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A comprehensive review: Recent advances in non-thermal technologies in food processing technology

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Abstract

Nowadays, Consumers demand clean and safe food without disrupting the nutritional and sensory qualities. Various thermal treatments are applied during processes to extend the shelf life of food. However, the commodity's nutritive and sensory qualities may suffer due to these thermal processes. Consumers today demand food that is safe and wholesome and has good organoleptic qualities. This is why the development and advancement of non-thermal technologies that are secure, safe, and environmentally friendly have captured the attention of the food industry. In non-thermal processing technology, the food is processed at room temperature; this reduces damage to food because heat-sensitive nutritious material stays intact in the food co, contrary to the thermal processing of food. These non-thermal technologies can process all kinds of food, such as fruits, vegetables, spices, pulses, meat, fish, etc. Non-thermal technologies have mainly emerged in the food sector in the last few decades. These food processing methods achieve microbial inactivation without damaging the food's nutritional content or sensory qualities. They also increase product shelf life and preserve the food's fresh-like physical, nutritional, and sensory qualities. These cutting-edge technologies, such as high hydrostatic pressure, pulsed electric fields, high-intensity ultrasound, ultraviolet light, pulsed light, hurdle technology, ionizing radiation, and oscillating magnetic fields, can inactivate microorganisms to varying degrees. With only minor nutritional losses, all food types, including fruits, vegetables, pulses, spices, meat, fish, etc., can be processed using these non-thermal technologies. Non-thermal technologies have grown in importance in the food industry over the last few decades. As a result, there is a need to research and develop these non-thermal technologies because they are becoming increasingly important in the food industry.

Keywords: Non-thermal technologies, food processing technology, nutritional

Introduction

The food industry is witnessing a growing demand for wholesome, natural, and easy-to-handle food products. In response to this trend, traditional food preservation methods such as intense heat treatments, salting, acidification, drying, and chemical preservation are being replaced with newer techniques. While conventional food preservation methods reduce contamination and microbial load, they can also cause unfavourable changes in the food, such as loss of nutritional components, changes in texture, and modifications to the organoleptic properties of the food. Moreover, thermal processing leads to the formation of chemical toxicants that is harmful to human health and carcinogenic in food. Heat-sensitive nutrients, including vitamins, minerals, pigments, antioxidants, and bioactive compounds, are present in food and are vulnerable to degradation during food processing. Retention of these nutrients in food products requires innovative approaches for process design due to their sensitivity to various physical and chemical factors. Non-thermal processing technologies, which process food at room temperature, have emerged as a viable alternative to thermal processing. These technologies preserve the heat-sensitive nutritious material in food, unlike thermal processing, which can damage such material. Non-thermal technologies can be utilized for processing all kinds of food, including fruits, vegetables, spices, pulses, meat, and fish. Although non-thermal technologies have mainly emerged in the food sector in the last few decades, they are increasingly used in the food industry to differentiate products and improve their quality [1].

Traditional techniques for preserving food involve exposing it to high temperatures, which can effectively eliminate bacteria and other contaminants but can also lead to undesirable changes in the food. These changes may include the loss of heat-sensitive nutrients, alterations to the food's texture, and changes to its sensory properties [2]. Food is exposed to heat for an extended period during thermal processing, which results in observable changes in the food and the creation of low-grade food [3]. The thermal preservation methods lead to the formation of chemical toxicants that are harmful to human health and carcinogenic in food [4, 5]. Food contains various heat-sensitive nutrients, including minerals, vitamins and nutrients, with functional properties such as antioxidants, pigments and bioactive compounds. However, during food manufacturing, numerous processes can harm these vital nutrients. The retention of nutrients in food products necessitates implementing innovative approaches in process design due to their susceptibility to various physical and chemical factors. These factors can cause biological functionality loss, chemical degradation, and incomplete or premature release. In non-thermal processing technology, the food is processed at room temperature; this reduces damage to food because heat-sensitive nutritious material stays intact in the food co, contrary to the thermal processing of food. These non-thermal technologies can be utilized for processing all kinds of food like fruits, vegetables, spices, pulses, meat, fish etc. Non-thermal technologies have mainly emerged in the food sector in the last few decades [6]. In order to successfully differentiate products, emerging and improved technologies are increasingly used in the food industry [7].

Among the most actively researched new preservation methods are non-thermal inactivation techniques like high hydrostatic pressure (HHP) and pulsed electric fields (PEF), packaging methods like modified atmosphere packaging (MAP) and active packaging, natural antimicrobial compounds, and bio-preservation [8]. Due to rising consumer demand for nutritious, delicious food products with a long shelf life, non-thermal techniques have attracted much research attention in the last ten years. However, the food industry has only recently begun to use these technologies [9]. Enzyme activity can be prevented by using non-thermal treatment, which helps in preserving the freshness of fruits and vegetables.

