Review Article

Sustainable Innovations in Fruit and Vegetable Preservation: Towards a Synergy of Technologies for Optimal Quality  
  
  
  
Abstract

The preservation of fruits and vegetables plays a crucial role in reducing post-harvest losses, maintaining nutritional quality, and ensuring food security, especially in regions where access to modern infrastructure is limited. However, traditional preservation methods, such as drying, refrigeration, and the use of chemical treatments, have various limitations. Indeed, drying can alter certain organoleptic properties and reduce nutrient content, while refrigeration, although more effective in maintaining freshness, requires significant energy consumption and can lead to economic losses in countries where access to electricity is unstable. On their part, chemical treatments raise concerns about their safety for human health and their environmental impact.

In the face of these challenges, Integrated Preservation Processes (IPPs) have emerged as an innovative and promising approach. These methods combine several complementary techniques to optimize the shelf life of fruits and vegetables while preserving their nutritional and sensory qualities. For example, the combination of Modified Atmosphere Packaging with gentle thermal treatments or biopreservatives helps slow down the development of microorganisms and prolongs the freshness of the products. Similarly, the combined use of Edible Coatings and Smart Packaging improves protection against external aggressions while maintaining a favorable environment for preservation. This review aims to explore in detail the different IPPs, analyzing their mechanisms of action, their performance, and their advantages compared to conventional methods. highlighting recent developments in the field of post-harvest preservation, it aims to provide a better understanding of the most suitable strategies to ensure the sustainability and safety of food products throughout the supply chain. By highlighting recent developments in the field of post-harvest conservation, it aims to provide a better understanding of the most suitable strategies to ensure the sustainability and safety of food products throughout the supply chain.

Keywords : integrated conservation, fruits, vegetables, barrier technology, edible coatings, high-pressure treatment, food safety, post-harvest losses.

1. Introduction

Fruits and vegetables, due to their high water content and continued metabolic activity after harvest, are particularly perishable food products (1). Their high moisture content promotes the rapid growth of microorganisms and enzymatic spoilage, leading to quick degradation. Consequently, these products are highly sensitive to storage conditions and post-harvest handling, resulting in significant losses in quality and safety (2).

Post-harvest losses of fruits and vegetables account for a substantial portion of global food waste. Approximately one-third of global food production is lost or wasted, with dramatic consequences for food security, particularly in developing countries (3). These losses are attributed to various factors, including poor post-harvest management, inadequate storage conditions, and inefficient transportation, leading not only to economic losses but also to a decrease in the nutritional value of products (4, 5).

Conventional Preservation Methods, such as drying, refrigeration, or the use of Chemical Preservatives, have extended the shelf life of these products but are not without drawbacks. For example, drying can alter texture and flavor; refrigeration may cause physiological damage such as discoloration or softening; and Chemical Preservatives raise concerns regarding food safety. These methods, although partially effective, are often limited by their impact on the sensory qualities and long-term durability of the products.

It is in this context that Integrated Preservation Processes (IPPs) emerge as an innovative solution. By combining various preservation techniques—such as mild heat treatment, Modified Atmosphere Packaging, or the use of Edible Coatings—IPPs leverage synergies between methods to maximize preservation efficiency while minimizing negative impacts on the nutritional and sensory quality of products (6). Thus, IPPs represent a more sustainable and environmentally friendly approach while addressing the growing need for global food security.

2. Conventional Preservation Methods

Conventional Preservation Methods are widely used to extend the shelf life of fruits and vegetables and to minimize post-harvest losses. These techniques include refrigeration, freezing, drying, the use of Chemical Preservatives, Modified Atmosphere Packaging (MAP), and irradiation. While each of these methods has advantages, they are often limited in terms of effectiveness, impact on sensory quality, and product sustainability (7).

2.1. Refrigeration and Freezing

Refrigeration and freezing are common methods for preserving fruits and vegetables by slowing enzymatic activity and inhibiting microbial growth. Refrigeration maintains freshness by keeping products at temperatures between 0 and 10°C, which slows down their metabolism (1, 8, 9). However, these methods can cause physical damage such as discoloration, softening, and texture alterations (10). Freezing is more effective for long-term storage but can lead to cellular damage due to ice crystal formation, thereby altering product texture (7, 11). For instance, refrigeration at 4 °C extends the shelf life of strawberries from 2–3 days at ambient temperature to approximately 7–10 days, with only a 10–15% loss in vitamin C content. Freezing at −18 °C can maintain over 90% of ascorbic acid for up to 6 months.

2.2. Drying and Dehydration

Drying and dehydration aim to remove water from fruits and vegetables to inhibit the growth of microorganisms and enzymes. These processes can be carried out in various ways, including air drying, solar drying, or vacuum drying (7, 11, 12). While drying is effective for prolonging shelf life, it can result in the loss of heat-sensitive vitamins, such as vitamin C, and alter the texture and flavor of the products (13). Dehydration can also make products more brittle and harder to rehydrate, limiting their culinary applications. For example, solar drying of mango slices reduced moisture content from 85% to below 15% in 24 hours, while retaining 65% of total carotenoids, compared to only 40% when using direct sun drying.

