Advances in Non-Thermal Food Processing Technologies

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Abstract

Non-thermal food processing techniques retain nutritional properties, sensory attributes, protect quality, and increase the shelf life of commodities while not exposing them to high temperatures. High-pressure processing uses 100-880 MPa and inactivates microorganisms. Ultrasound technique uses sonic cavitation for microbiological inactivation and extraction. Pulse electric field permeabilizes the cell membrane using an electric field, enabling better extraction of bioactive compounds and shelf-life extension. Cold plasma is ionized, which causes structural changes and changes the membrane potential across the transmembrane and inactivates the microorganisms by disrupting DNA linkages. Food surfaces and packaging materials are disinfected by PL using powerful light pulses. These approaches provide the food sector with energy-efficient, sustainable solutions while preserving customer preferences for minimally processed, fresh goods. To maximize their use across various food matrices, issues including industrial scalability, cost effectiveness, regulatory compliance, and consumer acceptance require more research and advancement. A potential area of food processing for improving safety, along with quality foods in contemporary diets, is non-thermal technology.

Keywords: Non-thermal processing, Food, Microorganism, Acoustic, Ionized gas

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Introduction

The process of converting natural foods like plants and animals into food or transforming food into other forms that are more suited to the nutritional needs of contemporary humans is known as food processing. The making, modifying, and manufacturing of food are only a few of the several components of food processing that call for a number of physical and chemical modifications to the raw ingredients (Zhu et al., 2021). As customers' need for safe, minimally processed, and highly nutritious foods has grown, these methods are continuously becoming more and more popular in the treatment, preservation, and decontamination domains. When it comes to plant-based foods, these technologies alter the microstructure of plant tissues and plant-based beverages, improving the ability to extract carotenoids, phenolic compounds, vitamins and minerals, and/or bio accessibility all of which are necessary for these substances to have a positive impact on health (Chiozzi et al., 2022).

Thermal technologies food is exposed to heat for a prolonged period, which causes undesirable changes in food nutritional composition, decreases the quality, imparts off-flavor, and forms heterocyclic aromatic amines. Non-thermal technologies do not expose food to higher temperatures, there is no formation of unwanted by-products inside food or on its surface, hence their preservation impact is greater than that of thermal technologies (Jadhav et al., 2021). Non-thermal technologies have been used extensively in the handling of food because they lengthen the shelf life, along with maintaining the freshness, nutritional value, and sensory attributes of food (Allai et al., 2023). Advanced non-thermal technologies are high-pressure processing, ultrasound, pulse electric field, cold plasma, and pulse light. The two basic principles of non-thermal technologies' sterilization methods are altering the composition of the cell membrane to render the microorganism incapable of regulating itself and damaging genetic components to result in metabolic abnormalities inside the microorganism. Pulse electric fields (PEF) and US technology are examples of technologies that may alter the structure of the cell membrane, making them suitable for use in extraction, drying, and other mass transfer procedures (Zhang et al., 2018). Both types of food processing techniques are given in Figure 1.

High-Pressure Processing (HPP)

HPP includes applying pressure to packed goods extending from 100-800 MPa for a ns pulse to minutes. After undergoing HPP processing, a product is conveyed to a high-pressure chamber that is filled with a pressure-transmitting fluid, often water, and placed in a sealed flexible material (Nabi et al., 2021). Through the inactivation of microorganisms and enzymes, foods may be pasteurized with less heating and still maintain their nutritional value and sensory qualities for a longer shelf life (Khouryieh, 2021). The five basic principles of HPP are the isostatic principle, Le Chatelier's principle, the electrostriction principle, the molecular ordering principle, and the Arrhenius principle. The isostatic principle deals with the homogeneity of pressure across the sample in the HPP process (Iqbal et al., 2025). Applying pressure causes the equilibrium to shift in favor of the state with the lowest volume according to Le Chatelier's equilibrium changes principle. In electrostriction, a compact arrangement of water molecules around electric charges results in higher ionization (Deiters & Kraska, 2023).

