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

**Gousia Gani1, Raies A Bhat2  and Mahmood Ahmad Khan3**

*1Department of Food Science and Technology, Sher-e-Kashmir University of Agricultural Sciences and Technology (SKUAST-K), Shalimar, India*

*3Assistant Professor Agronomy, KVK-Kupwara, Sher-e-Kashmir University of Agricultural Sciences and Technology (SKUAST-K)*

*3Department of Public Administration, Lovely Professional University, Punjab, India*

Food often undergoes different thermal treatments during processing to prolong its shelf life. Nevertheless, these processing methods can, at times, result in a reduction in the nutritional content and sensory characteristics 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 environment friendly. Such processing treatments involve 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 like fruits, vegetables, pulses, meat, fish, spices and more. In the food sector, the prominence of such technologies has markedly grown in recent decades.

**Keywords:** Food preservation, ultrasonication, cold plasma, supercritical technology, irradiation, pulsed electric field, high pressure processing, pulsed ultraviolet technology, ozone treatment, radio frequency, 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 characteristics of food product (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. Substances capable of inducing mutagenic transformations within the human body, such as heterocyclic aromatic amines, are instigated by techniques such as microwave cooking and deep fat frying (Oz, 2020). Furthermore, the application of thermal treatment can give rise to moisture loss in food, modifications in the fatty acid composition and oxidative changes in food lipids. 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).

Over the past few years, consumer awareness regarding food safety has notably increased. 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 preserves food texture, maintains nutritional composition of the food and retains its desirable mouthfeel (Beyrer *et al.,* 2020). In-depth investigations into non-thermal food treatment has been prompted by the increasing consumer demand for fresh food with superior sensory attributes and extended shelf life (Frewer *et al.,* 2011). Unlike thermal methods, which consume substantial energy and can result in lower quality products, these techniques for processing and preserving food offer advantages that are both consumer and environment friendly. These non-thermal approaches are also economically viable (Jadhav and Annapure, 2021). In recent decades, various non-thermal food processing technologies have become increasingly prominent and these include methods such as ultrasonication, pulsed electric field treatment, supercritical technology, cold plasma treatment, microwave treatment 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). Pulsed electric field treatment is a widely employed technique within the food industry among the various non-thermal processing approaches. It finds particular utility in treating foods having liquid consistency such as alcoholic beverages, non-alcoholic beverages and fruit juices. This method can be directly applied to whole fruits, where it leads to deactivation and reduction in microbial load by disrupting their cell walls (Vorobiev and Lebovka, 2019). Factors such as pulse intensity and pulse width influence the degree of microbial reduction, thus determine the effectiveness of pulsed electric field treatment (Niu *et al.,* 2020). Additionally, non-thermal processing has the ability to halt enzymatic activity thereby preventing the spoilage of fruits and vegetables. Extensive applications of cold plasma technique have been discovered in enhancing the physiological attributes of carbohydrates and proteins within food, rendering them suitable for numerous food processing applications. The utilization of gaseous cold plasma processing has led to enhancements in the textural and cooking qualities of grains (Thirumdas *et al.,* 2017). Moreover, it serves to inactivate surface-level microbes on food products and the achieved outcomes are significantly influenced by duration of cold plasma treatment (Deng *et al.,* 2020). An energy-efficient and non-thermal method, ultrasonication, often employed for enhancing processes such as preservation, extraction and synthesis in the realm of food and related products. Parameters like exposure time and ultrasonication duty cycle 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 irradiation and ultra-pressure treatment are harnessed within the food processing domain to ensure food safety with minimal impact on textural, sensory and nutritional 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 animal and plant 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).

Although these non-thermal technologies offer numerous benefits in the food sector and their implementation remains largely confined to laboratory settings, with limited adoption within food industries. Understanding the mechanisms and functionality of these non-thermal technologies, along with their effects on food, remains an essential prerequisite. However, a substantial body of scientific literature exists on these technologies, it is imperative to concentrate on the current status of non-thermal techniques within 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 technologists and scientists operating in the domain of non-thermal technology, given the growing research interest in non-thermal treatment owing to its pronounced advantages over thermal methods.

