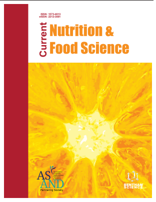
Current Nutrition & Food Science, 2024, *20*, 836-849

REVIEW ARTICLE

BENTHAM SCIENCE

Advances in Non-thermal Food Processing Methods-Principle Advantages and Limitations for the Establishment of Minimal Food Quality as well as Safety Issues: A Review



Anish Dangal[1,2], Prekshya Timsina[3], Sangam Dahal[4], Kishor Rai[2] and Angelo Maria Giuffrè[5,*]

[1]Nilgiri College, Tribhuvan University, Itahari, Nepal; [2]Purbanchal Agritech Pvt. Ltd., Itahari, Nepal; [3]Central Campus of Technology, Tribhuvan University, Dharan, Nepal; [4]Central Department of Food Technology, Tribhuvan University, Dharan, Nepal; [5]University of Studies "Mediterranea" of Reggio Calabria, Department AGRARIA, Reggio Calabria, Italy

ARTICLE HISTORY

Received: February 24, 2023
Revised: May 30, 2023
Accepted: June 08, 2023

DOI:
10.2174/0115734013250808230921105514

Abstract: ***Background***: The demand from consumers for safe, healthy food with a long shelf life, with no change in taste or nutritive value, has made food safety a key concern in today's world. Traditional thermal food processing technology has trouble meeting these standards. Conventional thermal and non-thermal processing has limitations and to overcome these limitations more studies are conducted regarding the novel non-thermal food processing methods.

Objective: The goal of this paper was to present an overview of the research on the development of non-thermal processing techniques, such as electrofreezing, high hydrostatic pressure, pulsed electric fields, ultrasound, pulsed light, and plasma activated water, as well as their advantages and limitations.

Methods: The present review aims to summarize findings related to novel non-thermal processing techniques, gathered from work published in scientific journals, related books, and book chapters from sources such as Web of Science (WoS), Google Scholar, Scopus and ScienceDirect.

Results: Non-thermal treatment may result in more desirable outcomes, such as greater preservation of heat-sensitive nutrients, fewer changes in sensorial as well as physico-chemical quality of the processed foods.

Conclusion: Compared to traditional heat processing, the nutritional value of foods is better preserved, and the sensory qualities of foods are less altered. These novel techniques can be combined with each other to achieve higher efficiency and overcome other limitations. More studies should be conducted regarding the combination of novel non-thermal techniques to achieve greater efficiency.

Keywords: Food safety, non-thermal processing, principle, advantages, limitations, food quality.

1. INTRODUCTION

The food matrix is frequently changed, the nutritional value of food is maintained, and the shelf life is increased by food processing. The food sector is looking for creative and more affordable ways to produce and preserve food items [1]. It is also working harder than ever to raise food safety and quality standards around the globe. There is a serious concern for public health due to a significant rise in the number of cases of food-related illness [2]. Assuring the microbiological safety of food by heat processing is a traditional method [3]. This method causes the sensory characteristics of the food to change due to overheating or lowers the nutrient value of the food products [4]. As an alternative to conventional heat treatments, a number of non-thermal processing technologies have been created due to the increasing customer need for foods with higher nutritional content and fresh-like sensory qualities [5, 6]. Throughout the manufacturing and distribution chain, proper technologies are necessary to prevent unwanted microbiological and fungal contamination, and deterioration, and also to maintain the sensory and nutritional standard of the food [7]. Non-thermal food processing methods have recently attracted a lot of interest because of the increased customer demand for fresh, safe, and nutrient-dense food [8]. In both emerging and advanced nations, foodborne illness caused by microorganisms, as well as other food impurities, poses a severe health risk. Fewer than 10% of foodborne disease cases were reported

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[*] Address correspondence to this author at the Department Agraria, University of Studies "Mediterranea" of Reggio Calabria, Reggio Calabria, Italy; E-mail: amgiuffre@unirc.it

by WHO, with emerging nations reporting below 1% of cases [9]. In 2010, there were 600 million cases of food-borne disease and 420,000 fatalities, according to a recent WHO study. The most common causes of food-borne sickness were agents that cause diarrhea, namely norovirus and *Campylobacter* spp. Mycotoxins, mainly aflatoxin, *Salmonella typhi*, hepatitis A, and *Taenia solium* were also major causes of foodborne mortality [10].

