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REVIEW ARTICLE

Harnessing non-thermal technology for preservation and decontamination of fresh produce: A comprehensive review

Pavithiraa D[1], Nageswari K[2*], Beaulah A[1], Anita T[1] & Sivakumar K P[3]

[1]Department of Postharvest Technology, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam 625 604, Tamil Nadu, India

[2]Department of Vegetable Science, Horticultural College and Research Institute, Tamil Nadu Agricultural University, Periyakulam 625 604, Tamil Nadu, India

[3]Department of Food Nutrition, The Community Science College and Research Institute, Tamil Nadu Agricultural University, Madurai 625 104, Tamil Nadu, India

*Correspondence email - nageswarihort@yahoo.co.in

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Abstract

Extending the storage duration without microbial contamination of fruits and vegetables using advanced and efficient scientific methods has been a significant research focus and practical concern. Non-thermal technology like cold plasma, irradiation, Ozone treatment, UV-light treatment, Pulsed light treatment and Ultrasound treatment is one of the most efficient and eco-friendly ways to improve significantly the preservation of these perishable items, among other strategies. The applications of non-thermal technology in fruit and vegetable storage encompass tasks such as decreasing pesticide residues, sterilizing and inactivating enzymes, as well as examining their impact on physicochemical properties. Moreover, it demonstrates that judicious utilization of non-thermal techniques has been validated to effectively prolong the storage lifespan of postharvest fruits and vegetables while maintaining their quality. This comprehensive review explores the potential of non-thermal technologies for preserving and decontaminating fresh produce. It examines the efficacy of high-pressure processing, pulsed electric field, ultraviolet irradiation, cold plasma, irradiation and ultrasound in microbial inactivation, nutrient retention and sensory quality. Additionally, the review evaluates the economic feasibility, environmental impact and practical applications of these technologies in the fresh produce industry.

Keywords: decontamination; fruits; non thermal technology; shelf life; vegetables

Introduction

The consumption of fruits and vegetables continues to rise annually as consumers increasingly prioritize healthy and functional foods. However, these perishable items are vulnerable to postharvest moisture loss, mishandling, mechanical injury and microbial contamination. Moisture loss after harvest impacts the ripening process, which can be assessed by examining key quality indicators, such as weight, texture, acidity, sugars, carotenoids, vitamins and phenolic compounds (1). Fruits and vegetables experience the highest postharvest losses compared to other food commodities globally, with estimates ranging from 28 % to 55 % of total production. These losses translate to approximately USD 750 billion annually. These losses can be attributed to different factors, including mechanical damage and biological factors such as pests, disease and microbial infection. Biological factors are estimated to account for over 40 % of the total losses in fruits and vegetables (2).

According to the Emerson food wastage and cold storage report, studies estimate that the annual value of the wastage of fruits, vegetables and grains in India is Rs 44000 crore. Most of this wastage is attributed to fruits and vegetables (3). Data from the Central Institute of Post-Harvest Engineering and Technology (CIPHET) reveals that 18 % of India's fruit and vegetable production, valued at Rs 13300 crore, is lost annually (4). Consequently, the postharvest storage of fruits and vegetables significantly impacts both economic and social benefits. Therefore, it is imperative to undertake relevant fundamental and practical research in this field.

Current methods of preserving fruits and vegetables include refrigerated storage, hypobaric storage, modified atmosphere packaging (MAP), controlled atmosphere (CA) storage, edible coatings, films and thermal technologies. Thermal technologies widely used for food preservation have several disadvantages when applied to fresh produce. High temperatures can lead to nutrient degradation, particularly the loss of heat-sensitive vitamins such as vitamin C and B-complex, reducing the overall nutritional value (5). Additionally, thermal treatments often cause undesirable changes in sensory properties, including flavour, texture, colour and aroma alterations. The loss of freshness due to softening and shrinkage further limits their applicability to delicate fruits and vegetables. Moreover, some heat-resistant microorganisms and spores, such as *Bacillus* and *Clostridium* species, can survive conventional heat treatments, necessitating higher temperatures or longer processing times, which can further deteriorate food quality (5). Thermal processing is also energy-intensive, increasing operational costs and a higher environmental footprint than non-thermal methods (6).

Additionally, potentially harmful compounds such as acrylamide and furan may form during high-temperature processing, posing food safety risks (7). Due to these limitations, non-thermal technologies are increasingly being explored as alternative preservation methods to maintain food safety while preserving fresh produce's freshness, nutritional integrity and sensory attributes. Moreover, contemporary consumers increasingly embrace sustainable consumerism, prioritizing food items with minimal additives yet high nutritional value and overall quality. In response to this consumer demand, researchers must strive to develop preservation methods for fruits and vegetables that are environmentally friendly, cost-effective in terms of energy usage, involve fewer additives and are economically viable.

Technologies utilizing infrared, radio frequency, microwave, pulsed electric field, ultrasound and ultraviolet light have gained considerable attention in food science and technology (Fig. 1). Non-thermal technologies exhibit a more significant preservation effect compared to thermal methods due to the absence of potential undesirable products or by-products developing within or on the food's surface. This is because non-thermal methods do not expose the food to high heat. Fruits and vegetables can be kept from spoiling using non-thermal treatment to stop enzyme activity effectively. In particular, cold plasma technology is frequently used to enhance the physiological characteristics of food proteins and carbohydrates, allowing their use in various food processing applications.

Although non-thermal methods offer numerous advantages, they are predominantly confined to laboratory settings and are rarely implemented on a larger scale. Therefore, it is crucial to comprehend the design, operation and impacts of these non-thermal technologies on fruits and vegetables. The existing body of scientific research on these technologies is substantial. This review examines the current status of non-thermal techniques for preserving fresh produce to extend its shelf life, including their effects, the equipment utilized, challenges for large-scale production, strategies for overcoming these challenges and the prospective applications of these techniques in the food processing industry moving forward. Considering the increasing research on non-thermal treatment, this comprehensive review will undoubtedly benefit food scientists and technicians working in the non-thermal technology sector.

Conventional preservation techniques

Traditional preservation methods are crucial in ensuring the safety and extended shelf life of fresh fruits and vegetables by removing contaminants, pathogens and spoilage microorganisms. Some of the widely used conventional decontamination techniques include washing with water and disinfectants, where simple rinsing or the use of chemical agents such as chlorine, hydrogen peroxide, or organic acids (citric acid, acetic acid) helps reduce microbial load and pesticide residues (8). Thermal processing, including blanching and pasteurization, effectively kills pathogens and spoilage organisms; however, these heat treatments may lead to nutrient loss and undesirable texture changes in fresh produce. Refrigeration and cold storage help slow down microbial growth and enzymatic activities, preserving freshness and preventing spoilage, yet they do not eliminate pathogens.

