processing and bioprocessing applications, often requiring minimal energy input. PEF technology offers several advantages over heat treatments. It effectively eliminates microorganisms while preserving the natural color, flavor, texture, and nutritional value of the untreated food. This makes it particularly suitable for safeguarding liquid and semi-liquid foods while simultaneously neutralizing microorganisms and generating valuable ingredients (Gomez-Lopez*et al.,* 2007).

**Working**

The PEF technology operates by delivering pulsating electrical power to a product positioned between a pair of electrodes that enclose the treatment gap within the PEF chamber. The setup consists of several components, including a high voltage pulse generator, a treatment chamber, a suitable fluid handling system, and the requisite monitoring and control mechanisms.The two electrodes are connected through a nonconductive material to prevent electrical flow between them. The food product is placed within the treatment chamber, which can have a static or continuous design. The electrodes are exposed to high-voltage electrical pulses generated by the apparatus. These electrical pulses are then conducted with high intensity to the product situated between the electrodes.The electric field generated within the food product exerts a force per unit charge that triggers the irreversible breakdown of microorganisms' cell membranes. This process causes the cell membranes of microorganisms to break down dielectrically, leading to their deactivation. Simultaneously, this breakdown opens channels for interactions with charged food molecules (Ekezie*et al*., 2018). In essence, PEF disrupts the structural integrity of microorganisms' cell membranes, rendering them unable to function and resulting in their deactivation.

**Applications**

PEF finds extensive application in extending the shelf life of food by reducing the microbial load. Various types of fish, including fresh, frozen, dried, brined, and marinated fish, can undergo pulsed electric field treatment. The electroporation of fish tissue enhances mass transport processes like moisture transport and removal. This leads to improved drying, brining, and marinating of fish products. Achieving fish cell disintegration typically requires a field strength of 1.0 to 3.0 kV/cm and an energy delivery of 3 to 10 kJ/kg. This disintegration, facilitated by the applied pulsed electric field, not only enhances production methods but also elevates product quality. Moreover, it contributes to the deactivation of parasites like nematodes (Gomez-Lopez*et al.,* 2007).The application of PEF technology extends beyond shelf-life extension. It accelerates food product drying, reducing processing times and energy consumption. This technique can be applied to various food items, including fruits, vegetables, potatoes, and meat. Another advantage of electroporation lies in its capacity to enhance extraction procedures. By employing PEF, extraction and pressing yields are increased, evident in the improved extraction of fruit juice, vegetable oil, protein, and algae oil.In the realm of freezing food products, PEF technology offers time and energy efficiency. The process accelerates freezing rates through cell disintegration. Cellular water exits the cells, initiating ice formation outside the cells. This accelerated freezing process results in smaller ice crystals, contributing to enhanced quality in frozen food products (Ekezie *et al.,* 2018). The versatility of PEF in various food processing applications underscores its potential to improve both the efficiency and quality of food production. A recent study conducted by Preetha et al. (2021) showcased the effectiveness of PEF with an intensity of 5.6 W/cm² in countering E. coli in flowable foods like pineapple and orange juice, as well as coconut water. The reduction in E. coli load was significant, with decreases of 4.5, 4, and 5.3 log CFU/ml for pineapple juice, orange juice, and coconut water, respectively. Similar favorable outcomes have been observed with moderate PEF intensity in microbial inactivation for fruit juices (Timmermans *et al*., 2019). While larger microbial cells are susceptible to PEF treatment, smaller ones may display resistance and remain unaffected (Toepfl et al., 2006).Beyond microbial inactivation, PEF has proven effective in deactivating food spoilage enzymes. Studies have demonstrated enzyme inactivation in apple and carrot juice (Mannozzi *et al.,* 2019) and pine nuts (Liang *et al.,* 2017). López-Gámez *et al.* (2020) investigated the impact of PEF treatment at 580 J/kg on carrots, revealing an increased anabolism in the production of phenolic compounds over a 36-hour storage period.