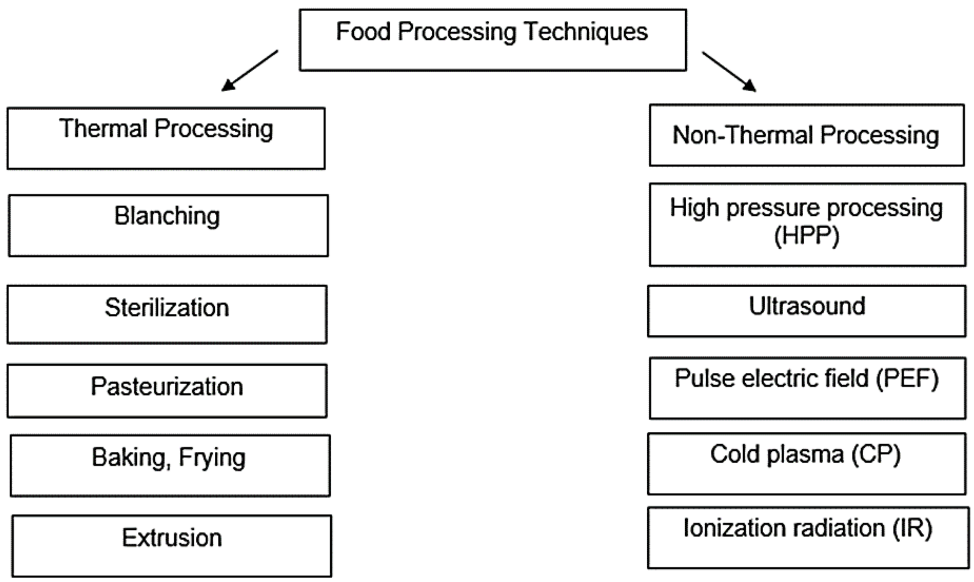

Fig. 1: Thermal and non-thermal techniques to process foods

The molecular ordering principle involves temperature and pressure; both have opposing effects on chemical processes, since the concept of molecular ordering states that molecules are more closely arranged under pressure at a constant temperature. In the Arrhenius principle, there is the antagonistic or synergistic effect of both temperature and pressure because thermal attributes also influence changes generated from pressure (Baldelli et al., 2024). Other food applications of high-pressure processing involve extraction, pasteurization, homogenization, freezing, and thawing with pressure ranging from 100-800 MPa. Commercial food applications that need pasteurization typically use pressures between 200 to 600 MPa at ambient or at a cooled temperature, with a holding time of five minutes (Aganovic et al., 2021). HPP is applicable to many kinds of liquid food items, particularly those that are heat-sensitive and extremely acidic, which inhibit the formation of spores. The conventional thermal methods for spores in low-acid meals include 180°C for 5 to 15 minutes, 180°C in a dry and wet environment for five hours, and 121°C in a high-pressure steam condition for 30 minutes. Sterilization using HPP requires a temperature and pressure 70°C and 600 and 1000 MPa. Under extreme pressure, food shrinks and can only be packaged in soft materials (Wang et al., 2015).

Ultrasound

The word "ultrasound" refers to sound waves that are higher than the audible frequency range, or more than 20 kHz. The medium particles undergo decompressions and compressions due to acoustic waves. Low-intensity and high-intensity ultrasound are the two types of ultrasonic waves (Sajid et al., 2025). Ultrasound waves that are low intensity or high frequency are also referred to as diagnostic waves. They are characterized by intensities below 1 W/cm^2 and a characteristic frequency of more than 100 kHz (Bhargava et al., 2021). Two common devices are an ultrasonic cell crusher (probe) and a single-frequency ultrasonic cleaning tank (bath) (Xu et al., 2021). During food processing, low-intensity ultrasonography is used as a nondestructive technique to track changes in physicochemical characteristics. High-intensity ultrasound is used for a variety of purposes, such as the emulsification and the inactivation of germs and enzymes, which enhances the shelf life (Taha et al., 2024).