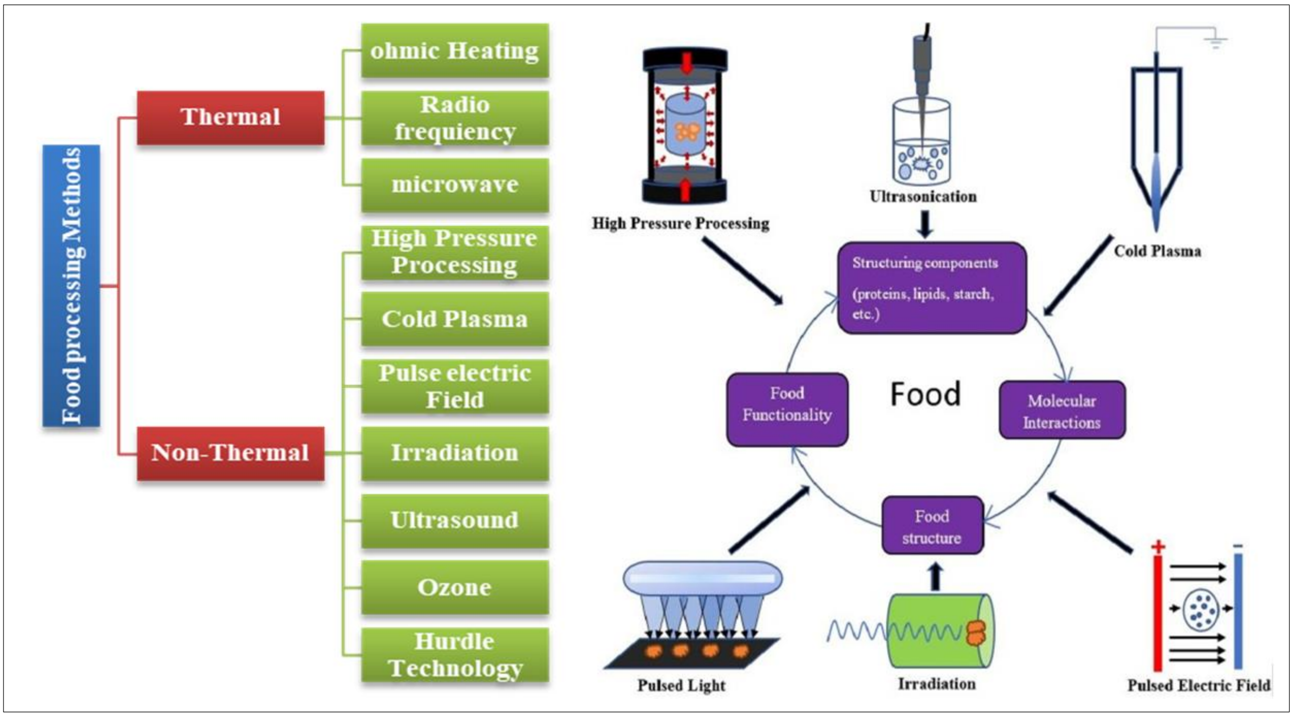

Fig 1: Graphical representation of Non-Thermal Technology in food processing Technology

New methods of non-thermal preservation have been researched and encouraged to reduce environmental impact further, lower food processing costs, and increase the value of the products while maintaining the physicochemical properties, extending shelf life, and guaranteeing food safety [11]. The non-thermal technologies available in the food sector have numerous advantages, but they are scarcely utilized in food industries and are mostly confined to laboratory-scale operations [12].

High pressure processing (HPP)

Application of high pressures (100-900 MPa), whether or not heat is added, to achieve microbial inactivation, change the characteristics of the food to produce qualities that consumers desire, or both, to preserve food substance. Other names for this technology include high hydrostatic and ultra-high pressure processing. HPP maintains the product's microbial shelf life, natural freshness, and food quality. The USFDA now acknowledges this technology for RTE foods. Processing heat-sensitive products at room temperature or in the refrigerator prevents thermal effects and cooked-off flavours from arising [13, 14]. This technology was used to extend the shelf life of products by eliminating deterioration and pathogenic microorganisms, as well as an alternative thermal treatment to packaged food materials [15].

Mechanism of High Pressure Treatment

The High-Pressure Processing (HPP) technique involves a pressurisation phase to initiate each processing cycle, wherein the pressure is elevated to facilitate processing, either with or without heat. The product is ideally packaged in a flexible or semi-flexible pouch that can endure exceptionally high pressures. The final stage involves immersing the finished product in a pressure-transmitting fluid, usually water, but other liquids such as castor oil, silicone oil, ethanol, or glycol, either alone or in various combinations, can also be used, subject to the manufacturer's guidelines [16]. During the process, adiabatic heating causes the product to warm up. The extent of temperature rise due to adiabatic heating depends on the type of fluid, pressurisation rate, temperature, and pressure. A pump pressurises the hydraulic fluid, and the resulting pressure is uniformly transmitted to the packaged food from all directions during the processing cycle. The processing is instantaneous and independent of food size or geometry so that the overall processing time can be reduced [17]. The technique applies to liquid and liquid foods with a certain degree of moisture. The structural integrity of the food is maintained even at high pressures due to the uniform and simultaneous application of pressure from all sides during transmission [18].