PEF technology has also found extensive use in extracting bioactive compounds from various natural sources. The treatment enhances the extraction of functional components with high purity, facilitating their use in nutraceutical applications within the food industry without necessitating further purification.In addition to its established applications in microbial inactivation, extraction, and physiochemical alterations, PEF has expanded into unit operations such as dehydration and freezing. Liu *et al*. (2020) reported that PEF with an intensity of 0.6 kV/cm and an exposure time of 0.1 seconds led to a 55% reduction in carrot drying time at 25°C and a 33% reduction at 90°C. Furthermore, PEF technology is being employed in the freezing of food, enhancing food quality during the subsequent thawing process (Li *et al.,* 2020). These diverse applications continue to underscore the versatility and potential of PEF in various aspects of food processing and preservation. PEF treatment brings about a range of benefits, including an enhancement in the coefficient of diffusion for water prior to drying. This, in turn, leads to reduced time requirements for both freezing and drying food products. Furthermore, PEF treatment contributes to maintaining the quality of rehydrated and thawed food over an extended period of time.PEF technology is also harnessed to improve the physical and chemical properties of essential food components like polysaccharides and proteins (Zhang *et al.,* 2017). It has proven effective in modifying substances such as potato starch (Chen *et al.,* 2020) and oat flour (Duque *et al.,* 2020), enhancing their properties.The application of PEF can also accelerate reaction rates due to its high intensity. This heightened intensity facilitates improved heat transfer, thereby increasing mass transfer in various reactions such as esterification (Lin *et al.,* 2012) and chelation (Zhang et al., 2017).Given the numerous positive effects of PEF on food products, it stands as a valuable non-thermal treatment method. However, there remains a need for the development of high-strength PEF instrumentation suitable for commercial applications. This technological advancement would further pave the way for widespread utilization of PEF in the food industry.

**High Pressure Processing (HPP)**

High Pressure Processing (HPP), also referred to as 'cold pasteurization,' is a technique that involves placing sealed or pre-packaged food products within a vessel and subjecting them to pressures typically ranging between 300 MPa to 600 MPa, using purified water, for a short duration at cold or low temperatures.The application of high pressure leads to the inactivation of a wide range of microorganisms including bacteria, viruses, yeasts, molds, and parasites. Additionally, it deactivates food enzymes such as polyphenol oxidase and lipoxygenase. The mechanism of action involves the prevention of undesirable changes primarily attributed to the structural rearrangement of proteins, as covalent bonds remain intact (Mujica-Paz *et al*., 2011). The primary forces and bonds impacted by pressure include van der Waals forces, electrostatic interactions, and hydrogen bonds (Mujica-Paz *et al.,* 2011).To enhance the efficiency of HPP, the optimization of process parameters is crucial. Factors such as temperature, applied pressure, holding time within the vessel, target microorganisms and pathogens, and food composition (including proteins, lipids, carbohydrates, added solutes, and water activity inducing a shielding effect) can be adjusted to improve the effectiveness of the process (Balamurugan *et al.,*2017). The versatility and effectiveness of HPP make it a valuable technology for preserving the quality and safety of various food products.

**Mechanism of Pressure Treatment**

In each High Pressure Processing (HPP) cycle, the process commences with a pressurization phase wherein the pressure is gradually increased. The actual processing operation can be conducted with or without the application of heat. For this procedure, the food product needs to be packaged in a flexible or semi-flexible pouch capable of withstanding extremely high pressures.The subsequent step involves immersing the packaged product in a fluid that serves as a pressure-transmitting medium. Water is commonly used for this purpose, but other liquids like castor oil, silicone oil, ethanol, or glycol can also be employed individually or in various combinations with water. The choice of fluid should align with the manufacturer's recommendations to prevent corrosion of the inner vessel (Dong *et al.,* 2020).During the pressure processing phase, a phenomenon known as adiabatic heating, causes the product to experience a rise in temperature. The extent of this temperature increase is influenced by factors such as the type of fluid used, the rate of pressurization, the initial temperature, and the pressure applied. Once the process is initiated, a hydraulic pump generates pressure in the hydraulic fluid, which is then evenly transmitted to the packaged food product from all directions. This approach, characterized by its instantaneous and uniform pressure application, is unaffected by the food's size or geometry. Consequently, the overall processing time can be reduced (Perera *et al.,* 2010).This technique is applicable to both liquid foods and foods with a certain moisture content. The structural integrity of the food remains intact even at high pressures due to the uniform and simultaneous application of pressure from all directions. HPP, with its ability to maintain the structural and textural qualities of food, holds promise as an effective food preservation method.