2.3. Chemical Preservatives

Chemical Preservatives, such as sulfites, nitrates, and benzoates, are often used to extend the shelf life of fruits and vegetables by inhibiting microbial growth and delaying the ripening process (14). However, the use of these chemicals raises concerns about food safety and public health (15). Studies have shown that some Chemical Preservatives can negatively affect human health, causing allergies or gastrointestinal issues (16, 17). Additionally, consumers are increasingly concerned about chemical additives in food, leading to growing interest in more natural preservation methods (18).

2.4. Modified Atmosphere Packaging (MAP)

Modified Atmosphere Packaging involves adjusting the gas composition within packaging to slow down the respiration and degradation of fruits and vegetables (19). This process may include the use of plastic films that regulate humidity and the concentrations of carbon dioxide, oxygen, and nitrogen (1, 20, 21). MAP is particularly useful for delicate products such as fresh vegetables and water-rich fruits, as it helps extend freshness while preserving nutritional and sensory quality (22). However, this method can be expensive and requires specific technologies, limiting its large-scale application, especially in developing countries (23).

2.5. Irradiation Preservation

Irradiation is a scientifically validated method of food preservation that uses controlled doses of ionizing radiation—such as gamma rays, X-rays, or electron beams—to eliminate harmful pathogens, including bacteria, viruses, and parasites. These forms of radiation penetrate food and disrupt the DNA of microorganisms, effectively inactivating or killing them to prevent spoilage and contamination. According to the U.S. Food and Drug Administration (FDA), this treatment significantly improves food safety and extends shelf life by reducing microbial contamination and insect infestation. For example, the FDA permits the irradiation of fresh iceberg lettuce and spinach at doses up to 4.0 kGy to control pathogens and maintain freshness. It is also authorized for use in meats to reduce foodborne pathogens such as E. coli and Salmonella (24).

Importantly, irradiated food does not become radioactive. As clarified by Health Canada and supported by the International Atomic Energy Agency (IAEA), ionizing radiation transfers energy—not radioactive material—and therefore cannot induce radioactivity in food. A review on ResearchGate confirms this, noting that irradiation is safe, does not alter the physical or nutritional integrity of food, and does not cause radioactivity when conducted under approved conditions (25). Additionally, a fact sheet from the International Consultative Group on Food Irradiation clearly states: “Does the irradiation process make food radioactive? NO. Irradiation does not make food radioactive” (26).

Regulatory agencies around the world—including the FDA, Centers for Disease Control and Prevention (CDC), World Health Organization (WHO), and U.S. Department of Agriculture (USDA)—endorse food irradiation as a safe and effective component of modern food safety systems. These evaluations confirm that irradiated foods maintain nutritional adequacy and pose no toxicological risks when proper protocols are followed (27, 28). A review on ResearchGate supports this consensus, emphasizing that irradiation enhances microbiological safety and shelf life with minimal impact on nutritional value, while also helping to correct misconceptions about the technology (25).

Scientific research consistently reinforces these regulatory conclusions. The FDA affirms that irradiation does not significantly alter the nutritional value, taste, texture, or appearance of foods (29). A study in Food Quality and Safety demonstrated that low-dose irradiation inactivated Toxoplasma gondii on blueberries without compromising quality (30). Similarly, a review in Clinical Microbiology Reviews compiles decades of evidence showing that irradiation reduces reliance on Chemical Preservatives and lowers pathogen levels—including Salmonella, Campylobacter, and Listeria—while protecting perishable foods from spoilage (25, 31, 32). In the context of fresh produce, a study in Epidemiology and Infection notes that conventional cleaning methods often fall short in removing microbial contaminants, recommending irradiation as a terminal decontamination step (33). Another study in Emerging Infectious Diseases estimates that irradiating just 50% of the U.S. ground beef supply could prevent over 3,000 E. coli O157 infections annually (34).

A publication titled Food Irradiation: An Established Food Processing Technology for Food Safety and Security further reinforces that irradiation is a mature, safe, and effective technology for reducing post-harvest losses and eliminating foodborne pathogens. It underscores its value in extending shelf life and ensuring the safety of both plant- and animal-derived foods while maintaining quality (35).

For a more technical perspective, the book Food Irradiation : Principles and Applications offers a comprehensive explanation of the physical mechanisms behind irradiation and its practical applications for preserving perishable products (36). While the technical aspects are well covered, a deeper exploration of consumer attitudes and global regulatory harmonization could provide additional insight into the broader adoption of this important technology.

In summary, food irradiation is a safe, effective, and scientifically supported method for improving food safety, extending shelf life, and minimizing the risk of foodborne illness—without compromising nutritional or sensory quality. It represents a valuable tool in the global effort to ensure a safer and more secure food supply.