Another standard method is modified atmosphere packaging (MAP), which involves reducing oxygen levels and increasing carbon dioxide or nitrogen to slow down microbial growth and oxidation, thereby enhancing shelf life (9). While conventional methods are effective, they have several limitations, such as nutrient degradation, residual chemicals, environmental concerns and limited microbial inactivation.

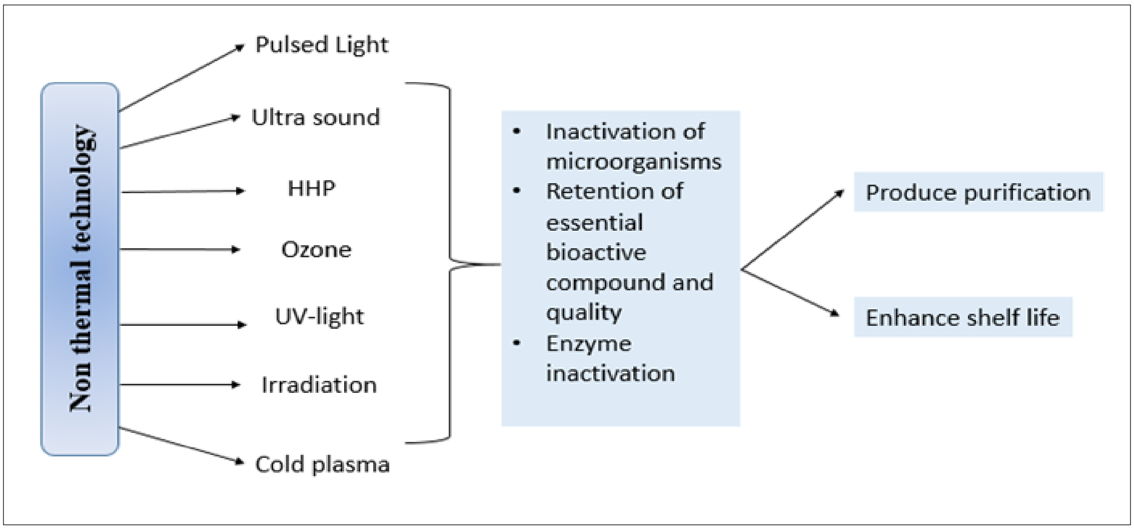

Fig. 1. Novel technologies for purification and enhancing shelf life of fresh produce.

Non-conventional method

Emerging strategies for preserving fresh fruits and vegetables focus on advanced disinfection techniques that enhance food safety while minimizing environmental and health impacts. Recent studies have highlighted innovative disinfection methods that offer a more sustainable approach to controlling common contaminants in fresh produce. These methods are broadly categorized into thermal and non-thermal treatments, with growing interest in non-thermal alternatives due to their ability to maintain fresh produce's nutritional, sensory and textural integrity (8).

This review explores various non-thermal disinfection techniques, including ozone treatment, electrolyzed water, cold plasma technology, high hydrostatic pressure, ultraviolet (UV) radiation, ultrasound and irradiation. The recent findings of some technologies have been listed in (Table 1). These innovative approaches provide effective microbial inactivation while reducing reliance on conventional chemical disinfectants. Furthermore, additional insights are provided on the impact of these disinfection methods on enhancing food quality, safety and shelf-life, positioning them as promising alternatives for sustainable and efficient fruit and vegetable preservation.

Cold plasma treatment

In place of more conventional thermal processing methods, cold plasma therapy is a well-researched non-thermal processing technique used in the food business to sterilize food while retaining its quality characteristics. There are two primary forms of plasma treatment: thermal plasma and cold (non-thermal) plasma. High temperatures are used by thermal plasma to generate a lot of energy. Non-thermal plasma works between the 25-65 °C temperature range (10-12). Because of the characteristics of plasma, it has been used in various sectors, including food, chemical engineering, textile, electronics and pharmaceuticals (13). In the food industry, an ionized gas which is made up of highly excited ionic and reactive the number of microorganisms present in food or on its surface, improving the physical and chemical characteristics of food components like proteins and fats, sterilizing food processing machinery, deactivating food spoilage enzymes, treating food packaging materials and treating wastewater (14, 15).

Mechanism

According to species such as gas atoms, free radicals and quanta of ultraviolet and electromagnetic radiation. Different gases, such as argon, helium, or their combination with oxygen, have been used as reaction gases to create plasma; irrespective of the gases chosen, reactive nitrogen and

Table 1. Effects of various treatments on fruits and vegetables

Crop	Treatment Type	Dosage/Exposure Time	Effect	Reference
Cold Plasma Treatment				
Fresh-cut Mango	DBD Plasma	75 kV for 3 min	Delayed reduction in organoleptic and nutritional parameters	(67)
Tomato	DBD Plasma	0-80 kV for 5 min	60 kV: lower respiratory rate, increased firmness, prolonged shelf life	(68)
Cavendish Banana	DBD Plasma	15 kV for 0.5 min	Controlled crown rot disease, reduced natural infection	(69)
Mango	DBD + Modified Atmosphere	50 V, 1.0×10^4 Hz	Controlled post-harvest anthracnose, prolonged shelf life	(70)
Strawberry	DBD Plasma	60 kV for 10-30 min	15 min: best result in maintaining quality and shelf life	(71)
Blueberry	Cold Atmospheric Plasma	Gliding arc plasma system	Controlled bacterial growth while maintaining nutrition	(72)
Apple Slices	Jet Plasma	1-5 L/min, 5 min ionization	5 atm, 3 min: maintained better physico-chemical properties; 6 min: higher moisture retention	(73)
Irradiation Treatment				
Bananas (cv. Prata)	Gamma Radiation	1.0-2.0 kGy at 16°C, 85 % RH	1.0 kGy: slowed starch degradation, delayed ripening by 7 days	(74)
Indian Jujube	Gamma Radiation	0-1.0 kGy, stored at 10°C	Improved storage life and quality	(75)
Pomegranate Arils	Gamma Radiation	1-5 kGy at 4°C, RH >80 %	1 kGy: improved quality, increased shelf life	(76)
Strawberry	E-Beam Irradiation	≤1 kGy	Increased biochemical properties, improved shelf life and quality	(77)
Tomato	Gamma Rays	600 kGy	Lower microbial load, less weight loss, 10 days longer shelf life	(78)
Cherry Tomato	Gamma Rays	≤1 kGy	Improved physicochemical properties, better post-harvest conservation	(79)
Green Onion	Gamma + Sodium Benzoate	1.0 kGy + 0.1 % sodium benzoate	Maintained biochemical properties, good condition for 16 days	(80)
Mushroom	Gamma Rays	0.25 kGy	Increased shelf life, retained mineral and chemical properties	(81)
Mango	E-Beam	0.5 kGy at 13°C	Reduced post-harvest disease, maintained quality	(82)
UV Treatments				
Guava	UV-C	2.0 kJ·m^{-1}	Delayed senescence, reduced weight loss (8.12 %) & firmness (3.94 N), extended shelf life by 20 days	(83)
Okra	UV-C	1.5-6.0 kJ·m^{-1}	6.0 kJ·m^{-2}: preserved biochemical compounds, maintained quality	(84)
Lemon	UV-B + Natamycin	0.1 J·cm^{-1}	Controlled fungal growth, maintained quality	(85)
Potato	UV-C + Shellac	2.4 kJ·m^{-2}	Controlled greening, antimicrobial effect, extended storage time	(86)
Peach	UV-C	1.5 kJ·m-2	Maintained quality, improved aroma-related volatile compounds	(87)