To combat food safety issues, many food preservation methods, such as reduced water activity (a_w), freezing, pasteurization, sterilization, acidification, drying, dehydration, antimicrobials, and fermentation have been investigated. Some of these technologies, however, have a negative impact on the sensory attributes and nutrition of food. Furthermore, contamination of food and microbial deterioration are significant issues that have not yet been fully addressed [11]. To prevent diseases caused by microorganisms and to guarantee that food products retain their original flavor, color, taste, and form, experts from the food business have worked to improve food processing techniques. Microbial status as well as other processes, such as biochemical and enzymatic reactions, alteration of structures, *etc*., are strongly linked to the safety and longevity of food. It also can indirectly have a substantial impact on how people perceive the quality of food. Despite the growing study of non-thermal technologies to counter the mentioned issues and their advantages, the non-thermal methods still have some limitations. The food industry uses sanitizers to assist in the destruction of microorganisms on surfaces of utensils and equipment as well as in food. The efficiency of a sanitizer to help eliminate infections is, however, diminished when bacteria adhere to food [12]. In order to achieve the highest level of efficiency for microbial inactivation, gas plasma has been applied directly over food products in the majority of studies performed. However, a small number of studies have shown that following the surface treatment, there are certain negative impacts, including color loss, surface topographical changes brought on by etching, and breakdown of bioactive components [13]. Fumigation is a treatment process in which a gas at certain concentration is supplied with the hope that it would spread uniformly, penetrate objects deep down to kill microbes and/or pests. Agricultural products, food items and food processing plants have a high demand for fumigation [14]. Ethylene oxide gas is banned in European Union (EU) for its uses in food because of its carcinogenic nature [15]. But still it is used as a fumigant in some parts of the world. To overcome all these issues related with conventional techniques, many studies have been carried out in novel non-thermal techniques. The goal of this review was to summarize the studies on novel non-thermal processing methods such as pulsed electric field, nano-technology, plasma activated water, high hydrostatic pressure, pulsed light processing, ultrasound, and electrofreezing. The principles and some of the advantages and limitations related to food quality and safety are also discussed.

2. NANOTECHNOLOGY

Nanotechnology is increasingly regarded as an appealing technology that has transformed the food industry [16]. The field of nanotechnology is just beginning to revolutionize many industries, including the food industry as well as mechanics and medicine. It is the study of manipulating and controlling matter at the molecular and atomic scale with at least one characteristic dimension often between 1 and 100 nm, known as nanometer range [17]. Nanomaterials differ from their macroscale counterparts in a number of ways [18]. It is thought that a nanoparticle works as a single entity with distinct traits and functions, creating a new activity level [19]. The rapidly evolving field of nanotechnology has an impact on all aspects of the food supply chain and system. Nanotechnology applications in the food packaging industry include mechanical, thermal, and barrier improvements to packaging as well as biodegradable and mechanical, thermal, and durability improvements to packaged goods [20]. Nanomaterials which have several applications in the food industry, are broadly classified as (1) nano-particles, (2) nano-clays, (3) nano-emulsions, (4) nano-laminates, (5) nano-capsules, (6) nano-fibers, (7) nanotubes, and so on, and can be created using a variety of processes [20].

2.1. Principle

All living organisms are nanoscale entities. The compounds that make up the foods we eat -carbohydrates, proteins, and fats- are formed by the nanoscale union of sugars, amino acids, and fatty acid molecules [21]. Nanoscale structures include cell membranes, hormones, DNA, and other components that are found in nature [22]. The food sector often uses either a ‘top-down’ or ‘bottom-up’ method for nanotechnology [23] or by combining both methods as per the requirement as well as the principle and engineering of the nano-particles to be used [24]. The 'bottom-up' method makes use of self-assembling properties of the molecule by balancing different interactions of non-covalent bonds, while the 'top-down' method utilizes physical processes like milling to reduce the size of particles resulting in the formation of nano-particles [23, 25]. Nano-particles can be used directly to remove chemical impurities or harmful microbes from food [26] and create magnetic nanoparticles with amine-functionalization to eliminate bacterial infections. These nano-particles provided high efficiency (88.5-99.1%), fast and effective bacterial eradication from water and food matrices [27]. The usage of nanotechnology in the food sector includes packaging, food biosecurity and safety, and nano-particle delivery systems [28]. Carotenoid nanoparticles could be dissolved in water and also blended into fruit drinks to improve their bioavailability. Nanosized micellar system based on canola was reported to supply nutrients like vitamins, minerals, or phytochemicals [29].

2.2. Advantages

Many industries have praised nanotechnology for its accomplishments. Being an intricate biological system, foods undergo a range of processing. Nanotechnology could be used to add fruits and vegetables to foods to increase their nutrient density. Food ingredients at the nanoscale can be encapsulated and combined in various ways with other foods [30]. This technique also appears to help dissolve additives that are not typically soluble, such as vitamins, minerals, antioxidants, phytochemicals, and healthy oils. Many items that are typically opaque or transparent can be made clear by using nanoparticles [31]. Spraying, immersion, or rubbing are common ways of applying edible nano-coatings [32]. They are usually made of eco-friendly components and are not required to be eliminated from food before consumption [33]. In order to add to the flavor of products, color, enzymes, antioxidants, and anti-browning substances, edible nano-coatings of ~ 5 nm thickness are applied in the meat processing business, agriculture industry (to protect fruit and vegetable products), cheese and bakery industry, and so on [26]. Food additives at the nano scale can be used to boost nutrition, enhance texture and flavor, and also to trace pathogens. The packaging of food involves edible nano-wrappers that enclose foods, limiting the exchange of gas and moisture, smart packaging with antimicrobial activators and nano-sensors for identifying spoilage of food and distributing nano anti-microbes to prolong the shelf life of food [34]. Nanowires and antibodies have been used in various devices to identify various toxins, pathogens, and chemicals in food packaging [35]. For example: Biogenic silver nanoparticles were added into polyvinyl alcohol-chitosan films to increase their antimicrobial activity. These films have >99.9% bactericidal effectiveness against *S. aureus, E. coli*, *B. cereus*, and *L. monocytogenes* [36]. Nanoparticle applications are not restricted to antimicrobial food packaging. Nanolaminates and nanocomposites have now been widely utilized in the packaging of food to extend the shelf-life of food and also to provide a barrier from severe thermal and mechanical damage [29].