Pulse electric Field

Pulsed electric field (PEF) processing is a non-thermal technique that utilizes high-voltage electric pulses to inactivate microorganisms in food preservation. Food preservation entails using brief bursts of high electric fields with durations of microseconds to milliseconds and intensities in the range of 10-80 kV/cm. The processing time is determined by multiplying the number of pulses by the effective pulsation duration. The product is placed between two electrodes, which involve delivering pulsed electrical currents to the product. The PEF chamber's treatment gap is the distance between the electrodes. The high voltage used generates an electric field that inactivates microorganisms [19].

The electroporation of cell membranes caused by the pulsed electric field renders the cell membranes of microorganisms, industrial materials, or animal tissue permeable. This electroporation technique can be used for a wide range of food processing and bioprocesses that require little energy. PEF technology has several advantages over heat treatments because it kills microorganisms while preserving the undressed food's original colour, flavour, texture, and nutritional value. It is appropriate for protecting liquid and semi-liquid foods while destroying microorganisms and creating beneficial ingredients [20].

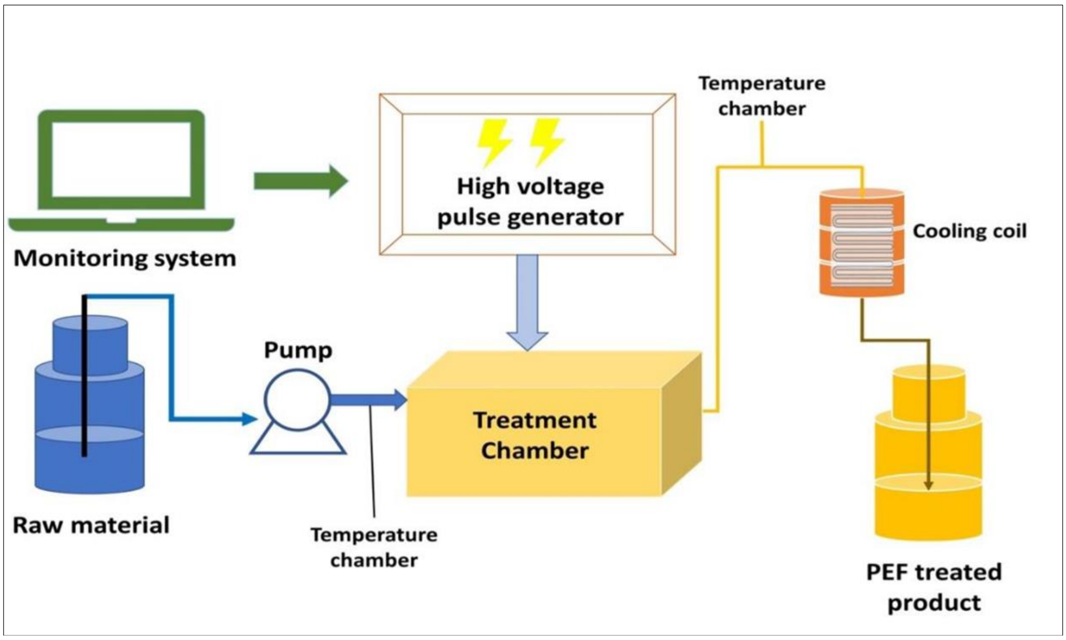

Fig 2: Pulse electric field Technology

Working

The PEF technology delivers pulsing power to a product sandwiched between electrodes that enclose the PEF chamber's treatment gap. The apparatus comprises a high-voltage pulsation generator, a treatment chamber, an appropriate fluid handling system, and the necessary monitoring and controlling impulses. Two electrodes are connected with a nonconductive material to prevent electrical inflow from one to the other. The food product is placed in the treatment chamber, either in a static or perpetual design. The electrodes are subjected to electrical pulses with high voltage that are generated, and the electrodes conduct these electrical pulses with high intensity to the product sandwiched between the two electrodes. The so-called electric field, which is present in food products, exerts a force per unit charge that causes microorganisms to break down their cell membranes irreversibly. This causes the microbial cell membranes to dielectrically break down, opening the door to trade with the charged food molecules [21, 22].

Application of Pulsed Electric Field in Preservation

Pulsed electric fields can be applied to various types of fish such as fresh, frozen, dried, brined, and marinated to enhance mass transport processes like moisture transport and removal. This leads to improved drying, brining, and marinating of fish. Fish tissue requires field strength of 1.0 to 3.0 kV/cm and an energy delivery of 3 to 10 kJ/kg for cell disintegration, which is caused by the pulsed electric field application. This method helps to improve production and product quality, as well as aiding in the deactivation of parasites like nematodes [20].

PEF technology can accelerate food product drying, reducing processing times and energy use for fruits, vegetables, potatoes, and meat. It also improves extraction procedures such as increased extraction and pressing yields in fruit juice, vegetable oil, and protein and algae oil. The freezing of food products is also accelerated by PEF technology, shortening processing times and lowering energy consumption. Cell disintegration accelerates freezing rates, and smaller ice molecules are created, improving the quality of the frozen food product [23, 24].