**Non-thermal technologies**

**Ultrasonication**

Ultrasonication is emerging as a notable non-thermal technology in the food sector, despite its well-established status in various other processing fields (Chemat *et al.,* 2011). In simpler terms, ultrasonication entails the transmission of sound waves at frequencies beyond the range of human hearing, typically surpassing 20 kHz (Mason and Cintas, 2007). This process involves the medium undergoing multiple cycles of expansion and compression as ultrasonic waves pass through it. 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 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 lipid and protein oxidation (Delmas and Barthe, 2015). In practice, ultrasonication is executed by employing 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 food matrices (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, cooking, emulsification, intensified synthesis and debittering. 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 animal and botanical sources. This method not only augments extraction yields but also enhances the physico-chemical attributes of the substances obtained. An illustrative study by Sun *et al.* (2020) revealed that ultrasonication-extracted proteins exhibited special 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) identified ultrasonication as an environmentally conscious method for extracting bioactive compounds 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 oil extraction from soybean, flaxseed, and olive fruit (Cavallo *et al.,* 2020). This technique is also harnessed for extracting the bioactives from various plant components, vegetables and fruits (Qin *et al.,* 2021). Ultrasonic-assisted filtration stands out as a remarkably effective process with significant relevance to the beverage and dairy sectors. Notably, membrane filtration emerges as a pivotal technique for achieving complete separation of milk protein from other milk solids in cheese production (Saxena *et al.,* 2009). This method also contributes to the optimization of freezing, drying, and thawing procedures applied to food products (Cheng *et al.,* 2014). Mothibe *et al.* (2014) utilized 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 apples. The use of ultrasound in this process not only speeds up the drying process but also improves and preserves the texture of the product after rehydration. Rehydration is the process of dried foods reabsorbing moisture (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 freeze drying and convective drying (Rojas *et al.,* 2020).

Ultrasonication finds practical use in preserving food items using saline solutions. Carcel *et al.* (2007) provided a comprehensive account of employing ultrasound to process pork loin with a saline solution, resulting in increased brine concentration, enhanced color, and improved texture of the pork loin portions when compared to untreated samples. This technology also demonstrates its worth in removing gas from carbonated beverages and serves as a substitute for pasteurization and sterilization to reduce microbial load in various food items (Rojas *et al.,* 2020). Ultrasonication's prowess within the food sector is evident across multiple crucial domains encompassing extraction processes, food preservation, refinement of food's physical and chemical attributes and intensified synthesis. Challenges have arisen in the widespread adoption of ultrasonication within the food industry due to both limited technical understanding of the process and a lack of consumer awareness regarding ultrasonically-processed foods. 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, which constitutes the fourth fundamental state of matter following 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, this technique segregates into two primary categories: cold plasma (nonthermal) and thermal plasma. Cold plasma, also referred to as nonthermal plasma, operates within the temperature range of 25–65°C (Niemira, 2012), while as thermal plasma harnesses high temperatures to yield substantial energy. Ionization of gas precipitates the formation of free radicals, including electrons and ions. The composition of the ionized gas itself significantly influences the composition of reactive species in plasma (Alves Filho *et al.,* 2019). Commonlyemployed gases in plasma generation encompass helium, argon, nitrogen, oxygen, and air (Keener and Misra, 2016). These gases are subjected to varying forms of energy input, including electrical, magnetic, and thermal fields, culminating in the formation of plasma replete with negative ions, positive ions, and reactive species such as singlet oxygen (O) and ozone (Misra and Roopesh, 2019). Diverse fields, including chemical engineering, chemistry, textiles, surface coatings, pharmaceuticals, electronics 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 components like proteins and lipids, sterilizing food processing equipment, deactivating enzymes responsible for food spoilage, addressing wastewater concerns and treating food packaging materials (Chizoba Ekezie *et al.,* 2017). Cold plasma operates at nearly ambient temperatures and achieves microbial inactivation without the reliance on elevated temperatures. To prevent thermal damage to heat-sensitive food materials, this temperature proximity is ensured (Chizoba Ekezie *et al.,* 2017).