dbd - dielectric barrier discharge **rh** - relative humidity **kvp** - kilo voltage peak **kgy** - kilo gray oxygen species are produced (16). Various charged particles (OH^-, $H2O^+$, electrons), excited molecules (excited O_2, N_2), UV photons, reactive oxygen species (ROS), reactive nitrogen species (RNS) and positive and negative ions are present in plasma (17). The recombination mechanism of these species creates an active particle cloud that holds energy for a while before emitting it as visible and ultraviolet light. So, the microbial decontamination process can be caused by the chemical reaction of charged particles, reactive species, or radicals with the cell wall by UV radiation damaging the cell wall and internal components of the targeted cell, or by UV light damaging DNA strands of the cell. The type and characteristics of plasma generated, including its energy levels determined by factors like gas type, temperature and density, impact the antibacterial mechanisms at work. Also, a given product may respond better to one mode of action than another. As a result, employing plasmas with several antimicrobial mechanisms might increase sanitizing efficacy by enhancing synergistic effects (10). The formation of cold plasma occurs at temperatures closer to room temperature and microbial inactivation also occurs at low temperatures. There is no risk of thermal damage to heat-sensitive food materials because the temperature applied is ambient (18).

Application cold plasma treatment

Cold plasma induces microbial inactivation through the impact of reactive species on microbial cells. These reactive species are responsible for DNA damage, protein oxidation and disruption of cellular components in microbes, ultimately leading to cell death (19). Mandarin oranges can be treated using in-package cold plasma therapy to reduce microbial load. *Penicillium digitatum* was made inactive by treatment at 26 and 27 kV for 1-4 minutes (20). Without affecting the oranges' flavour, consistency, or nutritional benefit, the antimicrobial agent and cold plasma treatment decreased the amount of *P. digitatum* in the package. The treated oranges showed less ripening when contrasted with the untreated oranges. Research indicates that bananas' shelf-life increasing by applying cold plasma technology (21).

A previous study has observed a decrease in respiration rate among the control & CP-treated tomatoes during storage (7). The impact of cold plasma treatment on the vitamin C content of fresh fruit and vegetable slices, including cucumber, carrot and pear slices, was investigated. The study revealed that the cucumber slices exhibited a vitamin C loss of 3.6 %, whereas the carrot and pear slices experienced losses of 3.2 % and 2.8 %, respectively (22). The minor decrease in the vitamin C content is predominantly caused by the oxidation process induced by the cold plasma.

Observations indicate that cold plasma treatment can produce both advantageous and adverse effects on various components. Additionally, this treatment has been found to modify the secondary structure of enzyme proteins, which leads to their inactivation. These modifications have also been associated with reducing the intensity and inhibitory activities of food allergens and antinutrients. Therefore, it can be concluded that by optimizing the parameters of cold plasma treatment, it is feasible to process food to mitigate adverse impacts on quality attributes, such as vitamin loss, accelerated lipid oxidation and sensory characteristics (23).

Irradiation treatment

Food irradiation entails deliberately exposing food to carefully regulated amounts of ionizing radiation, such as gamma rays, electrons and X-rays. This method is carried out within a chamber designed to protect against radiation (24). In food processing, irradiation is a primary method for preserving food products. Its efficacy in eliminating pathogenic microorganisms, such as *E. coli, Staphylococcus and Salmonella,* has been widely acknowledged (25). The effect of irradiation is realized without any rise in the food's temperature. This approach prevents any potential damage to heat-sensitive elements present in the fruits and vegetables (26).

Mechanism

Gamma-rays and electron-beams generate ionizing radiation, which consists of atoms or molecules that are electronically charged. When food is exposed to this radiation field, it is crucial to measure the total energy absorbed by the food to establish accurate protocols for maintaining the food quality. This measurement is typically expressed in Gray or Kilo Gray (kGy) units and plays a vital role in ensuring the safety and quality of the irradiated food. A dosimeter is used to measure absorbed energy. A dosimeter is placed inside food packaging to calculate the highest and lowest radiation doses. The required dose can be obtained by changing the exposure duration and the food product's position in relation to the radiation source. Likewise, the food's volume and texture affect how much energy it absorbs (27). The type of food being processed and the desired outcome dictate the radiation dose employed. The ideal radiation dosage for a product's processing is between the required and acceptable dosage. Furthermore, not all foods are suitable for radiation exposure because of their radiation sensitivity. International organizations have proven and approved the quality and safety of foods that are radioactively treated for human consumption according to nutritional sufficiency, toxicological safety, microbiological safety and radiological safety (24).

Application-irradiation treatment

Water molecules are the primary focus of ionizing radiation, producing free radicals and other reactive species. These highly reactive entities can break chemical bonds and modify a range of molecules. As a result, bacterial components are destroyed or rendered inactive (5). It is reported that the primary cause of microbial inactivation by radiation is DNA damage, which obliterates the cell's ability to reproduce and perform other functions (28) (Fig. 2). Food irradiation subjects the prepacked fruits and vegetables to electron beams, X-rays, or gamma rays. Because no heat is involved during radiation, it is often called cold sterilization. The food sector uses X-rays, electron accelerators, or gamma radiation from radioisotope sources (such as cobalt-60 and cesium-137) as its radiation sources (29). If the irradiation could not restore the ruined or over-ripened food to its original form, it might stop further spoiling and postpone ripening (30). The Food and Drug Administration (FDA) has approved low-doses (up to 1 kGy) for enhancing the shelf life of fresh and minimally processed fruit and vegetables. Treatments