The principle of ultrasound-assisted extraction (UAE) is sonic cavitation, which ruptures the cell wall of the plant matrix and facilitates the release of bioactive chemicals. By creating phases of expansion and compression, ultrasonic waves may travel through any material, such as mechanical waves between 20 kHz and 100 MHz (KhokharVoytas et al., 2023). When a strong sonic force is applied, it leads to cavitation bubbles forming, growing, and bursting in a liquid medium. This is frequently done to improve a number of food processing techniques (Singla & Sit, 2021) used in conjunction with pressure (manosonication) and temperature (thermosonication) to create a synergistic effect that increases their effectiveness (Bhargava et al., 2021). The acoustic cavitation performance is affected by the types of ultrasonic systems (probe or bath) and the operational parameters of frequency, processing time, acoustic power, and sample mass (Zhu et al., 2024).

The technical attributes of dairy and bakery products have all been enhanced by the direct application of acoustic radiation at lower energy densities in dairy and bakery products. Meat and meat products can be tenderized, cured, and homogenized using higher ultrasonic intensities (Strieder et al., 2021). A superior product was produced more quickly when 43 kHz waves were used to control the fermentation of wine, beer, and sake. This decreased the amount of dissolved carbon dioxide in solutions. When coarse emulsions were subjected to 40% of ultrasonic power (power density: 1.36 W/mL), the smallest and most stable nanoemulsion droplets were produced. The greatest resveratrol loading capacity and encapsulation efficiency can be achieved with dual-frequency ultrasonography at 28/40 kHz (Li et al., 2021).

Pulse Electric Field (PEF)

In PEF, pulses with electric field intensity ranging from 0.1 to 100 kV/cm are frequently applied to food between electrodes. An electric field is applied to the food product, whether liquid or solid, causing cell membranes to develop pores (Gohar et al., 2024). The transmembrane potential rises, the membrane becomes thinner, and opposing polarity charges are produced on both sides of the membrane by the applied PEF. However, a threshold, usually between 0.5 and 1.5 V, must be reached in the transmembrane potential differential before cell membrane electroporation may begin (Zhang et al., 2023).

Depending on the application and the intended food, electroporation occurs when biological cells are exposed to an applied voltage and corresponding electric field over the required critical transmembrane potential. Because they are bigger than microbial cells (10–14 kV cm-1), animal and plant cells require an electric field strength (0.5–2 kV cm^{-1}) for electroporation to create either permanent (irreversible) or transient (reversible) pores (Arshad et al., 2021b). The short processing time (ns to ms), enhanced effectiveness (greater permeability induction in cell membranes), lower energy input, structural protection, and improved final product quality are some advantages. Pulse electric field parameters involve temperature, treatment duration, electric field intensity, pulse width, and waveform. It also depends upon product and microorganism characteristics, stage of growth, type of microorganism, and concentration (Soltanzadeh et al., 2022).

The use of PEF for a variety of operations (such as inactivating bacteria or enzymes, recovering bioactive substances, or stimulating cells, altering structures, and freezing) has distinct processing requirements, including specific energy (J kg-1) and electric field intensity (kV cm-1). There are still some issues that must be resolved, including toxicity hazards, market acceptance, legal ramifications, economic disadvantages, and technological difficulties (Verma et al., 2021). Among the primary barriers to this technology's adoption, i.e., the primary barrier to PEF's commercial acceptance, is the lack of dependable and more useful electrical systems. Treatment chambers cause these electrodes to get dirty and corrode. Data comparison across laboratory and commercial scales is further limited by poorly defined processes (Arshad et al., 2021a).

Cold Plasma (CP)

Ionized gas known as plasma is made up of charged particles, reactive oxygen species (ROS: O, ozone (O_3), O_2, and OH), reactive nitrogen species (RNS: NO_2, NO, and NOx), ultraviolet (UV) light, and free radicals (Reuter & Sousa, 2025) Plasma is often produced when a gas that is present or moving between two electrodes with a large electrical potential difference is subjected to electrical energy. This results in gas ionization because of free electrons hitting gas molecules. It is referred to as CP when the ionized gas is created by relatively low energy (1-10 eV) and electronic density (up to 1010 cm^{-3}). The plasma generating techniques used in food processing come into the following categories: microwave (MW), radiofrequency (RF), corona discharge, plasma jet (PJ), and dielectric barrier discharge (DBD) (Laroque et al., 2022). O^-, HO_2, H_2O_2, N, N^{2-}, NO, NO_2, NO_3, N_2O, OH, O_2, O_3, O^{2-}, and O^{2-} are the reactive mixture mostly present in atmospheric air plasma (Singh et al., 2022).