Pulse light technology

One of the non-thermal technologies that have been researched in the food industry is pulse light, which has proven to be effective in decontaminating food packages and surfaces. The method involves exposing an inert gas in a lamp to a high-voltage, high-current electrical pulse that causes the gas molecules to emit a brief, yet intense light pulse capable of sterilizing food. The light spectrum used in this process typically ranges between 180 and 1100 nm, including visible light (400-700 nm) and ultraviolet (UV) rays (180-400 nm). By employing short light pulses, microorganisms present on food surfaces, equipment, and packaging can be swiftly inactivated. It's stated that primary mechanism behind this process is the photochemical action of the UV portion of the light spectrum, which leads to thymine dimerization in the DNA chain and ultimately results in cell death and hold significant implications for the food industry [25].

Principle and working

The principle behind producing high-intensity light involves gradually increasing low to moderate-power energy and releasing it in concentrated bursts of more powerful energy. Pulse Light devices consist of a flash lamp filled with an inert gas that emits an intense, highly brief light pulse when subjected to a high-voltage, high-current electrical pulse. In microbiology, UV rays are recognized as essential for the inactivation of microorganisms. As a result, the delivery of UV-C to bodies has been improved through pulsed light.

Medium-pressure UV lamps have been increasingly used due to their higher germicidal UV power per unit length, providing a polychromatic output that includes germicidal wavelengths between 200 and 300 nm.

Radiation Processing

Ultraviolet light:

UV light processing is a non-thermal technology that has gained popularity due to its simplicity, effectiveness against microorganisms, and low cost compared to other preservation methods.

This dry and cold process uses UV light with a 100 to 400 nm wavelength range divided into UV-A, UV-B, and UV-C. The USFDA has approved using UVC light for pasteurizing fruit juices, making it a popular technology for processing liquid foods and beverages. It is believed that the germicidal region of UV-C light is lethal to most microorganisms [26, 27].

Gamma Irradiation: There are significant Cobalt 60 radionuclide sources from which the rays for food processing are derived. This kind of radiation is mono-energetic (60 Cobalt emits two photons per disintegration simultaneously with energies of 1.17 and 1.33 MeV). Even when very complex source geometries, such as extended plaque sources, are used, it is possible to compute the dose distribution in irradiated food products using analytical techniques like the point kernel [28].

It is widely recognized that food irradiation (GI) is a reliable method for reducing foodborne microorganisms. The main mechanism through which GI achieves microorganism inactivation is by causing DNA damage. However, the resistance of vegetative cells to radiation may be influenced by several factors, such as the composition of the environment, the amount of moisture present, and the presence or absence of oxygen [24].

Ultrasound Technology

Another area in non-thermal approaches that takes advantage of the high-intensity sound waves' ability to preserve food is ultrasound. The preservative effect is achieved by mechanically inactivating microbes and spoilage enzymes. The mechanism is that shear forces are produced as ultrasonic cavitations spread through biological structures. This results in mechanical cell breakage and permits material transfer from the cell into solvents. Cavitation reduces particle size, which expands the surface area in contact during compound extraction. In the food industry, the application of ultrasound can be divided based on a range of frequencies:

1. Low-power ultrasound

The preservation of food materials' physical and chemical characteristics during analysis and monitoring is a crucial consideration in ensuring their overall quality and safety. To this end, using low-power level waves has emerged as a viable approach, providing a non-invasive means of analysis that minimizes the risk of altering the material's composition [26].

2. High-power ultrasound:

Ultrasonic waves with a power and intensity of 20 to 500 kHz have disrupted and enforced the physical, mechanical, and biochemical properties of various food items. The effects of these waves on food processing, preservation, and safety have shown great promise [26].

Irradiation technology

Irradiation is a method of sterilizing or extending the shelf life of food products by exposing them to low doses of radiation. This physical process involves exposing pre-packaged or bulk foodstuffs to gamma, x, or electron radiation. Food is typically exposed to gamma radiation from a radioisotope source, electrons generated by an electron accelerator, or X-rays. These rays can be used to preserve and improve food quality due to their high penetration power. The amount of ionizing radiation the food absorbs during the irradiation process is known as the "radiation absorbed dose" (rad), measured in rads or Grays [29].

Cobalt-60 is a radioactive element used to irradiate food with high-energy gamma rays. When an atom's nucleus releases photons or gamma rays, they have enough energy to knock electrons out of food molecules and turn them into charged ions. However, the rays cannot cause radioactivity in food because they do not have enough energy to remove neutrons from the molecules' nuclei. The amount of radiation received by food depends on its thickness, moisture content and other factors, as well as external variables such as temperature, the presence or absence of oxygen and subsequent storage conditions [30].

Effect of Irradiation on food

The nutritional value of food remains unchanged after irradiation. Food proteins, lipids, and carbohydrates retain quality, and minerals are not significantly affected. Irradiation only causes minor chemical changes in food, not impacting its nutritional value. The moist food is irradiated while frozen and without oxygen, the overall chemical yields are reduced by about 80%. Therefore, irradiating to a cumulative dose of 50 kGy at 30°C is equivalent to irradiating to 10 kGy at room temperature or below. A 1-10 kGy dose can control parasites causing trichinosis in food, while a minimum dose of 0.15 kGy can prevent insect infestation in dried fish. Irradiation is often necessary to ensure the safety of certain exported agricultural products. Radiation can also decontaminate food, even when packaged and frozen [31, 32].