2.3. Limitations

The rapid spread of nanotechnology in the food sector has, despite its many benefits, created concerns about public safety as well as environmental issues. There may be major differences in the physical, chemical, and biological properties of nanomaterials and those of their conventional forms, and these unidentified characteristics could lead to unpredictable risks [37]. Although nanotechnology has the potential to be beneficial in many aspects of food production and processing methods, most of the techniques are either too costly or too impractical to be used on a large scale for commercial purposes. For this reason, developing new functional materials, formulating foods, processing food at the nano and micro-scale levels, storage, and product development are all sectors of the food industry where nanoscale approaches are most cost-effective [38]. Nano-tubes may be categorized as potentially harmful nanomaterials due to the buildup of carbon nanotubes in living creatures and also the resulting production of reactive oxygen species. The structural alteration, size distribution, surface charge, contaminants, and functionalization are the key factors to influence their level of toxicity [39]. Because of their toxicity, the extensive use of emulsifiers and organic solvents in the manufacturing of nanocarriers can pose hazards [40]. In addition to the many advantageous applications of nanostructures, the increased usage of nanomaterials results in the excess production of reactive oxidative species due to the large number of active organic and inorganic compounds used in sensing and packaging of foods, resulting in cell-damaging effects [41]. According to a study [42], *in vivo* toxicity of nanoparticles of many metal oxides as well as metal species with anti-microbial capabilities have been shown to pose substantial health risks when consumed over a prolonged period of time. Silver and zinc oxide nanoparticles leached from packaging into the food, whereas nanoparticles of silver leached notably into exudates of meat [43]. Chewing gum has been found to release nano titania, which accumulates in the body and causes serious toxicity [44]. Mutation of DNA, apoptosis, unregulated cell signaling, allergic pulmonary inflammation, altered cell motility, cytotoxicity, and untreatable diseases such as cancer are all potential effects of severe nanotoxicity [43].

3. OZONE TREATMENT

A green, cost-effective, and useful technique that has attracted the interest of the food industry is the use of liquid or gaseous ozone in food. Ozone's oxidation effect has antiviral and antimicrobial activity, stimulates modification of starch, can eliminate pests and also can increase food quality and safety by degrading pesticides [45]. A strong oxidant, ozone (O_3) has been classified as GRAS (Generally Recognized as Safe) [46]. The use of ozone for wastewater treatment, sanitizing equipment in food plants, and treating fruit and vegetables has now been made possible due to this classification [47]. Ozone, in both aqueous and gaseous forms, is largely utilized as an anti-microbial agent and disinfectant for maintaining food safety. Ozone treatment has been proven to inactivate a variety of microorganisms, including fungus, Gram +ve and Gram -ve bacteria, protozoa, fungal spores, and viruses [48]. As a precursor, oxygen is used. The reaction between diatomic oxygen and free oxygen radicals results in the formation of ozone. Free radical oxygen is produced by the use of UV radiation as well as corona discharge-based processes. When the rates of generation and destruction are equal, high-purity oxygen can produce up to 6% of ozone [49]. On-site generation of ozone is performed for its use [50]. Ozone can also be used for the treatment of fruit juice [51].

3.1. Principle

Microorganisms are inactivated in the gaseous phase during ozonation at a constant flow rate, pressure, and specific concentration of ozone depending on the contamination level [52]. When ambient air is subjected to a source with high energy level such as electrolysis, ultraviolet or corona discharge, O_3 gas is produced. A UV meter can be used to measure the amount of O_3 gas [53]. When air or any other gas containing regular oxygen is exposed to a source with high energy, the resultant change in oxygen molecules creates ozone. Ozone is unstable and must be produced on-site to be used instantly since it quickly turns into regular oxygen. Ozone at 20°C in distilled water has a half-life of about 20-30 min [54]. Ultraviolet radiation, electrical discharge, and electrochemical reaction are the three main methods to produce ozone. The most commonly used commercial technique is the electrical discharge technique, which has a relatively low efficiency of about 2 to 10% and high power consumption. UV radiation and electrochemical techniques are less economical [50].

3.2. Advantages

Ozone is a technology that has been successfully used for antiviral, antimicrobial, antifungal, and antiparasitic treatments [55]. Ozone treatment uses significantly less energy than thermal, microwave, and radiation treatment [54]. Because of its swift impact and powerful oxidative properties, the food preservation and processing sectors frequently use ozone to ensure the safety of microorganisms in food. It rapidly undergoes to form molecular oxygen, ensuring that the food products are free of dangerous halogenated compounds [53]. As a result of its high oxidation potential in alkaline, ozone is a powerful anti-microbial agent [56]. At relatively low concentrations, it kills various types of microorganisms and fulfills the demand for ecological sustainability. Ozone will oxidize organic materials into safer substances. Ozone generators that use oxygen as the supply gas could be used for on-site production of ozone [57]. It is applicable to various kinds of food items, including beverages, spices, vegetables, fruits, meat, and fish [58]. Fresh produce, such as fruit and vegetables, dairy products, liquid foods, and grain products have all been treated with ozone [59, 60]. The process considerably extends the microbial shelf-life of the foods. In addition to microorganisms, ozone treatment can effectively remove mycotoxins and storage pests from food products [61]. Cereal items that have undergone ozone treatment are considered to be safe to eat [46]. It is clear that ozone possesses a huge ability to enhance the functionality of grain products while assuring the safety of food [62]. The excess ozone instantly breaks down to form oxygen and leaves hardly any residue in food is a key benefit of this technique [49]. Ozone treatment prevents tomatoes from becoming red and going bad. When kept at 15°C, the shelf life of tomatoes treated with ozone was extended by 12 days [63].