Furthermore, when plasma comes into contact with moisture, reactive species, including H_2O_2, NO_2, NO_3, and O_3, are created; they are known as persistent reactive gases (Locke et al., 2025) Since excited argon, neon, and helium atoms and molecules predominate in plasma formation, they are frequently utilized in this process. Inert gases are chemically inactive and have a larger ionization potential, which makes ionization easier and takes less power, therefore, they are used as working gases (Dharini et al., 2023). Plasma may be released by a microneedle, plasma jet, plasma torch, plasma chamber, and other methods. However, because of cost-effectiveness, the creation of plasma for large-scale food preservation is still in an early stage. Three general categories of the cold atmospheric plasma system are electrode contact, direct, and distant exposure (Ganesan et al., 2021). Food products are put in electrode fields that generate plasma in the electrode contact. The direct exposure approach involves exposing food items directly to the source of plasma formation, also known as active plasma. The food is exposed to a plasma-generating source at a distance in the remote exposure method. This process creates secondary chemical species from air and other gases that sterilize food (Ganesan et al., 2021).

Protein structural changes using atmospheric cold plasma have been documented for a variety of uses, such as deactivating enzymes, altering the rheological behavior of dough, functionalizing the surface of protein-based films, or lowering the immunogenicity of proteins (Sharma, 2020). Changes in primary and secondary structures of protein, starch, and oils, such as cleavage, polymerization, aggregation, and oxidation, have been seen when plasma reactive species interact with these compounds. Microbial decontamination and some structural changes are caused by plasma reactive species, which may also make it easier to absorb nutrients from organisms (Kaushik et al., 2023b). Continued residual fungicidal, bactericidal, and virucidal (including COVID-19) activity, the atmospheric cold plasma reactive species may interact with the substrate's surface to form compounds like peroxynitrites, nitrates, nitrites, or peroxides (Kaushik et al., 2023a).

These compounds stay in the environment or on the product for a few hours, significantly lowering contamination levels without compromising food quality and prolonging shelf life (Yepez et al., 2022). Cold plasma is utilized for preserving fruits, vegetables, meat, and poultry, and it maintains sensory attributes such as color, flavor, taste, appearance, and composition, among other physical and sensory characteristics. Treating fresh fruits with cold atmospheric plasma lowers their overall bacterial level (Ganesan et al., 2021). Although CP treatment is a safe and non-toxic process and the use of plastic in high-fat food products may cause the thiobarbituric acid reactive substances (TBARS) value to rise quickly due to the generation of ROS, including peroxide, ozone, and singlet oxygen. CP can be used with ultrasonic waves and other nanomaterials, including nanofibers, particles, and emulsions made from various bioactive substances (Ucar et al., 2021).

Pulsed Light (PL)

Another food processing technique is pulsed light (PL), which utilizes white light to disinfect surfaces that come into contact with food (Obileke et al., 2022) Food contact surface decontamination and PL technology use "for the production, processing, and handling of foods" were authorized by the U.S. Food and Drug Administration (FDA) in 1996. In order to achieve PL therapy, scientists suggested employing a xenon lamp with surface emission of wavelengths (λ) between 200 and 1100 nm. Like sunlight, the PL is white light, but it appears for a short time and has a very high intensity (Zhao et al., 2022). Infrared rays (700–1100 nm), visible light (400–700 nm), and ultraviolet (UV) (200–400 nm) are categories of light on the basis of wavelength. UV is again categorized as UV-C: 200–280 nm, UV-B: 280–315 nm, and UV-A: 315–400 nm, which are all included in this spectrum of electromagnetic radiation. The light energy is emitted in the form of a light burst in higher concentration for a short duration, lasting between 1 µs and 0.1 s (Kurup, 2021).