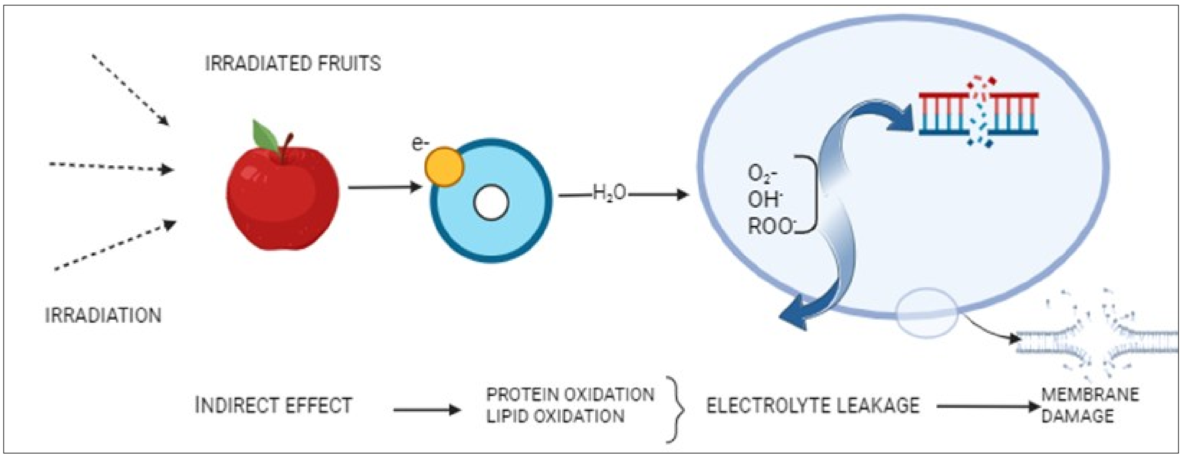

Fig. 2. The mode of action of irradiation on microbes.

include inhibiting sprouts, delaying ripening and lowering bacterial, parasite and protozoan populations (5, 31). If the dosage is too high, the food may deteriorate and become unfit for human eating and if the dosage is too low, the desired preservation effect may not be achieved. Further, to irradiate the item after packing, the packaging material must be chemically resistant to avert the breakdown of polymers, the creation of halogen-based polymers and low molecular weight hydrocarbons, which can route into food (32). Likewise, on the box or at the point of sale, all irradiated items must include the RADURA emblem or the words "treated by irradiation" or "treated with irradiation."

Ozone treatment

Ozone comprises three oxygen atoms and is identified as a colourless gas with a characteristic odour. Due to its highly reactive and unstable nature, ozone cannot be stored and must be generated as required. It is widely recognized for its effectiveness as a potent antibiotic against various food -borne pathogens. Ozone can be utilized in its gaseous form or combined with water to create ozonized water. The impact of ozone on microbial cells is diverse; it modifies cell permeability by inflicting damage on the membranes of microorganisms. Additionally, ozone disrupts protein structures, leading to the inactivation of microbial enzymes, which ultimately impedes metabolic processes and results in the death of microbial cells (33).

Mechanism

Ozone is created when oxygen molecules break into free radicals, which combine with oxygen molecules to produce ozone. However, breaking the chemical bond requires a lot of energy. High-energy electric fields or UV light having a wavelength of 185 nm are the primary sources of this energy. The corona discharge (CD) method/plasma technique (latter) is a commercially employed method (34). In the corona discharge method, ozone passes a dry, dust-free, oil-free, oxygen-containing gas between two unique electrodes that deliver a high-energy electric field. Diatomic oxygen is cleaved throughout the process and the resulting free radicals react with the diatomic oxygen to generate ozone.

At ambient temperature, ozone is a blue gas; however, people cannot see its colour in the concentrations during which it is typically generated. At -112 °C, ozone condenses to a dark blue liquid. Humans can easily detect ozone, which smells between 0.01 and 0.04 ppm. Prolonged exposure to concentrations exceeding four ppm can be fatal to humans. Still, even at lower concentrations, ozone causes eye and throat irritation and has a strong, unpleasant stench up to 1 ppm. Ozone lasts only 10-20 min in water before disintegrating into molecular oxygen. Consequently, it doesn't leave behind toxic residues like those produced by chlorine or chlorine dioxide, which helps keep produce clean during disinfection and makes it easier to gather used water from washing (5). It can dissolve in water and as the temperature drops, so does the soluble portion. Because ozone may oxidize up to 3000 times quicker than chlorine, this ability to do so has a negative consequence that leads to degradation and corrosion on metal and other surfaces that come into contact with it. The ozone treatments can be used in both aqueous and gaseous states. After it is created, ozone can be added regularly or occasionally to the storage space for produce, or it can be dissolved in water to form aqueous ozone, which can be used for cleaning and disinfecting. It is crucial to remember that ozone is extremely unstable when in an aqueous solution and relatively stable when in its gaseous state (35).

Application of ozone treatment

British scientist Benjamin Cornelius Fox first observed ozone in 1873 and it can destroy a variety of food-borne microbes. Fruits treated with ozone after harvest had improved physical, chemical and textural qualities as well as a decreased microbial load after 15 days of storage in modified atmospheric packaging (36, 37) showing that conidia can be destroyed after treatment with ozonized water for 3 minute, but the pathogenic fungi from seven plant which is artificially inoculated into fruit wounds are not destroyed even after a short time treatment (up to 1.5 min) with high ozonized water (1.5 $\mu g\ mL^{-1}$).

The effectiveness of ozone treatment for prolonging the shelf life/storage life of fresh produce, such as apples, pears, grapes, oranges, cucumbers, broccoli and berries like strawberries and raspberries, has been theorized and proven to depend on its capacity to lower the microbial inoculum and break down the ethylene produced. Except for sliced carrots, it was shown that ozone generally had no adverse effects on pigments like beta-carotene and essential elements like vitamin C in minimally processed vegetables (38).

Studies have shown the potential of ozone treatment for usage as a fresh fruit and vegetable postharvest pretreatment. Ozone's precise mechanism of action in deactivating dangerous bacteria is still unclear, though it has been demonstrated that using more ozone during the previous few decades lowers the respiration rate (39). Utilization of ozone technology in the fruit and vegetable business is still limited in scope. Too far, it has been chiefly employed by the fish, poultry, dairy (milk and its derivatives) and meat industries. While gaseous ozone canecting. It has been shown that ozone is more efficient than other chemical disinfectants against a wide range of microbes and has an oxidizing potential of 1.5 times more than chlorine (40).

Several authors stated that the quantity and kind of contaminating microbes, the physiological characteristics of fruits and vegetables, the maturity stage, reactor design, water quality, temperature and pH determine whether ozone can sterilize the produce The food industry finds it impractical to use longer treatment times with ozone doses, even though this results in a higher reduction of contaminant microorganisms. This is because ozone has a short half-life, reacts with organic materials, is not very soluble in water, diffuses poorly into packaging, breaks down quickly at high temperatures and pH levels and requires on-site generation. These factors make it challenging to use ozone in food engineering (41).

UV-light treatment

Ultraviolet (UV) radiation is a non-thermal treatment that can be applied to fresh produce to disinfect and reduce deterioration. The primary objective is to lessen the number of pathogens that food products are physically exposed to radiation.