3.3. Limitations

Commercial-scale ozone plants, in particular, have large starting capital and maintenance expenses. Above 4 ppm, ozone is corrosive and often very poisonous when inhaled, making monitoring essential, especially in indoor applications [64]. Given the complexity and necessary occupational safety precautions for large-scale commercial (especially industrial) ozone processes, operators with specialized training would be needed for an ozone processing plant. Another disadvantage is the reaction of ozone with organic materials, which may reduce the effectiveness of treatment or antimicrobial action [65]. Ozone has the potential to alter the biomolecules in food and produce byproducts. It produces bromate, a possible carcinogen, when it combines with bromide. Aldehydes and ketones are created when ozone reacts with biomolecules by oxidizing polyunsaturated fatty acids [66]. Another significant downside is that it is not well accepted by customers because it is thought to have toxic characteristics [67]. If high concentrations of ozone are necessary to lower the microbial population, caution needs to be taken because this could hinder the preservation of food quality by causing toxic symptoms. The loss of weight, firmness, and water content, as well as changes in color and volatile component content, are the most relevant symptoms for foods [68]. The fruit juices had certain unfavorable impacts as a result of the ozone treatment [69]. More than 90% of the color and anthocyanin in blackberry juice were degraded by ozonation.

4. PULSED LIGHT PROCESSING

Along with other significant technologies, pulsed light processing is a promising non-thermal technology for the preservation of food [70]. Pulsed light processing (PL) often entails a wide variety of short yet incredibly energizing pulses from the bandwidth of white light, which is known to contain ultraviolet, infrared, and visible light. In comparison, the power of pulsed light is 1,000 times greater than that of normal ultraviolet light, which is relatively constant [71, 72]. The pulsed light food processing method, created as a non-thermal food processing method, works by discharging electric pulses of high voltage (≤ 70 /cm) for a few seconds at a rate of 20 flashes/ sec into food positioned between two electrodes [73]. It is a decontamination technique that aims to reduce pests, spoilage microorganisms, and pathogens from food while having little to no effect on the qualitative aspects of the food. The technology can be considered as a technique used for decontamination or sterilization. Pulsed light processing is primarily used to inactivate surface microbes on food, packing materials, as well as equipment [74, 75].

4.1. Principle

The principle of pulsed light is the application of rapid, strong, broad-spectrum light pulses [76]. It involves using inert gas flash lamps to convert short-duration and high-power electric pulses into short-duration and high-power pulsed radiation that has a spectrum comparable with that of the Sun *i.e.*, 200–1100 nm [77]. Since ultraviolet light makes up a sizable section of the pulsed light spectrum, it is believed that ultraviolet light is crucial to the inactivation of microbial cells. Additionally, it was discovered that using a filter to exclude the ultraviolet (UV) wavelength lower than 320 nm had no killing effect [78]. To create photoproducts in the DNA, ultra violet (UV) light is absorbed by deoxyribonucleic acid in cells, which promotes cell death by interfering with DNA transcription and translation [79].

4.2. Advantages

Pulsed light (PL) treatments employ xenon flash lamp, which are safe because of their mercury-free features, and do not require synthetic preservatives and chemical disinfectants, so they allow the decontamination of packaged as well as unpackaged food and contact surfaces while producing no residues [80]. Additionally, this technique has a low cost of operation, a higher level of acceptance from consumers [81] and the choice of operating in batch or continuous mode.

The pulsed light technique uses lowered processing time and high-throughput since it is a more effective and rapid technique for the inactivation of microbes compared to continuous ultraviolet light, for an equal amount of supplied total energy [82]. Pulsed light is a food processing method used for fast disinfection. Furthermore, it does far less harm to the nutrient value of the foods to which it has been applied [83]. This technique has a clear advantage over UV radiation as it transmits energy in a very short period of time. In addition to the fact that pulsed light significantly reduces bacteria in a very short period of time, it is also highly adaptable and eco-friendly. As a result of pulsed light treatment, the threat posed by microbes responsible for food-inherent disease is lowered as well as food shelf-life being prolonged, and a higher economic return was expected, mainly during the period of transportation [84]. Additionally, pulsed light has demonstrated promising outcomes in preventing packaged products from contamination and is also known for its usage even though the food is within the packaging [85]. Bialka and Demirci used PL of about 72 J/cm^2 fluency in the surface of the raspberry and were able to reduce *E. coli* 0157:H7 by 3.9 log and *Salmonella* by 3.4 log, with very little fruit damage being detected [86].

4.3. Limitations

To be successful, pulsed light requires a significant investment of resources and costs. Foods that are opaque and have irregular shapes have been found to not be ideal for the application of pulsed light because they may serve as breeding grounds for bacteria [84]. Additionally, long PL treatments might have a “heating impact” on foods, which ultimately reduces the efficiency of bacterial killing [87]. According to studies performed, pulsed ultraviolet (UV) light can influence the texture and color of food, depending on the dosage of energy, and also the distance between the sample’s surface and the lamp [88]. As a technology used for decontamination of surface, the matrix composition and opacity have a significant impact on how effectively the treatment works. Additionally, it has a high initial investment cost, temporary lamps with a short lifespan, overheating of samples, high intensity results in changed color and pH [89], and the potential for ozone generation [90]. Slices of apples treated with pulsed light had decreased flavor, abnormal flavor, and a deeper brown color than untreated ones [91].