The pulse frequency or pulses per second mostly range from 1 to 3 Hz. Treatment should not exceed 12 J/cm^2, and the pulse width should not exceed 2 ms. PL therapy applies multiple bursts of intense light pulses to eradicate bacteria such as *L. monocytogenes* (Mandal et al., 2020). The effects of exposure period (between 0 and 15 s) and pulsed light fluency rate (0.18, 2, and 5.6 W/cm^2) on *E. coli* inactivation in juices were investigated. After being exposed to pulsed light levels of 95.2 J/cm,^{2} it led to a significant log reduction of up to 4.0, 4.5, and 5.33 in orange juice, pineapple juice, and tender coconut water, respectively (Preetha et al., 2021). Crystallinity affects how light passes through polymer-based films and, consequently, how transparent they are; non-crystalline polymers exhibit exceptional transparency (Zhao et al., 2023).

The best materials for PL treatment are transparent packaging materials with high light transmission, i.e., polymers with a low crystallinity index. Some gaps still need to be filled, such as expanding our knowledge of how PL affects the functional and safety characteristics of packaging materials. For food preservation, pulsed light technology in conjunction with packaging technologies, including vacuum, changed environment, active and intelligent packaging, coatings, and others, may show promise (Marangoni Junior et al., 2020).

Ozonation

Ozonation refers to the process of using ozone (O_3), a highly reactive molecule composed of three oxygen atoms, to achieve various applications such as disinfection, oxidation, and sterilization (Dubey et al., 2022). Ozone treatment is a chemical process that includes exposure of contaminated foods (fruits, vegetables, drinks, spices, meat, herbs, fish, and so forth) to ozone in either gaseous or aqueous form. Microorganisms are inactivated during ozonation in the gaseous phase at a consistent pressure, flow rate, and ozone concentration that varies based on the degree of contamination (Ziyaina & Rasco, 2021). A number of techniques can be used to create ozone, such as the chemical conversion of oxygen (O_2 to O_3), the photochemical approach (UV radiation), and the corona discharge method (high-energy electrical field). Only two approaches are commonly employed: the corona discharge (Locke et al., 2025) technique and the photochemical (UV) method (Brodowska et al., 2018). Ozonation works by oxidation, in which organic molecules break down into simpler, non-toxic compounds (Jamali et al., 2024).

When ozone reacts with their unsaturated bonds, microbial inactivation occurs by which ozone causing bacterial, viral, and fungal cellular barriers to break down, which inactivates and kills microorganisms (Ziyaina & Rasco, 2021). It may be used for deodorization, too, which involves odor-causing volatile molecules getting oxidized by ozone. It effectively inactivates pathogens such as *Pseudomonas aeruginosa*, *Staphylococcus aureus*, and *Listeria monocytogenes* in milk and meat products. Ozone improves germ control and shelf life when combined with technologies like CO treatment or freeze-drying (Khanashyam et al., 2022).

Low ozone levels (0.02–10 µg/L) improve ripening and storage for different varieties of cheese, while ozonated storage atmospheres (5–7 µg/L for 4 hours every 3 days) can prevent mold for up to 4 months. Ozonation greatly improves the quality of Swiss and cheddar cheeses and gets rid of smells in storage spaces (Pandiselvam et al., 2019). Ozonation deactivated the polyphenol oxidase enzyme in sugarcane juice by 67.8% and destroyed yeast and mold in watermelon juice by more than three logs (Dubey et al., 2022)

Ozone can degrade the quality of several food products, hence, research on its effects is necessary. Ozone treatment greatly reduces the antioxidant capacity that is attributed to the availability of vitamin C, carotenoids, anthocyanins, and polyphenols in fruits, vegetables, herbs, and spices because of its potent oxidizing action. Unlike alternative processing techniques (thermal procedures), ozone treatment does not degrade protein quality or harm amino acids. Higher ozone concentrations might cause PUFAs to be oxidized due to the quick reactivity with unsaturated organic molecules, and peroxidation rises as a result (Brodowska et al., 2018). Research on the impact of ozone on humans and the acceptance of treated foods is necessary to guarantee the safety of operators and consumers. To prevent negative effects on food quality, process optimization with clearly specified treatment parameters is crucial. To optimize ozone application in food processing systems, more investigation is required (Dubey et al., 2022).