**Applications**

High Hydrostatic Pressure (HHP) treatment has demonstrated its effectiveness in deactivating microorganisms across a wide array of food products. This includes processed fruits, meat and meat products, and dairy items, which provide conducive environments for microbial growth.A recent study by Bulut and Karatzas (2021) explored the efficacy of HHP against *E. coli* in liquid food. In this study, orange juice was first frozen at −80°C, followed by HHP treatment at 250 MPa for 900 seconds. The HHP treatment yielded reductions in microbial load of 4.88, 4.15, and 4.61 log CFU/ml for orange juice with pH values of 3.2, 4.5, and 5.8, respectively. Similarly, Cap *et al.* (2020) investigated the impact of HHP treatment on Salmonella spp. in meat. A pressure of 500 MPa applied for 60 seconds was adequate for inactivating *Salmonella spp*. in a sample of chicken breast without compromising the sensory attributes of the meat.Cava *et al.* (2020) demonstrated that dry-cured sausage can be preserved for over 60 days through the inactivation of *L. monocytogenes*. This was achieved with an HHP treatment of 600 MPa for 480 seconds, resulting in a reduction of 3.2 log CFU/g of *L. monocytogenes*. Importantly, there was no oxidative damage observed in the lipids and proteins of the food during the 60-day preservation period. One noteworthy aspect of HHP is that it does not induce lipid oxidation, thus avoiding the development of rancidity in food products.These studies underscore the effectiveness of HHP in preserving food safety while maintaining the organoleptic attributes and nutritional quality of the treated products. Indeed, the efficacy of HHP extends beyond microbial reduction; it can also be harnessed for the extraction of a range of valuable compounds with nutraceutical properties from various food sources. de Jesus *et al.* (2020) highlighted that HHP is effective in extracting antioxidants, anthocyanins, and phenolic compounds, each possessing unique nutraceutical qualities. Similar extraction studies have been conducted on tomato waste (Nincevi *et al.,* 2020), grape pomace (Cascaes Teles *et al.,* 2020), red microalgae (Suwal *et al.,* 2019), gooseberry juice egg and yolk (Naderi *et al.,* 2017).

Moreover, HHP technology has been shown to enhance the physical and chemical attributes of fermented juices, amplifying the presence of bioactive components within these products (Rios-Corripio *et al.,* 2020). Notably, HHP can be applied to the preservation of human breast milk (Malinowska-Panczyk *et al.,* 2020), signifying its potential impact in health and nutrition.Furthermore, HHP plays a role in enhancing the technical and functional properties of milk proteins, making them more versatile for use in functional and nutraceutical foods (Carullo *et al.,* 2020).These diverse applications highlight the versatility of HHP in not only microbial inactivation but also in the extraction and enrichment of antioxidants, phenolic compounds, bioactives, and functional components from various sources. This indicates its potential for application in nutraceutical, pharmaceutical, health, and food industries. However, the widespread adoption of HHP faces technical challenges in constructing units that are suitable for high-volume food treatment. As a result, there are currently limited HHP-treated food products available in the market. Despite this, the technology's promising capabilities continue to pave the way for its potential integration into various sectors.