Applications

Irradiation is a process that can eliminate pathogens and parasites in meat and meat products, making them safe for consumption. It also helps preserve the nutritive quality of food, improving its storage life. This process is known as "cold sterilisation" or "electronic pasteurisation." Lower dose irradiation can inactivate more than 90% of bacteria and extend the shelf life of meat. Irradiation in the dose range of 20 to 150 Gy can prevent the sprouting of potatoes, onions, garlic, shallots, yams, and other plants. This process biologically alters the products, significantly reducing or entirely avoiding sprouting. Fruit ripening is one of the physiological processes that can be delayed in the dose range of 0.11 kGy. These changes occur due to enzymatic modifications to the plant's tissues [32, 33].

Pulsed UV-light technology

A technique called pulsed UV light is used to eliminate surface microorganisms. It involves brief bursts of intense, broad-spectrum "white light" between the spectral range of 200 and 280 nm. Though each pulse is only a few hundred million or thousands of times as intense as sunlight at sea level, it still contains some ultraviolet light. When the cell's DNA absorbs the UV light, it produces photoproducts that prevent DNA transcription and translation, ultimately leading to cell death [20].

The three main components of pulsed UV-light technology are: (1) the power unit that generates high-power electrical pulses, (2) the treatment chamber that converts the light source into high-power light pulses, (3) the timing control and trigger generator. The technology effectively removes microorganisms from various foods during processing and packaging [34].

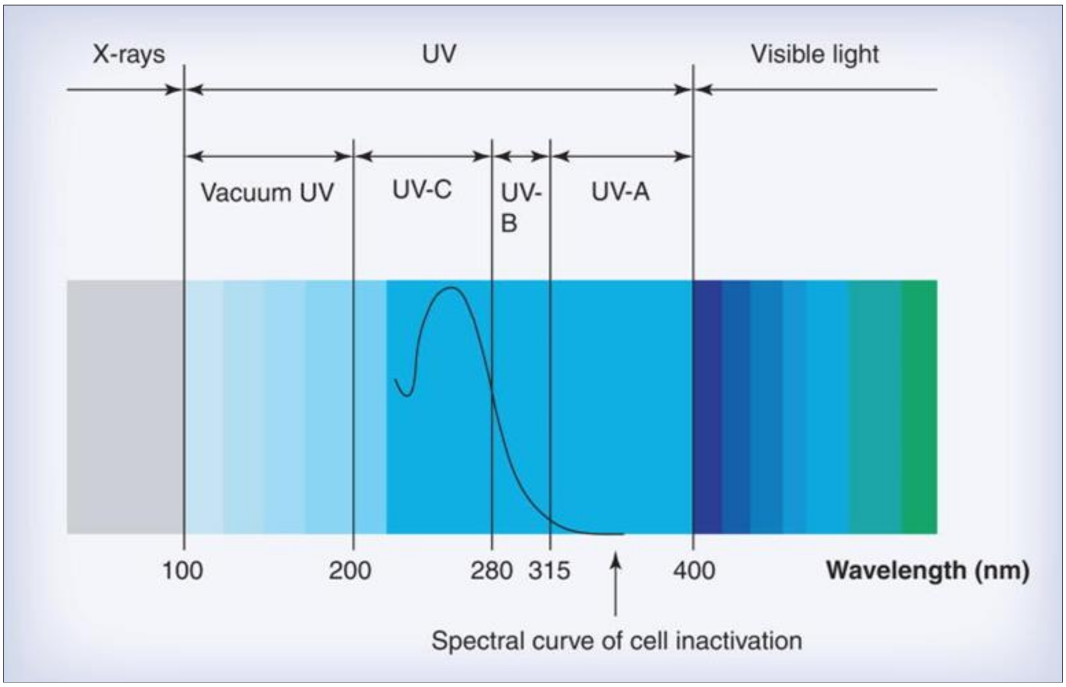

Fig 3: Graphic representation of UV-radiation

UV-C radiation

Ultraviolet radiation-C (UV-C) is a well-established disinfection method for water, air, and packaging surfaces. In 2000, the FDA approved using UV-C radiation for food decontamination. However, its application in meat products and food processing is still limited. Due to its low cost, simple installation and maintenance requirements, non-production of off-flavours, and practical application in meat products, this technology has been considered promising for food processing [35]. The broad spectrum of UV-C radiation between 200 and 280 nm has a germicidal effect, with a maximum response at 253.7 nm. Low-pressure mercury lamps are effective against bacteria, viruses, protozoa, yeasts, and algae [17]. UV-C radiation damages DNA and RNA by inducing thymine and cytosine binding, impairs transcription and replication processes, and inhibits the growth of microorganisms. The formation of pyrimidine dimers from UV-C radiation can prolong the latent microbial phase and speed up the process of microbial generation [36, 37]. Moreover, unsaturated organic molecules can absorb UV light, producing free radicals due to photochemical reactions that indirectly inactivate microorganisms [27]. Therefore, UV-C radiation's effectiveness depends on several factors, such as the type of microorganism, the number of microbes present, the matrix's composition, the geometry of the reactor, the energy emitted, the wavelength, the permeability of the product, and its topography [38, 39].