5. PULSED ELECTRIC FIELD

Foods are kept in between two electrodes and exposed to electrical pulses of high voltage for a brief period of time (from a few nanoseconds to a few milliseconds) in pulsed electric field (PEF) technology. This prevents any heating effect on the food [92]. Process variables, medium, and microbial parameters are crucial elements that may affect the inactivation of microorganisms utilizing PEF [93]. The strength of the electric field, temperature, time of exposure, and shape as well as width of pulse wave are all factors in PEF processing. Electric fields are created using equipment that is comparable to radar. A short square wave is generated by the most typical equipment, which also reverses polarity to prevent electrode degradation. Sinusoidal and exponential decay are two other waveforms that can be generated [73].

5.1. Principle

A capacitor is used to store energy during PEF processing, collected from a power source with high voltage, and released through foods in a treatment chamber which may be either stable or moving. This method uses short electrical bursts ranging from submicroseconds to milliseconds, which have negligible impact on the quality parameters of pumpable foods. This method discharges high voltage ranging from 10–80 kV/cm for less than a second at near-room temperature, into food held between two electrodes, followed by aseptic packaging and distribution of the food in the refrigerator [94]. This method, by breaking the cellular membranes in the liquid medium, kills most pathogenic bacteria with a 5-log reduction [73].

5.2. Advantages

PEF is recognized to preserve nutrients (for foods that are sensitive to heat), sensory qualities, encourage durability, and guarantee food safety. PEF, in comparison to conventional heat processing methods, is taken as a highly energy-efficient and environmentally friendly technique that also uses as little energy as is feasible [95]. In the processing of watermelon juice, PEF performed better than various non-thermal techniques, allowing the retention of significant amounts of anthocyanins after processing, in addition to its bacteriological actions against microorganisms [96]. It was shown that PEF had a number of advantages over conventional heat processing techniques for the treatment of juice, including lower energy costs, faster processing times, a reduction in the impacts of heat on components of food, and improved mass transmission [8]. Bhat *et al.* found that PEF improved chew ability by adjusting the distribution of sodium and salt, enhancing the salty flavor in food products. Bioactive component extraction from the by-products of food can be improved with the usage of PEF. After a PEF treatment, cranberry bush purée produced high levels of total soluble solids content, indicating a significant enhancement in the extractability of bioactive components [97]. Additionally, after treatment of PEF with 3 kV/ cm and 5-15 kJ/ kg, there was a rise in the preservation of bioactive components, with total phenolic content (TPC) of about 10–14% and total flavonoid content (TFC) of about 6–8% [98]. A study [99] treated whole milk with PEF to inactivate Gram$^+$ve and Gram$^-$ve bacteria at various doses, times, and temperatures. At the dose of 22–28kV cm^{-1} applied at 50°C for 17–101µs, the bacterial population was reduced by 5–6 log.

5.3. Limitations

PEF has a minor impact on microbial spores, is not suitable for products containing or producing air bubbles, and is ineffective on products with greater or varying electrical conductivity [100]. The downsides of PEF include high start-up expenses, which is one of the biggest barriers to using PEF on a large scale. The different types of equipment necessary for its initial setup are extremely costly [95]. Another concern is a lack of efficient processing. This may be the result of certain bacterial cells having developed resistance to PEF. Over time, this could pose a concern to the public's health [101]. Compared to partially liquid or solid foods like juice, PEF has reportedly not yet proven to be effective in treating solid foods [102].

6. HIGH HYDROSTATIC PRESSURE

Many nations, including South Korea, Japan, Mexico, Spain, and the United States, use high-pressure technology, and sales of this technology are rising quickly each year [103], reaching US $10 billion. High-pressure units are employed mostly in the Americas and have been increasing exponentially at an annual rate. The USFDA and USDA have authorized this technology to be used in food processing systems. As a result, the National Advisory Committee on Microbiological Criteria for Foods (NACMCF) recommended a redefinition of pasteurization, and HHP is also included as an additional non-thermal pasteurization technique. Ultra-high-pressure processing and high hydrostatic pressure (HH-P) are other names for high-pressure processing (HPP). As a non-thermal process, HPP typically uses pressures between 100 and 800 MPa. It is quite often used in the food industry to inhibit bacteria and increase the safety as well as quality of food items by reducing food destruction [104]. Foods are subjected to synchronous, and uniform pressures from all directions, as air and water are compressed in HPP resulting in irreversible changes to food appearance [105]. It is possible that such high pressure will alter the structure of related proteins. Typically, proteins undergo structural changes between 200 and 300 Mpa of pressure [106-108]. According to [109], HPP can significantly extend the cold-storage period of food and ensure the safety of any food under non-thermal circumstances or without the use of preservatives. Compressing the water surrounding the food serves as the foundation for applying high pressure. Typically, effects on biological materials become irreversible at pressures greater than 100 MPa. As a result, treating food at pressures between 100 and 1,000 MPa may be beneficial. Pressures up to 200 MPa may be employed for effects that are reversible. Alterations in the permeability of the cellular membrane are thought to be the cause of microbial mortality under greater pressures. Without negatively altering the sensorial qualities and nutrients of the food, high-pressure processes can make hazardous microorganisms inactive, enhancing the overall quality of food. Reactions connected to volume compression are strengthened by HPP. Low-molecular mass components are likely to be relatively unaffected by the breaking of covalent bonds since the change in volume is minimal [109]. Avocado, fruit-based, and meat-based products are the three industries that were the first to employ high-pressure processing (HPP) and are also the ones that hold the most market share for the technology [110].