**Pulsed Ultraviolet Technology**

Pulsed ultraviolet (UV) technology is an economical and non-thermal method used to reduce the microbial load on the surface of food materials. This technology utilizes different segments of the UV spectrum, including UV-A (320–400 nm), UV-B (280–320 nm), and UV-C (200–280 nm), to indirectly expose food to radiation.UV-C, with its wavelengths between 200 and 280 nm, is particularly effective in microbial inactivation. When food is exposed to UV-C radiation, these short wavelengths are absorbed by the nucleic acids within microbial cells. As a result, the absorbed photons cause breaks in the bonds and interlinking between thymine and pyrimidine of different DNA strands. This leads to the formation of dimers of pyrimidine, which in turn hinder DNA transcription and translation. Consequently, the genetic material becomes dysfunctional, ultimately resulting in the death of microbial cells (Guerrero-Beltrán *et al*., 2021).UV-A and UV-B photons, on the other hand, primarily act by damaging cellular membranes, proteins, and other organelles within microbial cells. This cumulative effect leads to the demise of microorganisms present in the food (Koutchma *et al.,* 2021).Pulsed UV technology, with its ability to target microorganisms on food surfaces, offers a non-thermal approach to microbial reduction, making it an attractive option in the food processing industry.

**Applications**

Pulsed UV technology is gaining popularity as one of the prominent nonthermal methods in the food processing sector. Its cost-effectiveness makes it an attractive option for experimentation on a pilot scale for microbial inactivation. A recent pilot-scale study conducted by Fenoglio *et al*. (2020) focused on UV-C inactivation of pathogenic microorganisms. The study demonstrated that a UV-C intensity of 390 mJ/cm2 effectively deactivated pathogenic bacteria in fruit juices. The results revealed impressive log reductions of 6.3 for *Lactobacillus plantarum,* 5.1 log CFU for *E. coli*, and 5.5 for *S. cerevisiae*.Similar studies have explored microbial inactivation in fruit juices, including apple juice (Xiang *et al.,* 2020), orange juice (Ferreira *et al.,* 2020), and cantaloupe melon juice (Fundo *et al.,* 2019). Ultraviolet inactivation is also commonly employed to target microorganisms in milk and milk products (Delorme *et al.,* 2020).Furthermore, ultraviolet radiation exhibits beneficial effects on the chemical and physical properties of food. Kumar *et al.* (2020) demonstrated that UV-C radiation at a wavelength of 254 nm was effective in enhancing the physical and chemical properties of wheat protein. This suggests that UV-C radiation holds potential for diverse applications within the food industry.Given its effectiveness in microbial inactivation and potential to influence food properties positively, pulsed UV technology is proving to be a versatile tool with applications in various aspects of food processing.

Recent studies have revealed that ultraviolet (UV) treatment applied to fresh fruits and vegetables post-harvest not only leads to microbial inactivation but also enhances the antioxidant content and its activity (Dyshlyuk *et al*., 2020). Moreover, UV treatment has been explored for its potential to reduce toxins in food (Zhu*et al.,* 2021). While UV treatment offers several positive effects on food, certain studies in the literature have indicated that high-dose UV treatment can lead to diminished color and adverse changes in the texture of solid food (Orlowska *et al*., 2013).Food products exhibit varying textures with uneven and rough surfaces, which can hinder the penetration of radiation into the food material, thereby reducing the efficiency of the inactivation process. To enhance the effectiveness of the process and achieve higher microbial inactivation rates, non-thermal techniques are often coupled or combined with UV treatment. This approach may involve the use of antibacterial agents along with UV treatment (Jeon and Ha, 2020).Given its straightforward implementation, UV technology has become a well-established non-thermal method adopted by the food processing industry to extend the shelf life of food products. The impact of UV treatment can be further amplified by coupling it with other processes to bring about desired alterations. UV treatment offers a range of benefits for food processing, including microbial inactivation, enhancement of antioxidant content, and reduction of toxins. While challenges exist, such as potential color and texture changes, these can be mitigated through strategies like process coupling or the use of complementary antibacterial agents. This underscores the versatility of UV technology as a viable option in the quest for safer and longer-lasting food products.