**Applications**

Microbial inactivation in cold plasma is attributed to the impact of reactive species on microbial cells, resulting in damage to DNA, oxidation of protein, and structural integrity compromise, ultimately causing cell death (Phan *et al.,* 2017). Lin *et al.* (2020) noted that cold nitrogen plasma had an inhibitory effect on *Salmonella enterica serovar Typhimurium* biofilms located on the outer surfaces of eggshells. Their study showed that a 2-minute treatment at 600 W reduced the catabolic and anabolic activities of *S. enterica serovar Typhimurium* by 82.2%. Likewise, Devi *et al.* (2017) conducted research demonstrating 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.

Cold plasma at atmospheric pressure is commonly used within the food industry, often in combination with other gases such as argon and helium. Recently, Bang *et al*. (2020) conducted research that notably delved into the synergy of antimicrobial washing and in-package cold plasma treatment for mandarin oranges. This combined approach effectively reduced microbial load. Specifically, applying a voltage of 26 to 27 kV for durations ranging from 1 to 4 minutes resulted in the inactivation of *Penicillium digitatum.* The synergistic effect of cold plasma treatment and antimicrobial solution washing successfully decreased the *P. digitatum* load within the packaging while preserving the sensorial, nutritional and textural attributes of the oranges. Furthermore, treated oranges exhibited reduced ripening damage in comparison to untreated counterparts. Liao *et al.* (2018) provided a comprehensive account of their exploration into novel mediums for cold storage of seafood, employing cold atmospheric pressure-activated water and plasma-activated ice. The storage of shrimps in plasma-activated water resulted in a prolonged shelf life, primarily attributed to the elimination of bacteria, while preserving the original texture of the product. Shrimp samples stored in plasma-treated ice exhibited a total volatile base nitrogen value of less than 20 mg/100 g on the ninth day, in stark contrast to the 30 mg/100 g value observed in samples stored in untreated water or ice. Furthermore, it is worth noting that cold plasma treatment has proven to be highly effective in combating pathogenic microorganisms in both raw and processed food items. Gan *et al.* (2021) conducted a study and illustrated the prowess of cold plasma against *Saccharomyces cerevisiae* and *Escherichia coli* within chokeberry juice. In this research, a 4-minute treatment led to reductions of 1.23 and 2.27 log CFU/ml for *S. cerevisiae* and *E. coli,* respectively. This treatment exhibited higher efficacy against *E. coli* inactivation compared to *S. cerevisiae.* Similar efforts targeting *E. coli* inactivation were also documented by Shah *et al.* (2019). Furthermore, cold plasma applications encompass the disinfection of food processing equipment surfaces to eliminate microbial loads before food processing. Hou *et al.* (2019) explored the impact of atmospheric pressure cold plasma on the quality of blueberry juice and bacterial inactivation. 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 this technique 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 reaches towards improving the physico-chemical characteristics of food components (Bulbul *et al.,* 2019). This includes augmenting the functionality and applicability of carbohydrates and proteins within the food context. According to a recent investigation 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, the unfolding of protein structures resulted in an increase in the hydrophilic nature of the proteins, thereby enhancing their water solubility. This solubility improved from 20.6% to 30.28%. Additionally, the tensile strength experienced a rise, reaching 7.17 MPa after a 10-minute treatment, although it slightly decreased to 4.73 MPa at the 15-minute mark. Sharma *et al.* (2020) provide a comprehensive analysis of the effects of cold plasma on milk proteins and various other compounds. It's worth mentioning that cold plasma contains various reactive species, which might play a role in the oxidation of lipids 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 subjecting a 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 TBARS assay, the quantification of malondialdehyde (MDA) is carried out. MDA is produced as a byproduct during lipid peroxidation processes. When MDA reacts with thiobarbituric acid, it generates a pink chromogen called TBARS. To control the oxidative degradation of lipids in food, adjustments can be made to the treatment conditions. This could entail exposing the food to plasma for shorter periods or introducing antioxidants to alleviate the adverse impact of cold plasma on the lipid content in food. Notably, foods with 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**

A variety of physical and chemical transformations are induced by cold plasma at the interface between the plasma and polymers, which can be utilized to enhance the surface characteristics 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 enhancements encompass properties related to barriers and migration, adhesion or anti-adhesion qualities, hydrophobicity, sealability, printability, and the polymer's capacity to endure 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. The aging process can be mitigated by utilizing gases like methane and oxygen, or other suitable gas mixtures for cold plasma treatment. This process is attributed to factors such as the agglomeration, inward diffusion, the repetition or reorientation of polymer chains, sublimation of low molecular weight organic molecules and the migration of additives from the bulk to the surface (Pankaj *et al.,* 2013).