6.1. Principle

The majority of spoilage and pathogenic organisms, as well as both Gram-positive and negative bacteria, can be effectively inactivated by the HPP technique, where water is used as a medium for transmitting pressure into the food samples. HPP has little influence on the flavor, texture, appearance, and nutritional content of food products [111]. In food processing, the range of pressure is normally between 300 and 600 MPa. The efficiency of microbial inactivation is affected by the temperature, holding duration, and pressure used, as well as the resistance of the microbe and the food matrix to HPP processing [111]. The heat exchange and temperature measurement system, pressure generation and maintenance system, process control system, and treatment chamber are all necessary components for the HPP system [107, 112].

6.2. Advantages

High hydrostatic pressure provides the food industry with a unique, emerging method for the preservation of food that lowers the loss of nutrients as well as physicochemical quality while meeting public demand for food items that taste similar to those that are freshly prepared [113]. The improved food safety and longer shelf life provided by the HHP process are a result of microbial inactivation, which is one of the main benefits of this technique [111]. Because covalent bonds are not broken, there are very few chemical changes in HPP-processed foods [114]. Food products that go through HPP retain the majority of their original nutrients and are simple for humans to digest [115]. It was discovered [115] that contrary to heat treatment in a cell model system, HPP has a positive influence on the regulation of Ca and P bioavailability. In contrast, the nutrition of food products may be significantly destroyed by conventional thermal procedures or the high-temperature short-time (HTST) approach, which uses extrusion and compression. Natural foods with minimum processing, or foods free of chemical additives can be produced with HPP without reducing their quality or safety [116]. Without negatively altering the sensorial quality or nutrient content of the food products, high--pressure processes can inactive hazardous microbes, enhancing the food's overall quality. High hydrostatic pressure improves reactions related to compression of volume. The impact of HPP on components with low molecular mass is likely to be minimal since volume changes following covalent bond breakage are low [109]. Furthermore, this technique can be advantageous in enhancing the extraction of components with health benefits due to its extract impact as a substitute for the heat extraction of foods that are sensitive to heat [117]. This technique could help in enzyme inactivation, and with a minor impact on color and flavor components of food items having lower molecular weight. It also can reduce the Maillard reaction, and drawbacks such as aroma and color fading due to the usage of conventional thermal pasteurization technology can be removed [118]. A comparison was made [119] between the effect of high hydrostatic pressure and heat treatments on the antimicrobial property of Manuka honey and it was discovered that without degrading the quality of honey, HPP can be used to increase antimicrobial action. The HPP technique can assist with the shucking of oysters while preserving the flesh quality and recovering up to 100% of the meat [120]. HPP-treated fruit juice had a vitamin C level similar to fresh juice that had been chilled, which revealed that the HPP method had little impact on the bioactive components of food [96]. Because of the denaturation and aggregation of treated protein under high-pressure, HHP has recently been looked into as a potential use for decreasing the immunoreactivity of food [121]. However, after the operational pressure has been reached, maintaining the pressure typically requires no additional power. HPP needs no additional energy for cooling the food items after the intended treatment time, in contrast to conventional heat-using technologies [122].

6.3. Limitations

High hydrostatic pressure is used mostly for high-quality foods in order to preserve their freshness as well as nutritional qualities, identical to that of an unprocessed product, as it is more expensive than thermal as well as non-thermal methods of preservation [123]. There is a growing need for high--pressure equipment, which is costly and challenging to produce, due to considerations of durability, pressure resistance, and container wall thickness. When compared to thermal sterilization, the early phase's production efficiency is inferior due to high initial investment capital, irregular operation, low workload, and low production volume. As a result, the initial phase's production cost is higher [124]. High hydrostatic pressure is not recommended for use in foods that are porous or dehydrated [71]. This is due to the fact that, despite such items needing to be kept in a dry environment, water is necessary for the HPP process [125]. Furthermore, goods that have been HPP treated must be stored in the cold or a refrigerator. This is due to the fact that using pressure in combination with such temperatures is more successful at inactivating vegetative microbe cells than using pressure alone. The HPP approach could end up being expensive and difficult. For HPP products, plastics seem to be ideal as packaging materials because packaging materials that can be compressed to at least 15% are required [125], this shows up as a drawback because it restricts the usage of a variety of packaging materials. High hydrostatic pressure also has been related to negative effects on components of milk and dairy-related products [126].

7. PLASMA ACTIVATED WATER

According to scientific terminology, the 4th state of matter is known as plasma and is made up of electrons, both negative and positive ions, neutral and excited atoms, UV photons, free radicals, and molecules in their ground as well as in an excited state [127]. Recently, there has been great interest in cold plasma on the part of the agricultural and food industries, particularly for the preservation and sterilization of food [8]. The use of plasma-exposed water has generally been accepted as an alternative technique for disinfecting microorganisms in food items [128]. Plasma-activated water has remarkable and broad antibacterial action, making it a cost-effective and environmentally friendly disinfectant that opens up possibilities of new opportunities for use in the biomedical, agricultural, and food sectors [128, 129]. PAW ice was used for the preservation of food [130].