Cold plasma technology

Plasma is the fourth state of matter, different from solid, liquid, and gaseous states. When matter absorbs energy, its state can change. The intramolecular and intraatomic structures break, releasing free electrons and ions. Plasma is an ionized gas made up of neutral molecules, electrons, and positive and negative ions. Plasma can transfer energy to other gas molecules by colliding with them, creating several highly reactive species that can interact with food surfaces. These species include reactive hydroxyl radicals, hydrogen peroxide, ozone, nitrogen oxide, and UV radiation [40, 41]. The composition of plasma depends on several factors, such as the carrier gas (air, oxygen, helium, nitrogen, and argon), the plasma generator (radio wave, microwave, plasma jet, and dielectric discharges), and the operating conditions (pressure and temperature) [42].

Cold plasma is a method that does not depend on thermal effects to kill pathogens. It is generated at or near room temperature, which helps preserve food quality during treatment [43]. The cold plasma system includes a discharge device, treatment chamber, gas control, and pressure control system. The composition of cold plasma is affected by the type of carrier gas (air, oxygen, helium, nitrogen, and argon), plasma generator (radio wave, microwave, plasma jet, and dielectric discharges), and operating factors such as pressure and temperature [42, 43, 44].

Mechanism

Cold plasma is a mechanism to eliminate microorganisms by generating reactive oxygen free radicals. These radicals affect the macromolecules of microbial cells, including DNA, proteins, and other components, leading to oxidation. The accumulation of charged particles on the surface of microbial cells results in the breakdown of the membrane and the oxidation of cell components [45].

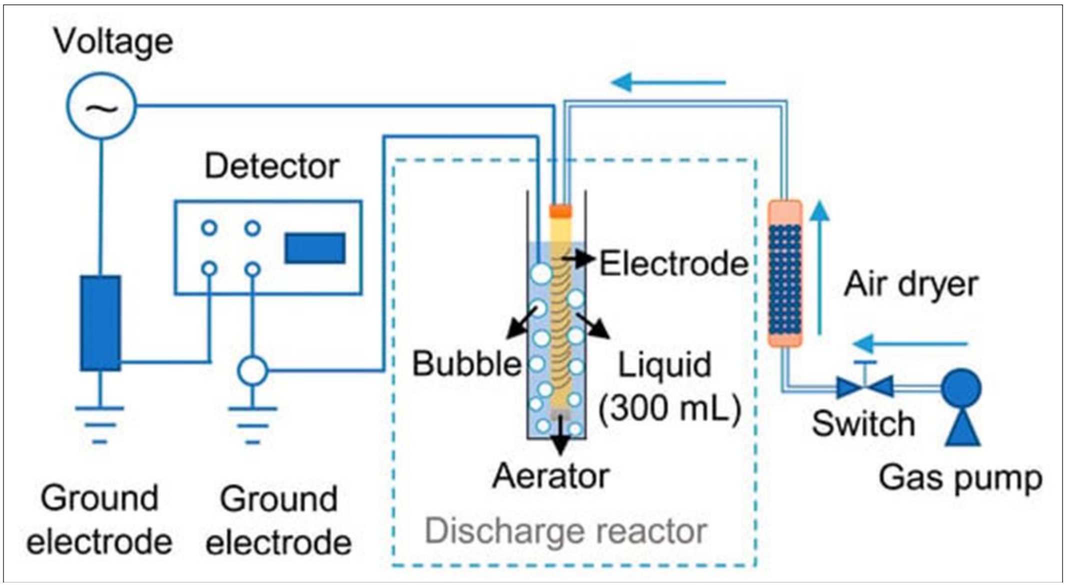

Fig 4: Graphic mechanism of Cold plasma Technology

Cold plasma in food packaging

The most common plasma operations in packaging are labeling, such as labeling jam jars, printing on glass containers, or sealing liquid packaging. A crucial factor in the packaging industry is the ability to reuse materials reliably and affordably. Pre-treatment with an atmospheric pressure tube makes it possible to reuse different materials and coatings that are sometimes very thin, such as in the production of composite packaging. When packages are reprocessed at high speed and a strong bond is required, recesses in the area of the relevant surfaces generally have to be taken into account, especially in the case of high-gloss plastic-coated containers. Using Open-air tube technology, similar high-gloss adhesion points are directly and extensively pre-treated inline to ensure reliable bonding. An atmospheric pressure tube is used for pre-treating glass in labeling glass bottles, allowing the use of a universal and low-cost water-based adhesive [45, 46].