Cold plasma treatment finds application in the sterilization of packaging materials and the decontamination of materials enclosed within packages. This encompasses various materials, including PET foils, polystyrene, polyethylene (LDPE, HDPE), polypropylene, and multi-layer packaging such as 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 including *L. monocytogenes*, *E. coli,* *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 thresholds, it transitions into a supercritical state, becoming a supercritical fluid. This state combines features of both gases and liquids: it possesses a density resembling that of a liquid and exhibits the diffusivity and viscosity typically associated with gases (Brunner, 2004). Supercritical fluids showcase enhanced properties similar to liquids, which make them efficient solvents that expedite the mass transfer process when extracting bioactive compounds from various plant and animal sources. These fluid characteristics can be adjusted by manipulating temperature and pressure conditions. While several fluids are employed in supercritical processes, carbon dioxide stands out due to its suitability as an exceptional supercritical fluid for food processing. This is due to its capacity to attain a supercritical state at relatively moderate temperature and pressure values (31.1°C and 7.4 MPa, respectively). Within the food industry, supercritical fluids find extensive usage in diverse applications, including microbial inactivation, enhancement of mass transfer and extraction. 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. Consequently, the extracted substance achieves a notable degree of excellence and can function as a key component in diverse nutraceutical formulations. Recent research carried out by Lefebvre *et al.* (2020) underscores supercritical carbon dioxide as a potent method for selectively isolating 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. In a separate investigation conducted by Santos *et al.* (2020), they explored the retrieval of bioactive compounds from feijoa leaves, utilizing two distinct extraction techniques: supercritical extraction and pressurized liquid extraction. The study revealed that pressurized extraction resulted in a greater quantity of antioxidant and antibacterial constituents; however, these constituents exhibited diminished functionality. Conversely, the supercritical extraction process, conducted at 55°C and 30 MPa, demonstrated heightened effectiveness in combatting pathogenic bacteria, such as *E. coli*, with its extracted antioxidant and antibacterial components*.* This technique finds application in extracting nutraceutical and functional 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. Supercritical carbon dioxide extraction has been widely employed in the food processing industry for many 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 meant for both anabolism and catabolism. Consequently, bacterial cells perish, leading to a reduction in microbial populations within food and related products (Spilimbergo and Bertucco, 2003). Supercritical technology plays a significant role in preserving fresh agricultural products, such as fruits, vegetables, and their juices, as highlighted by Silva et al. (2020). In a study conducted by Bertolini et al. (2020), they investigated the effects of supercritical carbon dioxide on microbial reduction in pomegranate juice, comparing the outcomes with traditional pasteurization and high-pressure processing methods. The researchers observed that pomegranate juice treated with supercritical carbon dioxide exhibited bacterial levels below the threshold of detection, even after 28 days of storage. Additionally, this treatment led to a 22% increase in the total phenolic content, while traditional pasteurization resulted in a 15% decrease. n comparison to high-pressure processing and traditional pasteurization, the supercritical-treated juice exhibited significantly higher antioxidant activity in its phenolic components. 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 potential of supercritical fluids in food preservation is not limited to fruits and vegetables; it also extends to ground meat. In a study conducted by Yu and Iwahashi (2019), ground beef was subjected to high-pressure carbon dioxide at a pressure of 1 MPa for 26 hours, resulting in a noticeable reduction in microbial load. A comprehensive review of the literature further emphasizes the promising applications of supercritical technology in the field of food processing. 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. High-energy gamma rays, X-rays, and rapidly accelerated electrons are authorized forms of radiation employed in the food processing industry. These rays have the capacity to penetrate food items and are utilized to preserve and enhance their quality. Typically, foods undergo exposure to gamma radiation via 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 amount of ionizing radiation that food absorbs during exposure is referred to as the "radiation absorbed dose" (rad) and is quantified 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, a radioactive element, serves as a primary source of these high-energy gamma rays employed in food irradiation applications. 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 presence or absence of oxygen, temperature and storage conditions subsequent to irradiation, can impact the efficiency of radiation treatment (Barbosa-Canovas and Bermudez-Aguirre, 2016). In the food processing sector, X-rays with energies of up to 5 MeV are harnessed, and high-speed electrons with an energy level of 10 MeV are applied across various facets of the food industry (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). High-speed electrons with an energy level of 10 MeV possess the capability to penetrate foods with high moisture content effectively, with a penetration depth extending up to 39 mm. Both X-rays and gamma rays have the ability to deeply penetrate food materials (Bashir *et al.,* 2021). These radiations have several consequential effects, including the unwinding of DNA, harm to nucleic acids, and the ionization of water molecules. These processes collectively lead to oxidative damage within microbial cells. This cumulative effect ultimately results in a reduction in 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 shelf stability. This technique is often referred to as "cold sterilization" or "electronic pasteurization". By employing lower doses of irradiation, it becomes feasible to inactivate more than 90% of bacteria, consequently extending 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 is primarily applied in the food processing industry to preserve a wide range of 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. Certainly, regardless of the numerous advantages offered by irradiation technology, especially in the realm of food preservation, low consumer acceptance continues to pose a significant challenge. 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 duration is calculated by multiplying the total number of pulses by the effective duration of each pulse. 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 application of high voltage generates an electric field that efficiently 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 flavor, natural color, nutritional value and texture of the untreated food. This characteristic renders it especially well-suited for preserving liquid and semi-liquid foods, all the while eliminating microorganisms and producing valuable components (Gomez-Lopez *et al.,* 2007).