**Ozone**

Ozone, denoted chemically as O3, consists of three oxygen molecules. This colorless gas possesses a distinctive odor and forms when molecular oxygen (O2) interacts with singlet O. In gaseous form, ozone is denser than air. However, due to its high reactivity and instability, ozone cannot be stored and must be generated on-site as needed. Ozone is widely utilized as a potent antibacterial agent against various bacteria in the food industry. It can be employed in its gaseous state or mixed with water to create ozonated water.The mechanisms through which ozone induces microbial cell death are diverse. Ozone causes alterations in the permeability of cell membranes, thus damaging them. Furthermore, ozone is recognized for its ability to disrupt the structure of proteins, leading to the dysfunction of microbial enzymes. This disruption in enzymatic activity affects microbial metabolism and eventually culminates in the demise of the microbial cells (Oner *et al*., 2016).

**Applications**

Gimenez *et al.* (2021) conducted a study on the efficacy of ozone against L. monocytogenes in meat. Their results indicated that treatment with 280 mg O3/m3 for 5 hours, using ozone pulses with a 10-minute interval over a duration of 30 minutes, was effective. However, prolonged treatment times led to changes in meat color and oxidative damage to its lipids. To address this issue and minimize exposure time, ozone treatment is often combined with other food additives or treatments to enhance its effectiveness without causing damage to the food. Similar approaches have been explored for Salmonella inactivation (Mohammad *et al.,* 2020) and the control of spoilage microorganisms (Taiye Mustapha *et al.,* 2020).Post-harvest ozone treatment of fruits has been shown to enhance their physical, chemical, and textural attributes while reducing microbial load during storage in modified atmosphere packaging for up to 15 days (Pinto *et al.,* 2020). Ozone treatment has also found application in the reduction of microbes in fruit juices and in the inactivation of toxins present in food (Porto *et al.,* 2020). While research literature showcases the potential of ozone in the food industry, these studies are typically conducted on a laboratory scale and have not been commercialized. Ozone is utilized in the industry for disinfecting processing equipment. However, due to its high reactivity with various components in food, ozone can induce undesirable changes. For instance, it can lead to lipid oxidation. Therefore, combining ozone treatment with other techniques is often recommended.In-depth research is needed to determine optimal ozone doses that minimize undesirable changes in food while maintaining its acceptability. Efforts should be directed towards increasing consumer acceptance of ozone-treated food, which could drive the food industry to adopt this technology for food processing and market ozone-treated products.

**Radio Frequency (RF) and Microwave Technology**

RF energy, spanning from 10 MHz to 50 MHz, and microwave energy at frequencies such as 2450 MHz and 915 MHz, exhibit properties similar to visible light. They possess the ability to be concentrated into beams and conveyed through empty conduits. These forms of energy, categorized as non-ionizing radiation, can interact with various materials based on their dielectric characteristics, either undergoing reflection or absorption processes. Notably, microwaves can even traverse packaging materials like glass, ceramics, and thermoplastics without being hindered.

Upon direct interaction with dielectric substances like food, electromagnetic energy prompts the generation of heat through dipole rotation and ion polarization. The microwave spectrum is characterized by rapid alternation of polarity, with changes occurring at an astonishing frequency of 2.45 x 109 cycles per second for a frequency of 2450 MHz. This swift polarity shift compels polar molecules, for instance water molecules, to undergo rotation. Consequently, this rotational motion within the molecules results in friction between them and their surroundings, culminating in the production of heat.Industries and laboratories commonly employ two distinct techniques for generating heat using RF technology: the free running oscillator approach and the 50 Ω systems method (Zhang *et al*., 2020). When considering the application at hand, the choice between these methods is influenced by factors like penetration depth. RF energy boasts greater penetration capabilities compared to microwaves due to its utilization of longer wavelengths. This property makes it suitable for achieving more even and uniform heating, along with enhanced control over product temperature. Consequently, depending on specific use cases, RF energy emerges as the preferred option (Altemimi *et al*., 2019).