7.1. Principle

In general, atmospheric cold plasma discharges fall into three types namely - direct discharges within liquids, multiphase discharges, and discharges in the gas phase over the surface of liquids. The most typical sources of plasma used to create plasma-activated water are surface micro-discharge, dielectric barrier discharge, gliding arc discharge, and plasma jet. Reactive species are produced and the physicochemical characteristics of the treated solutions undergo dramatic changes when plasma comes in contact with liquids. These complex chemical reactions take place at the interface of the media used [131].

7.2. Advantages

Plasma-activated water (PAW) treatment at higher temperatures also increased the inactivation efficiency of microorganisms in foods, like grapes [131], beef [132] and kimchi cabbage with salt [133]. Taylor *et al*. found that PAW used immediately after production showed a 5.6 log reduction and after aging for 30 min showed 2.4 log reduction of *E.coli*. The decrease rate stayed at about 1 log on day 1 and day 2, but on day 7, the reduction was not observed [134].

7.3. Limitations

The operational costs are increased by the usage of inert gases in the plasma production process [128, 135] Surface roughness has a significant impact on PAW's ability to inactivate a substance. Fruits often have microorganisms attached to them or trapped inside their grooves or cavities, shielding the cells from washing or disinfecting procedures.

8. ULTRASOUND

A pressure wave oscillating within the frequency band required for ultrasonic operations *i.e*., 20 kHz to 10 MHz, can be referred to as an ultrasound [136]. Power ultrasound can transport a large quantity of power *via* tiny mechanical actions, which reduces processing times, boosts reactivity, and improves the mass transfer phenomena [137]. Various ultrasonic systems and factors can be utilized for a range of applications in the food industry, including the extraction of bioactive components from food samples, and the processing and preservation of food [138]. As mentioned [137], membrane filtration enhanced by the use of ultrasound, commonly known as acoustic filtration, is a recently suggested alternative. The utilization of ultrasound in membrane technology has been shown to improve the efficiency of filtration by puncturing the layer of cake formed at the surface of the membrane [139]. The development of active augmentation methods like vibrating modules has been observed in recent years. Vibrating modules promote particle back diffusion into the bulk solution by producing larger shear rates, which raise the turbulence at the membrane surface. However, the disadvantage of this system is the large energy input demand and also the complexity of the rotating components, resulting in the increase of operating expenses and has prevented their scaling-up until now [140].

8.1. Principle

There are three varieties of ultrasound: power ultrasound within the range of 16-100 kHz, high-frequency ultrasound within the range of 0.1-1 MHz, and diagnostic ultrasound within the range of 1–10. Sound waves of a frequency higher than the range of human ability to hear *i.e.*, around 20 kHz, are defined as ultrasound. When sound travels in a medium, the movement of uninterrupted longitudinal waves results in sound waves that can cause the medium's particles to alternately compress and rarefy, followed by the bursting of bubbles resulting in cavitation [141]. When gas bubbles are created in a liquid medium by energy from sonic waves of frequency greater than or equal to 20,000 Hz (ultrasonic waves), they immediately rupture, significantly increasing the temperature and also creating a rise in pressure. The generation of free radicals, localized heating, and thinned cell membranes are the main causes of microbial death [73]. Ultrasound-induced cavitation can quickly raise temperatures up to 5500°C as well as raise pressure up to 50 Mpa [141]. It is also employed to speed up mass transfer, displace particles, damage cellular membranes, and alter the molecular structure of components [142].

8.2. Advantages

This technology has the advantages of being simple, energy-efficient, and economical [143-145]. In the last few years, ultrasound has demonstrated various uses in the food business as a technique that is both economical and ecologically beneficial [146]. According to a study [8], ultrasound technique has several advantages, including a considerably shortened treatment period for food products, minimal energy usage, and higher input as well as output of material. Additionally, it has gained popularity since it is thought to be secure and environmentally friendly [72]. The procedure is also thought to be highly practical because it is less complicated and expensive than traditional heat processing methods [147]. It was reported [148] that applying ultrasound to dairy products manufactured with probiotics reduced processing time and boosted probiotic viability. High-intensity ultrasound increased oligosaccharide levels, and decreased acetic and propionic acid, resulting in lowered unfavorable taste, and decreased use of basic ingredients like prebiotic, beta-galactosidase in dairy items with lower lactose levels. High-intensity ultrasound was found to shorten the ripening period in dairy products like cheese while accelerating proteolysis, improving the nutritional, textural, and sensorial qualities. According to the study performed by Ojha *et al*., for food fermentation, ultrasonic waves at low frequencies ranging from 20 to 50 kHz can enhance cellular permeability as well as mass transfer, resulting in higher process efficiency and rate of production. Low-frequency ultrasound may also boost the occurrence of probiotics. The process would result in fast hydrolysis of lactose as well as transgalactosylation of bifidobacteria, and also reduces the fermentation time by up to 30 min, all of which would be dependent on the probiotic culture. Furthermore, the researchers demonstrated that ultrasound may be applied to eradicate microbiological organisms that can interfere with the process of food fermentation [149].