**Working**

PEF technology functions by administering pulsating electrical energy to a product situated between two electrodes that encircle the treatment space inside the PEF chamber. This setup comprises various components, including a high-voltage pulse generator, a treatment chamber, an appropriate fluid handling system, and the necessary monitoring and control systems. The two electrodes are linked through a non-conductive material to prevent electrical conduction between them. The food product is positioned inside the treatment chamber, which may have either a static or continuous configuration. The electrodes receive high-voltage electrical pulses produced by the device. These electrical pulses are subsequently transmitted with high intensity to the product located between the electrodes. The electric field generated within the food product exerts a force per unit charge, leading to the irreversible disruption of the cell membranes of microorganisms. 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 technology is widely used to extend the shelf life of food by diminishing the microbial count. Different types of fish, such as fresh, frozen, dried, brined, and marinated fish, can undergo pulsed electric field treatment. Electroporation of fish tissue enhances mass transport processes, including 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 energy consumption and processing times. 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 investigation carried out by Preetha et al. (2021) demonstrated the efficacy of PEF at an intensity of 5.6 W/cm² in combatting E. coli in flowable foods such as pineapple and orange juice, along with coconut water. The reduction in E. coli count was substantial, with respective decreases of 4.5, 4, and 5.3 log CFU/ml for pineapple juice, orange juice, and coconut water. 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 phenolic compounds’ production over a period of 36 hour storage.

PEF technology has been widely employed in the extraction of bioactive compounds from diverse natural sources. This treatment method enhances the extraction of functional components with a high level of purity, making it easier to use them in nutraceutical applications within the food industry without the need for additional purification. In addition to its established applications in microbial inactivation, extraction, and physicochemical modifications, PEF has extended its reach into unit operations such as freezing and dehydration. 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 offers various advantages, including an improvement in the water diffusion coefficient before the drying process. Consequently, this leads to reduced processing times for both freezing and drying food items. Additionally, PEF treatment plays a role in preserving the quality of thawed and rehydrated food products for an extended duration. Furthermore, PEF technology is employed to enhance the physical and chemical attributes of crucial food components, such as proteins and polysaccharides (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). Due to the numerous beneficial effects of PEF on food products, it stands out as a valuable non-thermal treatment technique. Nevertheless, there is still a requirement for the advancement of robust PEF equipment suitable for widespread commercial applications. This technological advancement would further pave the way for widespread utilization of PEF in 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). Pressure primarily influences various forces and bonds, including 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. The specific target microorganisms and pathogens are being targeted by factors such as applied pressure. temperature, holding time within the vessel, and these factors also affect food composition (including carbohydrates, proteins, lipids, added solutes, and water activity inducing a shielding effect) can be adjusted to make the process effectiveness (Balamurugan *et al.,* 2017). The versatility and effectiveness of HPP make it a valuable technique for preserving quality and enhancing safety of various food commodities.