Mechanism

There are three categories in the electromagnetic spectrum: UV-A, which is found between 320 and 400 nm; UV-B, which is found between 280 and 320 nm and UV-C, which is found between 200 and 280 nm (42). Extended exposure to ultraviolet radiation also triggers the production of chemicals that are beneficial to health, including flavonoids, stilbenes and anthocyanin. An additional benefit is the comparatively low-cost and user-friendly equipment required. On the other hand, treated tissue may sustain harm from excessive UV radiation exposure. Treatment causing direct bacterial DNA damage or developing pathogen resistance mechanisms (5). However, because UV-C has an inferior penetration rate into solids, microbial inactivation is done only on the surface of the produce. The UV-A and UV-B photons destroy the microbes, which also damage microbial cell proteins, membranes and other physiological organelles (43). Recent studies indicate that UV treatment positively impacts the physiological, microbiological and qualitative attributes of fruits and vegetables when used as a post-harvest method.

Application of UV-light treatment

Ultraviolet light treatment has recently demonstrated significant efficacy in delaying postharvest senescence in fruits and vegetables. This method has been shown to prolong the shelf life of these products, preserve their quality throughout storage and mitigate the chilling injuries associated with cold storage. UV treatment can partly slow the onset of senescence because it can lower the pace at which fruits and vegetables respire while being stored after harvest. UVC treatment (3.0 kJ m^{-2}) decreased the respiratory rate. It delayed the onset of respiratory climacteric in peach fruit at 20 °C by reducing the activity of two vital respiratory enzymes in plant cells, succinate dehydrogenase (SDH) and cytochrome C oxidase (CCO), while also maintaining mitochondrial integrity (44). Fresh-cut produce or fruits and vegetables may be effectively decontaminated by applying non-ionizing, germicidal UV-C radiation.

UV-C impacts several plant physiological functions. Immediately following irradiation, there was a temporary rise in CO_2 generation in tomato fruits. However, the fruits exposed to UV light produced less CO_2 than the control group and the CO_2 climacteric surge occurred seven days later. The production of ethylene (C_2H_4) also followed the same pattern. The delayed climacteric rise (CO_2 and C_2H_4) was thought to be a sign of UV-induced delayed senescence. It was assumed that the brief increase in CO_2 and C_2H_4 seen in tomato tissue after UV treatment represented an adaptation of the tissue to the oxidative stress brought on by UV radiation. A recent study demonstrated that wheat protein may be improved chemically and physically by UV-C light at a wavelength of 254 nm (45). UV-C radiation inhibits cell wall-degrading enzymes such as polygalacturonase (PG) and pectin methyl esterase (PME). According to reports, cherry tomato (PG) and (PME) activity were drastically reduced by UV-C treatment (4.2 kJ m^{-2}), which also preserved the tomatoes' high acid-soluble pectin and cellulose content and repressed the expression of associated genes during postharvest (46).

As an abiotic stressor, UV-B treatment stimulates the fruit's antioxidant system in advance, triggering a defence mechanism that reduces secondary oxidative stress damage caused by low temperatures. The effect of UV treatment on fruit chilling damage appears to be similar to that of phenolic compounds. UV is one of the well-known non-thermal processing techniques used by the food processing industry to provide food with a longer shelf life because of its easy-to-use operation. The effect will be amplified if UV is combined with other procedures to produce the desired alterations.

Pulsed light treatment

As an innovative non-thermal technology, pulsed light (PL) offers significant potential for food preservation, enabling the decontamination, preservation and enhancement of food's nutritional and sensory qualities. Pulsed light (PL), otherwise referred to as high-intensity light pulses (HILP), is used as an alternative to ultraviolet light (47). Many researchers have demonstrated that exposure of Fruits and vegetables to Pulsed Light (PL) during the postharvest period is responsive to stress in plant tissues. This stress triggers the production of protective secondary metabolites with antioxidant and antibacterial properties.

Mechanism

The PL treatments expose fresh produce to a spectrum of polychromatic light ranging from 200 to 1100 nm (48). This spectrum encompasses ultraviolet wavelengths (180-400 nm), visible light (400-700 nm) and near-infrared wavelengths (700-1100 nm). The light is delivered through intense, short pulses between 1 microsec and 0.1 sec, generated by an inert gas lamp, such as xenon. PL uses xenon lamps to produce strong, short waves of wide-spectrum "white light," with maximum outputs of 400-500 nm. These waves can range from ultraviolet wavelengths of 200 nm to infrared wavelengths of 1000 nm.

It is essential to emphasize that the rapid exposure periods of PL treatments may greatly encourage industrial application (49). However, although PL technology has been thoroughly studied for its potential use in food sterilization, relatively little research has been done on its possible uses as a postharvest treatment to enhance the nutritional value and shelf life of fruits and vegetables. The amount of delivered pulses and intensity (expressed in J cm-2) determine how effective PL is at decontamination efficiency. The UV-C (200-280 nm) portion of the light spectrum that the flash lamp emits is particularly lethal to most of the pathogens and essential for the microbial decontamination that causes photochemical damage to DNA, denaturation of proteins, agglutination of cytoplasmic material resulting in a rupture of the cell membrane, eventually, cause cells to become inactive. Based on recent studies, PL eliminates yeast using a multi-hit or mechanical method that, depending on the dosage supplied, modifies the stability of DNA and macromolecules, cell membrane permeability and functionality. (50).

Application-pulsed light treatment

Research has shown that very low doses (<1 J/cm^2) of short wavelength UV-C light (200-280 nm) applied to fresh-cut fruits and vegetables (e.g., tomatoes, mushrooms, strawberries, baby spinach, broccoli, peppers and blueberries) may promote the biosynthesis of protective secondary metabolites with antioxidant potential and improve nutritional value (49). Specifically, it has been shown that many fruits and vegetables exposed to PL after harvest may stress plant tissues, promoting the production of protective secondary metabolites with antioxidant and antibacterial properties (51). Scientists confirmed that, once a considerable decontamination impact was detected compared to the control, the surface imperfections just marginally, but not considerably, limit the treatment effectiveness. The surface population of Saccharomyces cerevisiae on fresh tomatoes—both naturally occurring and artificially inoculated—was reduced without affecting the nutritional value (52). The concentration of carotenoids rose slightly, while vitamin C remained unchanged.

However, PL caused a significant physiological loss and noticeable shrinkage within three days, significantly decreasing product quality acceptance. Similarly, (53) found that 30 light pulses (12 J cm^{-2}) had a detrimental impact on the colour and texture of fresh-cut watermelon. Combined treatment of dielectric barrier discharge plasma (DBD) and intense pulsed light (IPL), the apricot showed an effective response by decreasing the microbial load and, increasing the non-enzymatic antioxidants and ultimately increasing the shelf life (54).

Gram-positive bacteria may be more resilient against the PL treatment because their cell walls are thicker and more robust than Gram-negative bacteria. Another study shows that post-harvest PL treatment enhances anthocyanin formation and colour in figs; it also seems to be a workable solution to compensate for insufficient sun exposure to promote the development of colour in figs and other fruits. Also, the study found that a brief postharvest PL exposure may substitute inadequate amounts of solar stimulation for the appropriate development of fruit colour (55). Therefore, this technology's benefits include significant and rapid microbial inactivation in brief treatments, the absence of residual chemicals and high adaptability. PL is a newly developed postharvest procedure (56). However, further study is required since, in certain circumstances, researchers have produced contrasting data about the ideal ripening stage, energy dosages and storage conditions.