8.3. Limitations

Free radicals may be produced during the cavitation process when ultrasound is applied to liquid food products, which could initiate the degradation in food product quality [89]. Following this, lipid oxidation, protein denaturation, and vitamin c degradation occur, which all have an adverse effect on sensory characteristics [150]. Ultrasound technology has been found to have negative impacts on food qualities, including sensory parameters and nutrient content [8]. Additionally, high power ultrasound (20 kHz) has been demonstrated to only partially inactivate some microorganisms, particularly *Listeria monocytogenes*, under ambient temperature and pressure. This can be improved by either raising power of the sonication or by increasing the pressure (manosonication) [151]. According to a study [152], contact ultrasound exposure would be more dangerous than airborne ultrasonic exposure since air transfers much less than 1% of this sort of energy. The industrial scale of ultrasound appears to still have limits due to the dangers it brings to the operators or workers: reports suggest that ultrasound can expose operators to occupational hazards.

9. ELECTRO FREEZING

The term ‘electro-freezing’ refers to a process of freezing facilitated by current flow or external electric field (direct field and alternating field). Various studies were carried out by passing a direct current or alternating current voltage between electrodes directly in contact with [153] or without making direct contact with the sample [154, 155].

9.1. Principle

9.1.1. Electric Charge Flow Assisted Freezing

It is typically performed by providing an uninterrupted or pulsed high direct current between electrodes kept relatively close and directly in contact with the subject. The process is often used to enhance nucleation in supercooled fluids at higher nucleation temperatures than spontaneous nucleation temperatures [153].

9.1.2. Freezing Under External Electric Field

The first ever static electric field-facilitated experiment of freezing was carried out by another study [156]. It has been noted that the static electric field (SEF) treatment affects all phases in the process of freezing. The use of SEF while freezing enhances nucleation at a relatively low degree of supercooling, reduces the time period to persuade nucleation (induction time), extends the phase transition period, and initiates nucleation when compared to conditions with no field [155, 157]. The potential of nucleation of ice during the freezing process influenced by a static electric field is determined by the intensity of the static electric field and the temperature of nucleation. Under SEF conditions, the possibility of nucleation rises as the temperature of nucleation reaches spontaneous nucleation temperature as well as at the increased strength of the static electric field [154]. The usage of the static electric field during freezing has the potential to affect the free energy (ΔGn) barrier for phase change, influencing the process of nucleation. It is hypothesized that reducing the critical radius of an ice nucleus, lowers the system's Gibbs free energy and, as a result, increases the nucleation rate [158, 159]. SEF forces polar molecules to align in the path of the electric field vector. This mechanism improves the bonding of hydrogen between molecules of water in the path of the electric field. It is possible to reorganize the water cluster structure as a result, which could facilitate nucleation. Static electric field, in other word, binds polar molecules of water along the field, impacting nucleation of crystal and its growth rates as well as surface theory [160, 161]. The creation of a double electric layer at water-dielectric interface was among the factors that boosted the rate of nucleation during the freezing of water drops enhanced by the presence of a static electric field [162].

9.2. Advantages

By altering the ice-forming process, food electro-freezing is being found to enhance the quality of frozen food. The electro-freezing technology, particularly electric field-aided freezing, is gaining popularity as it provides intensive freezing conditions with lower energy and offers improved quality preservation [163].

9.3. Limitations

The conversion of these technologies from the laboratory to the industrial scale will be a significant issue. This problem requires specialized optimization of settings and conditions in terms of ultimate product quality, energy needs, and safety [163].

CONCLUSION AND FUTURE PROSPECTS

The health of consumers is directly connected to the food industry. The main aim of these industries and the latest technologies is to provide consumers with healthy and nutritious food [164]. The requirements of consumers for minimally processed foods of high quality have inspired studies of non-thermal technologies. Food quality alterations brought on by thermal processing frequently include vitamin degradation, alteration of food texture and color, and the emergence of bad flavors. Some non-thermal processing methods have a negligible impact on the nutrient content of foods while increasing the bioavailability of specific bioactive food ingredients. Without using additives or preservatives, non-thermal technologies enhance the lifespan of food while preserving its color, flavor, texture, nutritive values, and other functional characteristics.

Before the implementation of the non-thermal techniques by food industries, the principle of the techniques has to be studied carefully along with their advantages and limitation [165]. The selected novel non-thermal technologies, such as nanotechnology, high hydrostatic pressure, ozone treatment, pulsed electric field, electrofreezing, ultrasound, plasma-activated water, and pulsed light processing, are reviewed along with their respective principle, advantages and limitations. Contrary to the negative consequences brought on by many conventional heat treatments and non-thermal techniques, these techniques have demonstrated their ability to maintain products close to their original fresh state, which is highly desired by customers. The food industry must continue to push for complete adoption of non-thermal food processing technologies because consumers will expect nutritionally fresh foodstuffs. Combining these technologies with established or newly developed methods of food preservation should be studied to be able to increase the usage of non-thermal processing in the food sector. As a way to move ahead toward the future, the food industries must not only properly understand the action of non-thermal food processing methods, but also their advantages and limitations. Despite the advances in non-thermal food processing technology over the years, further study is required to find more efficient uses of these methods within the food sector, while also addressing quality and safety issues of food products.

LIST OF ABBREVIATIONS

WoS = Web of Science
PL = Pulsed light

CONSENT FOR PUBLICATION

Not applicable.

FUNDING

None.

CONFLICT OF INTEREST

The authors declare no conflicts of interest, financial or otherwise.

ACKNOWLEDGMENTS

Declared none.

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