Ionization Radiation

Ionizing radiation has very short wavelengths and high intensity, which is high enough to change atoms through the removal of an electron to create an ion, but not high enough to split them (Omer, 2021). Some typical examples of ionizing radiation are electron beams, gamma rays, and X-rays. Electron beams with an energy range of 3 MeV to 10 MeV are appropriate for surface treatments or the focused reduction of bacteria and pathogens. Because of their short penetration depth, electron beams are mostly used for surface-level sterilization. Gamma rays, on the other hand, have more than 100 keV and wavelengths shorter than 10^{-11} meters (Sakai et al., 2024). Gamma rays prevent bacteria from reproducing by interfering with their DNA (Sahoo et al., 2023). The penetrating power of this radiation is quite similar to that of gamma rays. With energy between 100 eV and 100 keV, and wavelengths between 10^{-8} and 10^{-12} meters, X-rays can penetrate semi-dense materials and food packaging materials with modest to extremely high penetration abilities (Bisht et al., 2021).

Food irradiation raises the temperature by 2.8°C for every 10 kGy of irradiation. The typical irradiation dose is less than 10 kGy, and obtaining the best results is not guaranteed. According to reports, minimal doses less than 25 kGy for peanuts, 30 kGy for soybeans, 25 kGy for tree nuts, and 10 kGy for white sesame do not significantly alter allergenicity (Pi et al., 2021). Food is exposed to a regulated quantity of ionizing radiation by the use of the three radiation sources (electron beams, gamma rays, and X-rays). Without changing the taste or texture of the food, the rays prolong the shelf life and prevent spoiling by breaking chemical bonds, eliminating pests, and destroying microorganisms' DNA (Mshelia et al., 2023).

Thermal procedures change the flavor, color, and nutritional content of food; this ionization process does not change these qualities, making it appropriate for sensitive foods and its applications for several food items, including meat, processed foods, and fresh produce (Bisht et al., 2021). Ionizing radiation consumes less energy and promotes more ecologically favorable preservation techniques. The process is also environmentally benign, making food processing more sustainable (Ahmad et al., 2021). Ionization can be used with other technologies to optimize food advantages, including the potential to further reduce allergens in food items and pave the way for allergy-free foods (Dhillon & Moncur, 2023). Technological advancements are being made with the goal of creating affordable, portable ionization equipment that can be applied on a smaller scale, including small-scale or local food production environments. This would improve food safety and preservation at the local level by making ionization more available to a wider variety of food producers (Dhillon & Moncur, 2023). Table 1 elaborates principles of some common non-thermal processing techniques.

Table 1: Principles of some common non-thermal processing techniques

Non-Thermal Techniques	Conditions	Principle	References
High pressure processing (HHP)	100 to 800 MPa	Le Chatelier's equilibrium and isostatic electric	(Evrendilek, 2023)
Ultrasound	>20kHz; 20kHz to 100kHz	Cavitation: Contraction and rarefaction	(Tang et al., 2024)
Pulse electric field	0.1 to 100Kv/cm	Electroporation (shift transmembrane potential)	(Ruiz-Fernández et al., 2022)
Cold plasma	Ionized gas; charged particles and reactive oxygen species	Reactive species (NO_3, N_2O, OH, O_2, O_3, O^{2-}, and O^{2-})	(Kaushik et al., 2023a)
Pulsed light	UV light	Inactivate the microorganism; structural changes (DNA and Protein)	(Alhendi, 2021)
Ozonation	Conversion of O_2 to O_3	Oxidation of organic molecules	(Lim et al., 2022)
Ionization radiation	Electron beams, X-rays, gamma rays	Interfere with the DNA linkages	(Chaudhary & Kumar, 2023)

Conclusion

This chapter provides a comprehensive and detailed understanding of non-thermal food processing techniques, their source, and the mechanisms of action for microbial inactivation, extraction, and structural modification of food and food components. Unlike many traditional heat application methods, these methods demonstrate their ability to preserve foods close to their original fresh state, which is highly sought by customers. Certain non-thermal approaches enhance the bioavailability of certain bioactive food ingredients while having a negligible impact on the nutritional makeup of meals. Food processors are becoming more interested in novel processing technologies as they can lower the expenses, increase the added value of the products, and produce food products of better quality and a smaller environmental impact.

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