**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 processing operation can be carried out with or without the use of heat. For this procedure, the food product needs to be placed in a flexible or semi-flexible pouch that can withstand exceptionally 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). In the pressure processing phase, the product undergoes an increase in temperature due to a phenomenon called adiabatic heating. 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 method is applicable to both foods with a certain moisture content and liquid foods. 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 meat and meat products, dairy items and processed fruits which provide conducive environments for microbial growth. Bulut and Karatzas (2021) explored in their study 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 characteristics 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). The various uses mentioned demonstrate how versatile HHP is, not only in eliminating microorganisms but also in extracting and enhancing antioxidants, phenolic compounds, bioactive substances, and functional elements from different origins. This suggests its potential applicability in the nutraceutical, pharmaceutical, healthcare, and food sectors. Nevertheless, the widespread adoption of HHP encounters technical obstacles when it comes to developing equipment suitable for high-capacity food processing. Consequently, there is currently scarcity of HHP-treated food products 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 affordable and non-thermal technique employed to decrease the presence of microorganisms on the surfaces of food substances. 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 subjected to UV-C radiation, these brief wavelengths are absorbed by the nucleic acids found within microbial cells. Consequently, the absorbed photons lead to the disruption of bonds and connections between thymine and pyrimidine molecules in various 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 microbes 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 food processing sector. Its affordability renders it an appealing choice for conducting pilot-scale experiments aimed at 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 findings demonstrated significant reductions, with a decrease of 6.3 logs for Lactobacillus plantarum, 5.1 logs for E. coli, and 5.5 logs 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). Moreover, ultraviolet radiation has advantageous impacts on the chemical and physical characteristics of food. Kumar *et al.* (2020) demonstrated that UV-C radiation at a wavelength of 254 nm was effective in improving the physico-chemical characteristics 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 research has unveiled that the application of ultraviolet (UV) treatment to fresh fruits and vegetables after harvest not only results in the inactivation of microbes but also boosts 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). Although UV treatment provides numerous beneficial effects on food, specific studies in the literature have suggested that UV treatment with high-dose can lead to diminished color and adverse textural changes in solid food products (Orlowska *et al*., 2013). Food products display diverse textures with rough and uneven surfaces, which can impede the rate of radiation penetration into the food material, subsequently diminishing the efficacy of the inactivation process. To augment the effectiveness of the process and attain higher rates of microbial inactivation, non-thermal techniques are frequently integrated or employed in conjunction 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 food processing industry to extend shelf life of food products. In order to bring about desired alterations, the impact of UV treatment can be further amplified by coupling it with other processes. 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 due to the interaction of molecular oxygen (O2) with singlet O. In gaseous form, the denser ozone is higher than air. However, due to high reactivity and instabilityof ozone, it cannot be stored and must be generated on-site as needed. It is widely utilized as a potent antibacterial agent in the food industry against various bacteria. 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. It results in alterations in cell membranes permeability, thus damaging them. Furthermore, ozone is recognized for its ability to disrupt the structure of proteins and 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, ozone treatment is often combined with other food treatments or additives to reduce damage and enhance effectiveness of food, thereby minimizing exposure time. 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 microbial reduction in fruit juices and inactivation of toxins present in food (Porto *et al.,* 2020Although the research literature highlights the potential of ozone in the food industry, it's worth noting that these studies are usually carried out on a laboratory scale and have not yet been implemented on a commercial scale and is utilized for disinfecting processing equipment in the industry. 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 focused on enhancing consumer acceptance of ozone-treated food, as this could encourage the food industry to adopt this technology for food processing and introduce ozone-treated products to the market.

**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. Significantly, microwaves are capable of passing through packaging materials such as ceramics, glass, and thermoplastics without encountering any obstacles.