High hydrostatic pressure treatment

A relatively new and promising non-thermal food processing technique called high hydrostatic pressure (HHP) processing exposes liquid or solid foods with or without packaging to pressures ranging from 50 to 1000 MPa. As a cold pasteurization process, it does not significantly alter food's nutritional or organoleptic properties. It improves the quality and shelf life of perishable foods like fruits and vegetables. This makes it a good substitute for heat treatments to eradicate food-borne pathogens and inactivate enzymes.

Mechanism

The food product goes into the pressure vessel that can maintain the appropriate pressure level in an HHP process and it is submerged in a liquid that serves as a pressure-transmitting medium. The pressure is distributed evenly and almost instantly across the food sample (Fig. 3). Consequently, unlike heat treatments, the amount of time required for pressure processing is irrespective of the size or form of the food (57). The technique produces high-quality food because it may be run at room temperature or lower temperatures, which minimizes heat-induced degradation of nutrients and natural tastes and colours. Numerous studies have demonstrated that HHP is helpful in the preparation of fresh fruit and vegetable products.

Application of high hydrostatic pressure treatment

The impact of high-pressure processing on food colour varies depending on the processing circumstances; high pressure often has little effect on food colour deterioration at room temperature or mild temperature. Research indicates that 3 W/L ultrasound combined with 0.4 g/L ε-polylysine treatment has improved the storage life in fresh-cut lettuce (11). Research has been carried out on vegetables like carrots and spinach to evaluate the HHP treatment, resulting in a positive impact by decreasing pathogenic contamination and improving the shelf life of the produce (12). The study was conducted at 4 °C, 21 °C and 38 °C, with a pressure of 340 MPa for 15 min. The bacterial count was reduced to 3.0, 3.1 and 2.5, extending the shelf life. The plate count of yeast and mould was fewer than 50 cfu/g for the treated pineapple slices. Research indicates the effectiveness of HPP on sour cherries and 600 MPa for 3 min at 4 °C showed an effective result in primary decontamination of microbes and extended the shelf life up to 5 months at cold storage (58).

Furthermore, HPP treatment may be able to maintain the nutritional value and sensory qualities of fruits and vegetables because of its restricted impact on the covalent bonds of low molecular mass molecules like vitamins, colour and taste chemicals. There is no alteration to the fundamental structure of low-molecular-weight molecules (such as vitamins, amino acids, volatile chemicals, pigments, etc.), which promotes greater nutrient retention and food sensory qualities. However, depending on the food type (whole, bits, juice, purée, mousse, or smoothie) and processing parameters (pressure, hold time and temperature), the impact of HPP on vegetable products differs. Plant kinds and pH levels are intrinsic elements that affect the process. As a result, it is common to get contradicting findings for the same matrix. While there is increasing research on this innovative technology, most studies on plant-based meals have been on purees and juices, with relatively few on whole fruits and vegetables. Furthermore, research is needed to employ HHP to enhance the storage life of fruits and vegetables.

Ultrasound treatment

Ultrasound (US) emerges as a sustainable processing technique with considerable potential in the food industry, primarily due to its ability to deactivate microorganisms on the fruit and vegetable surfaces. Additionally, it benefits affordability, productivity and efficiency, leading to decreased processing times, enhanced quality and minimized health hazards.

Mechanism

The US treatment depends on energy derived from sound waves with frequencies higher than those humans can hear. The components of the US system include an energy source from the generator, a transducer and an emitter that emits US waves into the medium from the transducer (59, 60). Ultrasound frequencies ranging from 20 to 100 kHz deactivate microorganisms in food processing by inducing acoustic cavitation. This phenomenon leads to various effects, including the breakdown of cell wall structure, heightened permeability of cell membranes, thinning of cell membranes and the generation of free radicals. Consequently, these actions result in the inactivation of microorganisms (Fig 4). There are two categories for the US band: high-power (low frequencies) and low-power (high frequencies). A previous study found that the low frequencies, which range from 18 to 100 kHz, cause physical disturbance and mechanical, chemical and physical changes that impact the produce's surface pathogens (60).

Application of ultrasound treatment

Frequency in the 20 kHz–100 kHz range is utilized in food processing for enhanced synthesis, heating, debittering, emulsification and bioactive extraction, among other processes. Traces of pesticides on pakchoi leaves (pyrazophos, chlorothalonil and carbendazim) were eliminated by using US treatment (6). All three pesticide residues dramatically decreased following ultrasonic treatment. The US is more effective at removing pesticide residues than regular water immersion. When paired with other technologies to reduce pesticide use and clean fruits and vegetables, ultrasonic technology may yield greater results than when used alone. The effects of electrical current (EC) and ultrasonic (US) treatments on the elimination of pesticide residues (metalaxyl, thiamethoxam and captan) in tomato samples were examined (61). The combination of US and EC produced more significant outcomes than each technology. With the right combination of treatment settings, there was a considerable reduction in all three pesticide residues.

Tomato fruits were ultrasound-treated to investigate the impact of quality and microbiological load on storage. According to the findings, ultrasound, when used with two processing settings (80 % power level for 15 minutes and 100 % power level for 19 min), can greatly lower the initial microbial load that occurs immediately after sonication (62). Towards the end of storage, yeasts, molds and microbial count of control samples had the highest values when compared to ultrasonic treated samples. Notably, the tomato samples treated with ultrasound maintained a similar level of firmness to the untreated ones.