Ozone Processing

Ozone has a strong antimicrobial effect and a wide range of antimicrobial properties that are used in food preservation technology. In the food industry, Ozone has been commonly used to wash and store fruit and vegetables through gaseous treatment. The recent FDA approval of Ozone as a direct food additive has increased the possibility of using Ozone in liquid food operations [47, 48]. Ozone processing in the food industry has been carried out on solid foods through gaseous treatment or washing with ozonated water. With the FDA approval of Ozone as a direct contributor to food, the potential for ozonation in liquid food operations has started to be explored. Several commercial fruit juice processors in the USA have begun using Ozone to meet the recent FDA requirement of a 5-log reduction of the most resistant pathogens in their finished products [49, 50]. Ozone is extensively used in water and wastewater treatment due to its powerful oxidation and disinfection capabilities. As an oxidant, Ozone is utilized in natural water treatment, washing and disinfecting fruits and vegetables, and juice processing to deactivate pathogenic and spoilage-causing microorganisms [22]. Ozone has a strong antimicrobial effect and a wide range of antimicrobial properties that are used in food preservation technology. In the food industry, Ozone has been commonly used to wash and store fruit and vegetables through gaseous treatment. The recent FDA approval of Ozone as a direct food additive has increased the possibility of using Ozone in liquid food operation [47]. As an antimicrobial agent, Ozone has multiple potential applications in the food industry due to its advantages over traditional antimicrobial agents, such as chlorine and potassium sorbates. Ozone processing in the food industry has been carried out on solid foods through gaseous treatment or washing with ozonated water. With the FDA approval of Ozone as a direct contributor to food, the potential for ozonation in liquid food operations has started to be explored. Several commercial fruit juice processors in the USA have begun using Ozone to meet the recent FDA requirement of a 5-log reduction of the most resistant pathogens in their finished products [50]. Ozone is extensively used in water and wastewater treatment due to its powerful oxidation and disinfection capabilities. As an oxidant, Ozone is utilized in natural water treatment, washing and disinfecting fruits and vegetables, and juice processing to deactivate pathogenic and spoilage-causing microorganisms [22].

Dense phase carbon dioxide: Dense phase carbon dioxide (DPCD) processing refers to the use of liquid carbon dioxide (LCD) and supercritical carbon dioxide (SCCD), which is CO2 above its critical point of 31.1°C and 7.38 MPa, or high-pressure carbon dioxide (HPCD). This method is a surfacing, non- or mild-thermal preservation system alternative to high-pressure processing or traditional heating of fruit juices. HPCD, near-critical CD, and SCCD can be used at temperatures and pressures that are relatively safe for heat-labile composites and are sufficient for the inactivation of microorganisms and tissue enzymes. The CO_2 used in this process is relatively inert, affordable, nontoxic, non-flammable, recyclable, and readily available in high purity. It leaves no residue when removed after the treatment process. The effectiveness of DPCD for microbial inactivation depends on several factors including exposure time, pressure, temperature, pressure cycling, original medium pH, water activity, cell growth phase or age, species of microorganisms, and treatment system type. Most DPCD inactivation studies published in the scientific literature were conducted on spoiled or contaminated foods [51]. High pressure facilitates CO_2 dissolution in water and passage through cell walls. It also increases viscosity, which enhances mass transfer. Advanced temperature improves deactivation by enhancing cell membrane fluidity, making them easier to access, and by enhancing CO_2 diffusivity. However, advanced temperatures make CO_2 less effective at penetrating low-volatility substances and less soluble in aqueous media. CO_2 is generally recognized as safe (GRAS), meaning it can be used safely on food products [52].

Non-thermal hybrid drying: Non-thermal processes do not involve heat generation but can induce a change in temperature within a product. In other words, these processes do not depend on the source's temperature. Non-thermal methodologies involve technologies that are effective at room or lower temperatures. These technologies could affect the rise in temperature during processing. Hybrid drying involves the combination of two or more different processing unit operations or drying systems as a single unit or multistage arrangement. The combination of NT (Non-Thermal) and combined convective hot-air drying (CHAD) can improve and control the crucial influence of CHAD, minimize the inflexibility of each technology due to the synergetic effect, enhance the final quality of the dried product, and improve overall drying effectiveness compared to using just combined convective hot-air drying [53, 54, 55].

Combined ultraviolet and hot-air drying: Ultraviolet (UV) radiation falls within the electromagnetic spectrum with wavelengths ranging from 100 to 400 nm. UV light is traditionally classified into UV-A (315 - 400 nm), UV-B (280 - 315 nm), UV-C (200 - 280 nm), which is considered the germicidal range, and vacuum UV (100 - 200 nm). UV technology is nonthermal and free of chemicals and waste discharges, making it an environmentally friendly energy source. Although UV treatment has been associated with the term "irradiation," UV light is non-ionizing radiation and should not be associated with other types of irradiation (e.g., gamma radiation) [54].

UV-combined CHAD is a promising non-thermal technology, especially for artificial operations. When fully developed, this technology has the potential to become an environmentally friendly, easy-to-operate, cost- and energy-effective drying technology [55, 56, 57, 58].