**Applications**

The primary and foremost application of RF energy lies in the pasteurization of eggs, a process crucial for preserving the integrity of the eggshell while effectively neutralizing Salmonella bacteria (up to 99.999% efficacy). This procedure achieves these goals without compromising the quality of the egg white (albumin) and ensuring the desired final yolk quality, along with preserving functional attributes (Geveke *et al.,* 2016). RF technology finds further utility in various domains, including drying operations, where its advantages manifest as uniform heating, substantial penetration depth, and heightened control over product temperature stability.

In the food industry, RF technology is employed for diverse tasks such as heating bread, post-baking procedures within the biscuit manufacturing sector, and pasteurization of yogurt. It proves especially effective for treating fresh products characterized by high water activity and for processing meat. This technology has been successfully implemented with a range of products, including wheat flour, peaches, fruit juices, crackers, pepper spice, almonds, potatoes, rice, lentils, legumes, and walnuts, to name a few. The intention behind these applications is to neutralize a diverse array of microorganisms, as evidenced in studies concerning agricultural materials, where RF heating leads to a reduction of pathogens by 4 log cycles. Notable outcomes include the inactivation of microorganisms like *Bacillus cereus* and *Clostridium perfringens* in pork meat, *E. coli* and *Listeria innocua* in milk, and *Clostridium sporogenes* in scrambled eggs (Altemini *et al.,* 2019). RF energy also finds its place in postharvest applications, specifically for the pasteurization and disinfection of agricultural commodities. It can effectively replace traditional practices like fumigation and seed treatment. Additionally, RF technology serves in processes such as thawing and tempering of fish and meat, sterilization and pasteurization (particularly for low-moisture foods), roasting peanuts, blanching apples, mustard, and vegetables. Particularly noteworthy is its ability to enhance ascorbic acid content, thereby maximizing Vitamin C levels in treated produce (Altemini *et al.,* 2019). Within the realm of packaging, RF technology intersects with Radio Frequency Identification (RFID) sensors, which exhibit selective capabilities in detecting freshness and bacterial growth in foods like milk and fish (Potyrailo*et al.,* 2012). This dynamic field is advancing through the integration of computer simulations for optimization, applicable across a multitude of scenarios (Altemini *et al.,* 2019).

**Ohmic heating**

Ohmic heating of food occurs within a continuous system and is particularly effective for products that encompass a broad pH spectrum and possess larger particles, traditionally challenging to heat-process due to insufficient heat penetration (Indiarto and Rezaharsamto, 2020). In this method, heat is generated by passing alternating current (AC) with frequencies of 50 Hz to 60 Hz through a conducting solution, often brine. The product is positioned between electrodes (usually composed of materials like Cr/Mn/Ni/Fe) that transmit the AC current. Various configurations such as batch, transverse, or collinear ohmic setups can be employed (Indiarto and Rezaharsamto, 2020). Through the Joule effect, the electrical resistance of the food brings about volumetric heating, exhibiting remarkable efficiency.Throughout the ohmic heating process, both micro and macro structural changes become apparent in food products. These changes encompass moisture migration, starch gelatinization, and protein denaturation, contingent on process conditions and the composition of the treated material. Beyond thermal effects, non-thermal consequences like electroporation and electrical breakdown contribute to altering cells and tissues, thereby influencing the texture of certain food items, especially fresh foods. To strike a balance between texture softening kinetics and other advantageous factors, the optimization of parameters in the ohmic process, including electrical specifications, process time, temperature, and product formulations, is imperative (Feng *et al*., 2019).