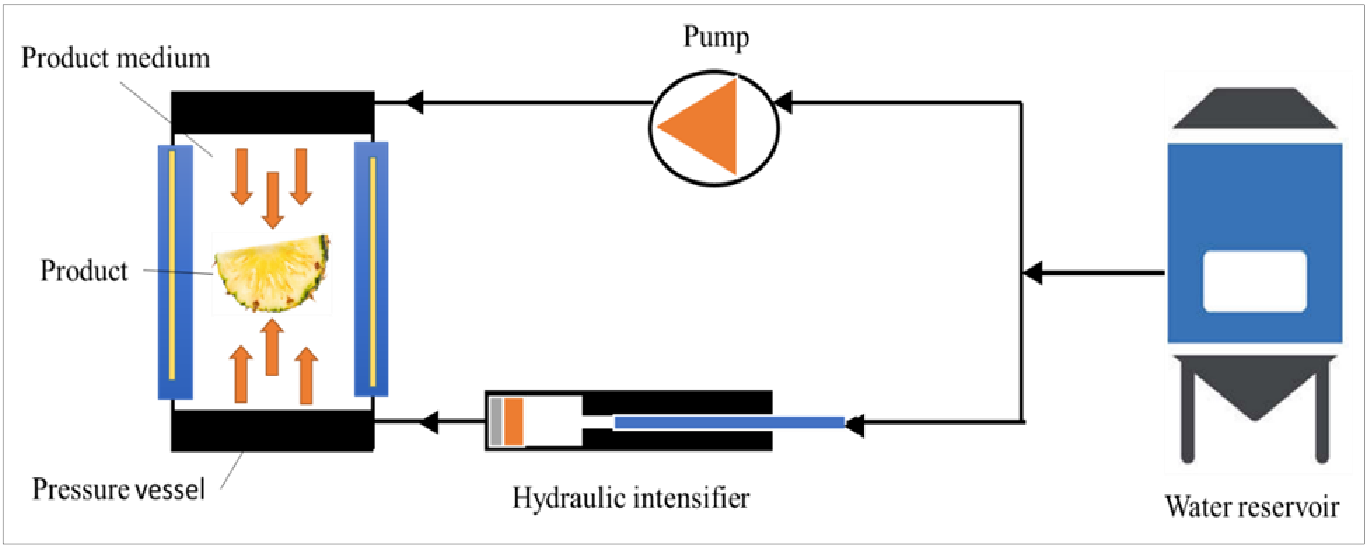

Fig. 3. Mechanism of High Hydrostatic Pressure.

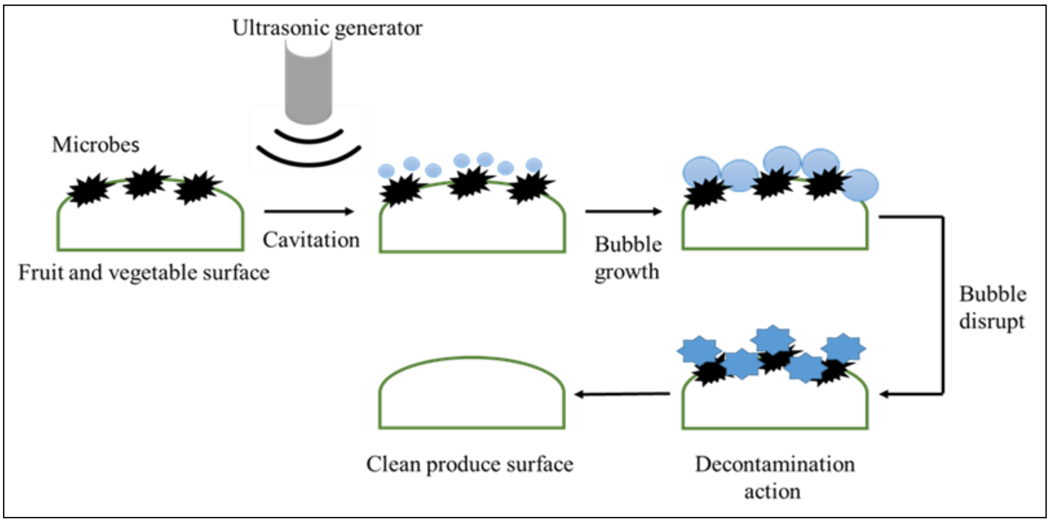

Fig. 4. Decontamination action of US treatment.

Studies have been conducted on the use of ultrasonic therapy to lower microbial populations in freshly harvested strawberries. Studies have shown that, throughout a 15-day storage period, ultrasound may drastically reduce the quantity of bacteria, yeast and mould. Strawberry microbial load can be decreased by ultrasonic treatment, which can also preserve the fruit firmness and increase its antioxidant activity. The pomegranate and 30 min of US treatment at 20 °C can improve the shelf life by decreasing the microbial load, with minimum weight loss and preserving all the biochemical compounds (63). Combining US and slightly acidic electrolyzed water treatment can improve the grape's shelf life by up to 12 days (64).

It is evident that using ultrasonic technology helps preserve the physico-chemical indices of produce after harvest, increases shelf life and guarantees that produce is rich in nutrients. Researchers are gaining more interest in using ultrasonic sterilization treatment, particularly concerning fruit and vegetable post-harvest preservation. The integration of ultrasound with other preservation methods has been well documented in the literature and has demonstrated excellent application outcomes, suggesting a wider potential application base. Each non-thermal method is assessed by considering microbial inactivation, nutrient retention and economic feasibility (Table 3).

Regulatory approvals and safety concerns for non-thermal food processing

The implementation of non-thermal food processing technologies requires stringent regulatory approvals to ensure food safety, nutritional quality and consumer acceptance. It has both advantage and limitation which is listed in Table 2. In India, the Food Safety and Standards Authority of India (FSSAI), the Atomic Energy Regulatory Board (AERB) and the Bureau of Indian Standards (BIS) oversee these technologies (65). Globally, regulatory agencies such as the U.S. Food and Drug Administration (FDA), the European Food Safety Authority (EFSA) and the Codex Alimentarius Commission (FAO/WHO) establish guidelines for the safe application of these methods.

Table 2. Comparison of non-thermal technologies for food preservation (88)

Technology	Advantages	Limitations
Cold plasma	- Effective against a broad range of microorganisms. - Maintains sensory and nutritional quality. - Can be applied to fresh and processed foods.	- Limited penetration, mainly surface treatment. - Equipment cost is high. - May cause oxidative damage to some food components.
Irradiation	- Extends shelf life significantly. - Effective in reducing pathogens. - Penetrates deeply into foods.	- Consumer acceptance issues due to perceived radiation risks. - Requires regulatory approval.
Ultraviolet (UV) treatment	- Chemical-free method. - Effective for surface decontamination. - Minimal impact on sensory attributes.	- Limited penetration depth, effective only on exposed surfaces. - May cause photochemical changes in food.
Pulsed electric field (PEF)	- Preserves nutritional and sensory properties. - Suitable for liquid and semi-liquid foods. - Energy-efficient compared to thermal methods.	- Ineffective against spores. - Limited to pumpable foods (liquids, juices). - High initial investment.
High-pressure processing (HPP)	- Retains fresh-like quality and nutrients. - Effective against bacteria, yeasts and molds. - Extends shelf life while maintaining sensory characteristics.	- High equipment costs. - Limited effect on bacterial spores. - Not suitable for foods with large air pockets (e.g., bread).
Ozone treatment	- Effective against bacteria, viruses and fungi. - Leaves no chemical residues. - Can be used for water and air treatment in food facilities.	- May affect sensory properties of some fruit and vegetable. - Can cause oxidative damage to certain compounds. - Strict safety regulations due to ozone toxicity.
Ultrasound technology	- Enhances microbial inactivation in combination with other treatments. - Improves mass transfer in food processing (e.g., drying, extraction). - Non-chemical method with minimal heat generation.	- Limited effectiveness as a standalone method. - Requires optimization for different food matrices. - May cause quality changes in delicate foods.