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.

RF technology is employed in the food industry for diverse tasks like 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 fruit juices, wheat flour, peaches, almonds, crackers, pepper spice, legumes, potatoes, lentils, rice, and walnuts. 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 pathogen reduction of by 4 log cycles. Notable outcomes include inactivation of microorganisms like *Clostridium perfringens* and *Bacillus cereus* in pork meat, *Listeria innocua* and *E. coli* 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. Furthermore, RF technology plays a crucial role in various processes, including the thawing and tempering of fish and meat, the sterilization and pasteurization of low-moisture foods, and the roasting of peanuts as well as the blanching of apples 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 the Radio Frequency Identification (RFID) sensors, which exhibit particular capabilities in detecting bacterial growth and freshness in foods like fish and milk (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 is employed in a continuous system and proves particularly effective for products that span a wide pH range and consist of particles of larger size, which have traditionally posed challenges for heat processing due to inadequate heat penetration (Indiarto and Rezaharsamto, 2020). In this method, heat is generated by the passage of alternating current (AC) with frequencies ranging from 50 Hz to 60 Hz through a conductive solution, often brine. Products are situated between electrodes (typically composed of materials like Cr/Mn/Ni/Fe) that transmit AC current. Various configurations, such as batch, transverse, or collinear ohmic setups, can be utilized (Indiarto and Rezaharsamto, 2020). The Joule effect, resulting from the electrical resistance of the food, leads to volumetric heating, demonstrating remarkable efficacy. Throughout the ohmic heating process, both small and large structural changes become evident in the 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 result in alteration of tissues and cells, thereby influencing the food texture, especially in 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). Ohmic heating finds diverse applications, encompassing the extraction of various components like inulin, tepurang fruit oil, anthocyanins, and phenolic compounds, achieved by inducing electro-permeability of cell membranes. Additionally, it is employed in processes such as dehydration, pasteurization, blanching, evaporation, thawing, fermentation, sterilization, and enzyme inactivation. The enzymes affected by ohmic heating include pectin methylesterase, peroxidase, tyrosinase, polyphenol oxidase, lipoxygenase, lycopene, β-carotene (Indiarto and Rezaharsamto, 2020). The technology effectively inactivates pathogenic microbes (such as *Zygosaccharomyces rouxii, E. coli, Listeria monocytogenes, Alicyclobacillus acidoterrestris, Salmonella typhimurium*) and enzymes, enhances the thawing process and safeguards the nutritional, functional and sensory attributes of food. Ohmic heating is also employed as an alternative technique in the processing of sweet whey and the manufacturing of various dairy products. It can modify factors like water solubility index, water absorption index, thermal properties, and pasting properties of food constituents (Kaur and Singh, 2016). This versatile approach has been modeled and applied to an array of food commodities, including cereals, fruits, vegetables, solid-liquid mixtures, eggs, meat and fish 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 application of this technique is diverse and includes processes such as the extraction of components like inulin, tepurang fruit oil, anthocyanins, and phenolic compounds, which is achieved by inducing electro-permeability of cell membranes. Moreover, it is employed for various tasks including pasteurization, evaporation, blanching, fermentation, sterilization, thawing, dehydration and the inactivation of enzymes such as peroxidase, pectin methylesterase, polyphenol oxidase, lipoxygenase, tyrosinase, lycopene, and β-carotene. The enzymes like polyphenol oxidase, tyrosinase, and lipoxygenase, and the pathogenic microbes like *Alicyclobacillus acidoterrestri*, *E. coli*, *Zygosaccharomyces rouxii*, *Salmonella typhimurium*, *Listeria monocytogenes* can be effectively inactivated by ohmic heating. Furthermore, it enhances the thawing process and helps in maintaining the nutritional, functional and sensory attributes of food products. Ohmic heating serves as an alternative method for dairy and sweet whey processing, affecting properties such as water solubility index, water absorption index, pasting properties and thermal characteristics of food products (Costa *et al.,* 2018). This technology has demonstrated successful applications in a wide range of food products such as cereals, solid-liquid mixtures, eggs, fruits, vegetables, meat and fish 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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