One of the primary benefits of ohmic heating lies in its ability to consistently heat both the interior and exterior of food products, with potential enhancements facilitated by pre-treatments. This results in uniform heating of solid pieces and liquids, thereby minimizing heat-induced damage (Indiarto and Rezaharsamto, 2020). The applications of ohmic heating are diverse and include the extraction of components like inulin, tepurang fruit oil, anthocyanins, and phenolic compounds (achieved by inducing cell-membrane electro-permeability), as well as processes such as pasteurization, blanching, fermentation, sterilization, dehydration, thawing, and enzyme inactivation (including enzymes like pectin methylesterase, peroxidase, tyrosinase, polyphenol oxidase, lipoxygenase, lycopene, and β carotene), and evaporation (Indiarto and Rezaharsamto, 2020).The technology effectively inactivates pathogenic microbes (such as *E. coli, Zygosaccharomyces rouxii, Alicyclobacillus acidoterrestris, Listeria monocytogenes, Salmonella typhimurium*) and enzymes, enhances the thawing process, and safeguards the functional, nutritional, and sensory attributes of food.Ohmic heating also finds utility as an alternative technique in sweet whey processing and the production of various dairy items. It can modify factors like water absorption index, water solubility index, thermal properties, and pasting properties of food components (Kaur and Singh, 2016). This versatile approach has been modeled and applied to an array of food products, including fruits, vegetables, cereals, solid-liquid mixtures, eggs, fish products, and meat products (Indiarto and Rezaharsamto, 2020).Despite its potential, ohmic heating, along with High Pressure Processing (HPP), has emerged as an early 21st-century technology that, while revolutionary in concept, hasn't garnered widespread appreciation and adoption (Kaur and Singh, 2016).

**Applications**

The primary advantage of ohmic heating lies in its ability to ensure consistent heating throughout the interior and exterior of food products, aided at times by pre-treatments. This results in uniform heating for both solid pieces and liquids, minimizing heat-induced damage (Indiarto *et al.,* 2020). The technique finds application in various processes including the extraction of components such as inulin, tepurang fruit oil, anthocyanins, and phenolic compounds, achieved by inducing cell-membrane electro-permeability. Additionally, it is utilized for tasks like pasteurization, blanching, fermentation, sterilization, dehydration, thawing, and the inactivation of enzymes (such as pectin methylesterase, peroxidase, tyrosinase, polyphenol oxidase, lipoxygenase, lycopene, and β-carotene), as well as for evaporation (Indiarto *et al.,* 2020). Pathogenic microbes like *E. coli*, *Zygosaccharomyces rouxii*, *Alicyclobacillus acidoterrestri*, *Listeria monocytogenes*, *Salmonella typhimurium*, and enzymes (like tyrosinase, polyphenol oxidase, and lipoxygenase) can be effectively inactivated. Furthermore, it enhances the thawing process and helps maintain the functional, nutritional, and sensory attributes of food. Ohmic heating serves as an alternative technique for sweet whey processing and the processing of dairy products, affecting properties such as water absorption index, water solubility index, thermal characteristics, and pasting properties of food components (Costa *et al.,* 2018). This technology has been successfully applied across a spectrum of food products such as fruits, vegetables, cereals, solid-liquid mixtures, eggs, fish products, and meat products (Costa *et al.,* 2018). Despite its potential, ohmic heating, along with high-pressure processing (HPP), introduced as revolutionary techniques in the 21st century for continuous food heating, has not garnered significant attention and acceptance so far (Costa *et al.,* 2018).

**Conclusion**

Non-thermal treatments have emerged as a focal point of research within the food industry, driven by consumer demands for safe and nutrient-rich foods devoid of harmful microorganisms. These treatments involve exposing food products to short durations of non-thermal processing at ambient temperatures. The use of brief exposure time and low temperature, non-thermal methods safeguard heat-sensitive nutrients, maintain food texture, and prevent the formation of toxic compounds caused by heat. As a result, these techniques offer consumers processed foods that are both fresh and rich in nutrition, boasting appealing color and flavor profiles. However, this coin has two sides: while these methods carry advantages, they also present potential drawbacks.

Extended exposure or higher intensity treatment with non-thermal technologies could yield undesirable alterations in food, including lipid oxidation and the loss of color and flavor. Nonetheless, when compared to traditional thermal processing, these technologies hold numerous benefits. The advancement of bulk food processing equipment employing non-thermal methods, a deeper understanding of underlying mechanisms, the establishment of processing standards, and dispelling consumer misconceptions are all essential steps in propelling the adoption of non-thermal technologies within the food industry. By systematically overcoming these challenges, non-thermal methods can expand their potential for growth and commercialization, facilitating the production of safe, nutritious, and appealing food products for consumers.

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