Table 3. The assessment of various non-thermal food processing methods (89, 90)

Method	Microbial inactivation	Nutrient retention	Economic feasibility	Other considerations
Pulsed electric field (PEF)	Disrupts microbial cell membranes; effective against vegetative cells but not spores.	Minimal impact on nutrients; excellent for liquid foods.	Requires high-voltage equipment but is energy-efficient for liquids.	Best suited for pumpable foods (e.g., juices.)
Ozone treatment	Oxidizes microbial cell components, effectively inactivating bacteria, viruses and fungi.	Minimal impact on nutrients; may degrade some antioxidants.	Cost-effective with relatively low operational costs.	Used for surface decontamination and water treatment; must control ozone levels to prevent off-flavors.
Ultrasound processing	Disrupts microbial cells via cavitation and shear forces; works best in liquids.	Minimal effect on nutrients, but prolonged exposure may degrade some compounds.	Moderate cost; more affordable than HPP and PEF but requires optimization.	Often combined with heat or antimicrobials; used in juice, dairy and emulsified products.
Irradiation (Gamma, X-ray, Electron Beam)	Breaks microbial DNA strands, eliminating pathogens and spoilage organisms.	Some loss of vitamins A, C and E, but generally minimal.	Requires regulatory approval and specialized facilities.	Public perception challenges; used for spices, meats and fresh produce.
Cold plasma	Produces reactive species that disrupt microbial structures.	Minimal effect on nutrients.	Still in development; needs optimization for large-scale use.	Effective for fresh produce and packaging sterilization.
Ultraviolet (UV) irradiation	Damages microbial DNA; effective for surfaces and transparent liquids.	Minor losses; some vitamins (e.g., riboflavin) are light-sensitive.	Low-cost, easy to implement for surface and water treatment.	Limited penetration; less effective in turbid or opaque foods.
High-pressure processing (HPP)	Effective against bacteria, yeasts and molds; spores require additional treatment.	Excellent retention of heat-sensitive nutrients (e.g., vitamins C and B).	High initial investment; lower operational costs than thermal pasteurization.	Preserves fresh-like sensory qualities; mainly used for juices, meats and dairy

Food irradiation is one of the few widely approved non-thermal technologies, permitted in India by FSSAI under the Food Safety and Standards (Food Products Standards and Food Additives) Regulations, 2011 (66) and regulated by AERB under the Atomic Energy Act, 1962. It is approved for spices, pulses, onions, potatoes and meat to reduce microbial load and extend shelf life. The FDA and EFSA have also approved irradiation for various food products, with mandatory labelling to address consumer concerns. High-Pressure Processing (HPP) is widely accepted for juices, seafood and ready-to-eat meals, though clear regulatory guidelines in India are still evolving. Ultraviolet (UV) treatment is permitted for water purification and food surface decontamination but requires further regulatory validation for direct food applications. Ozone treatment is allowed as a food processing aid under FSSAI, mainly for disinfection and microbial control. Meanwhile, emerging technologies like Cold Plasma and Pulsed Electric Field (PEF) are under research and pilot testing but lack widespread commercial approval in India (18).

Despite their advantages, non-thermal technologies pose several safety concerns. Some methods, such as Cold Plasma and Ozone Treatment, may generate oxidative by-products, potentially altering food composition. Technologies like PEF and Ultrasound may have limited effectiveness against bacterial spores, requiring complementary treatment methods. Another challenge is consumer perception and awareness. While the FDA, EFSA and Codex Alimentarius recognize food irradiation as safe, public resistance persists due to misconceptions about radiation exposure. FSSAI mandates strict labelling of irradiated foods in India to promote transparency and build consumer trust.

As research progresses, India is expected to expand its regulatory framework for Cold Plasma, PEF and other novel non-thermal techniques. The role of FSSAI, AERB and BIS in aligning Indian standards with global best practices will be crucial in fostering the adoption of these innovative food processing technologies.

Future prospect

Recent findings indicate that non-thermal methods may offer an advantage over conventional thermal processing technologies in enhancing food quality and safety. Non-thermal treatments, such as high-pressure processing (HPP), pulsed electric fields (PEF), ultraviolet (UV) light treatments, cold plasma and irradiation treatment have a more significant impact on the future for its effectiveness in the inactivation of pathogens, without compromising the nutritional properties and preserving the essential vitamins, antioxidants and other beneficial compounds in fruits and vegetables. Depending on the kind of microorganism, degree of contamination, kind of product being treated, etc., different sensitivity to non-thermal methods was noted in the case of microbial load. The samples should be handled carefully because extended use of these methods can negatively impact the quality of the produce.

Integrating non-thermal treatments into smart agricultural systems enhances the quality and safety of fruits and vegetables throughout the entire supply chain, from farm to table. Utilizing data analytics, IoT sensors and automation enables real-time monitoring of produce quality, ensuring timely non-thermal treatments to reduce losses and maintain freshness. Future research should aim to lower the cost of these technologies and establish clear regulatory frameworks and standards for non-thermal technologies, which will be essential to ensure quality and safety.

Conclusion

Studies on non-thermal technologies have already been carried out in recent years. There is no way that any thermal technique can be a novel approach to cleaning surfaces that come into contact with food. These solutions positively impacted preserving the produce's visual quality during storage. In general, non-thermal technology promises to enhance the quality and extend the shelf life of fresh produce. There are several promising areas for further study in non-thermal food preservation, particularly by combining these methods with other cutting-edge technologies. One exciting direction is the development of hybrid approaches that integrate non-thermal preservation techniques, such as high-pressure processing (HPP) or pulsed electric fields (PEF), with innovative packaging solutions. For instance, coupling these methods with smart and active packaging, which can control gas composition, release antimicrobial agents, or absorb ethylene, could enhance fresh produce's shelf life and quality. Another key area is integrating artificial intelligence (AI) for real-time monitoring and process optimization. AI-based systems could analyze data from sensors embedded in both the preservation process and packaging to adjust parameters dynamically, ensuring maximum efficiency and consistency in treatment.

Additionally, machine learning algorithms could be used to predict the optimal conditions for various types of produce, further improving preservation methods. AI could also aid in quality control by using computer vision to detect spoilage or damage in produce during processing and packaging. Furthermore, exploring the synergy between non-thermal techniques and natural preservatives, such as plant extracts or antimicrobial coatings, could provide more sustainable and effective preservation solutions. Collectively, these hybrid approaches could overcome the limitations of non-thermal methods, making them more scalable, energy-efficient and commercially viable while ensuring the quality and safety of fresh produce.

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Authors' contributions

PD and NK wrote the original draft and contributed in conceptualization, revision of draft, inclusion of tables and figures, proof reading. PD, NK, BA, AT, SKP performed revision, formatting and supervision. All the authors read and approved the final version of the manuscript.

Compliance with ethical standards

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