Hurdle Technology

Hurdle technology is a multiple-barrier technology that employs multiple preservative measures strategically applied to control the growth of microorganisms in food efficiently [59]. It is an essential area of food microbiology that describes the potential of multiple preservation approaches that synergistically inhibit microorganisms in foods [60]. The concept of hurdle technology involves optimizing preservation techniques that ensure safe products with more excellent sensory and nutritional quality at lower costs [61]. Combining hurdle technologies has great potential to improve safety, stability, and freshness by minimizing destructive processing and preservation methods [62]. A combination of inhibitor factors or additives at a minimal level limits pathogenic growth by providing cumulative stress that makes microbial survival difficult [63]. For an ideal synergistic action, the antimicrobial should have different mechanisms of action [64] so that different factors can work synergistically by hitting different targets (e.g. cell membrane, DNA, enzyme systems, pH, aw, Eh) in the microorganisms [65]. Combined factors destroy microorganisms by disturbing one or more cell homeostasis mechanisms, preventing multiplication and making the microorganism inactive [66].

There is a need to develop mild preservation methods that will meet the needs of producers and consumers by providing fresh-like foods that are safe, stable, nutritious and palatable. Combining antimicrobial use at lower concentrations disturbs microbial activities more than single antimicrobial use at higher concentrations [67]. The adverse effects of conventional food processing on nutrients, texture and acceptability could be minimized or eliminated by hurdle technology. Intelligent combinations of different hurdles ensure microbial safety, minimize energy consumption, reduce emissions, and increase profit, affordability, and overall quality [68]. Novel physical factors such as hydrostatic pressure, pulsed electric fields, ultrasound, ozone, pulsed light, and ultraviolet light, among others, are now used to replace deleterious processes such as thermal processing [66]. This technology is vital in producing ready-to-eat and ready-to-cook stable products [69].

Principles of Hurdle Technology

Conventional food preservation methods such as heating, chilling, freezing, freeze-drying, drying, curing, salting, sugar-addition, acidification, fermentation, smoking or oxygen removal are used to make food safe and stable [70]. The microbial safety, stability, and sensory attributes of many processed foods, including those traditionally processed, depend on the combined effects of many hurdles. Food preservation methods are more concerned about the physiology and behaviour of microorganisms in foods, *viz*., stress response, homeostasis and metabolic difficulties. The novelty of the multi-target food preservation approach is based on a clear understanding of the physiology and behaviour of contaminating microorganisms [71]. Different hurdles were combined smartly at lower levels to develop preservation measures that are mild but very reliable [72]. Hurdles simultaneously apply barriers (hurdles) such as heat, aw, irradiation, chemicals, pH, and competitive flora to contaminate microorganisms [71]. These barriers act synergistically and induce injuries that are more severe than those of a single barrier. The microorganisms required certain efforts to overcome each of the hurdles. Microorganisms will require more effort to overcome the hurdles when they are many [72].

The most important factors used in the hurdle technology are the intrinsic factors (aw, pH, Eh, and chemicals), the extrinsic factors (temperature of storage and gas atmosphere), and the processing factors (heating, drying, fermentation) [73]. Novel physical factors such as hydrostatic pressure, pulsed electric fields, ultrasound, ozone, pulsed light, and ultraviolet light, among others, are now used to replace deleterious processes such as thermal processing [66]. This technology is vital in producing ready-to-eat and ready-to-cook stable products [74]. Food preservation methods are more concerned about the physiology and behaviour of microorganisms in foods, *viz*., stress response, homeostasis and metabolic difficulties. The novelty of the multi-target food preservation approach is based on a clear understanding of the physiology and behaviour of contaminating microorganisms.

Hurdle Applications in Food Preservation

Application of hurdle technology is progressing globally; the technology is used in developed countries to improve the stability, safety and quality of foods. Hurdle technology has proved to be more helpful in developing countries for creating novel foods that are minimally processed and ambient stable. It also plays a vital role in modifying and improving traditional food to produce stable, intermediate-moisture foods with better sensory qualities. It is essential to know their effects and limits to inhibit or inactivate relevant microorganisms and their side effects on the sensory and nutritional quality of the food [75].

Conclusion

New preservation technologies offer an exciting opportunity to create high-quality food products with a longer shelf life. When evaluating these new technologies, it is essential to consider their impact on the quality and safety of the processed products. Methods such as irradiation, ultrasound under pressure, high hydrostatic pressure (HHP), and pulsed electric fields (PEF) effectively eliminate microorganisms in food. However, their effectiveness is limited by the adaptability of spores, so they are not used as the sole preservation method. These new technologies are seen as hurdles that ensure food safety by eliminating microorganisms while maintaining high-quality products. To fully realize their potential, further research is needed to understand the inactivation mechanisms, especially for HHP and PEF, and to explore the effects of environmental factors and stress adaptation on food safety.

Interest in non-thermal food processing technologies has grown significantly in the past decade. Methods such as ultraviolet (UV) light treatment meet these conditions. UV-C light treatment has effectively reduced microbial pathogens in fresh fruits and vegetables. Combining non-thermal technologies with traditional preservation methods can help overcome current limitations. Exploring the use of advanced or lower temperatures than room temperature is an exciting option to enhance the effectiveness of these new technologies. The use of hurdle technology in food preservation changes the manner of food preservation in recent years. More natural foods are consumed now, and nutrients and organoleptic qualities suffer less. The safety of many foods was improved, and the storage life of many perishable foods was extended. Resistance microorganisms are suffering, and many can be eliminated by a smart combination of different preservatives.

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