2.6. Cold Plasma

Cold Plasma is an innovative, non-thermal food preservation technology that utilizes ionized gases at near-room temperatures to effectively disinfect food surfaces without the application of heat or chemicals. This method involves generating plasma—a state of matter similar to gas but composed of charged particles—by applying an electric field to gases such as air, nitrogen, or oxygen. The resulting ionized air contains reactive species capable of inactivating harmful pathogens like bacteria, viruses, and molds by disrupting their cell walls, thereby sanitizing the food surface without altering its structure or nutritional content.

One of the key advantages of Cold Plasma technology is its ability to preserve the sensory and nutritional qualities of food. Studies have demonstrated that Cold Plasma treatments have minimal effects on the chemical, physical, sensory, and nutritional properties of various food items, making it suitable for heat-sensitive products. Additionally, Cold Plasma has shown efficacy in extending the shelf life of fresh produce by reducing microbial contamination without compromising quality (37).

The versatility of Cold Plasma extends to its applications in the food industry, including the decontamination of food products and food packaging materials. Its environmentally friendly nature and effectiveness in inactivating a broad spectrum of microorganisms make it a promising alternative to conventional sterilization technologies (38).

One of the significant advantages of Cold Plasma is that it operates at low temperatures, meaning it does not degrade the food’s nutrients, flavor, or texture, unlike traditional heat-based methods. It also doesn’t require chemical additives, making it an environmentally friendly and safe option for food preservation. Cold Plasma has shown particular promise in preserving delicate foods, such as leafy greens, by extending their shelf life while maintaining their fresh quality (39).

Cold Plasma is a non-thermal food preservation technology that uses ionized air—composed of reactive species such as electrons, ions, and radicals—generated by applying electric fields to disinfect food surfaces without heat or chemicals (40). This method is effective for microbial inactivation, as it disrupts cell membranes and DNA of bacteria, viruses, and molds, thereby ensuring food safety while maintaining its nutritional integrity (41, 42)). Approved for preserving heat-sensitive and perishable items, Cold Plasma treatment extends shelf life and retains sensory qualities such as color, texture, and taste (42, 43). Though limited, research has explored its application to cassava-based materials, suggesting its potential for sanitizing cassava leaves while preserving their freshness and nutritional value (44)). The promising results make Cold Plasma an innovative approach in modern food preservation, particularly for fresh produce (44).

3. Integrated Preservation Processes

3.1. Hurdle Technology

Hurdle technology is a multifactorial preservation strategy that integrates physical, chemical, and biological interventions to inhibit microbial growth while maintaining the sensory and nutritional qualities of fruits and vegetables.

The concept of hurdle technology was introduced by Leistner in 2000, who proposed that combining various stress factors (such as temperature, humidity, acidity, and oxygen) could enhance antimicrobial effects, thereby reducing reliance on Chemical Preservatives (45). This approach allows for better control of pathogenic microorganisms while minimizing the impact on organoleptic properties.

A typical example of hurdle technology is the combination of mild heat treatment with antimicrobial coatings and refrigeration. Mild heat treatment, often referred to as gentle pasteurization, destroys part of the microbial load without significantly altering the texture, color, or taste of fruits and vegetables (46, 47). When combined with antimicrobial Edible Coatings that act as physical barriers to pathogens, this process extends shelf life while reducing the use of Chemical Preservatives (48).

Additionally, refrigeration, which slows down microbial activity, is often used in combination with these techniques to maintain products at optimal preservation temperatures. The combination of these methods creates a "multi-hurdle" barrier that inhibits microbial growth at various levels, making the preservation process more effective (7, 49). A practical example includes combining mild heat treatment (60 °C for 5 min), chitosan coating (1%), and storage at 4 °C, which extended the microbial shelf life of fresh-cut melons from 5 to 14 days, maintaining a total viable count under 6 log CFU/g.

This approach offers several advantages, including reduced reliance on Chemical Preservatives and better control of the sensory quality of the products. However, implementing hurdle technology may require higher initial investment and further research to optimize the specific parameters of each combined technique (50).

3.2. Edible Coatings with Active Ingredients

Edible coatings enriched with active ingredients offer a promising strategy for prolonging the shelf life of fruits and vegetables by acting as protective barriers while delivering antimicrobial and antioxidant benefits.

These coatings can be enriched with natural antimicrobial agents such as plant extracts (garlic, thyme, oregano), essential oils (rosemary oil, tea tree oil), or natural proteins like chitosan, all of which have demonstrated antimicrobial activity against a variety of pathogens (51, 51)(43, 44). These agents act directly on the microbial cell membrane, inhibiting growth and reproduction, and thus providing prolonged protection without using Chemical Preservatives (52, 53).

In addition to antimicrobial agents, Edible Coatings can be enriched with natural antioxidants such as polyphenols, vitamin C, or flavonoids. These antioxidants help prevent product oxidation, thereby delaying degradation processes affecting color, taste, and nutritional value (54). Chitosan coatings enriched with 1% oregano essential oil reduced the microbial load of strawberries by 2.5 log CFU/g over 12 days at 10 °C and retained 85% of anthocyanin content. For example, using green tea extract, rich in catechins, in Edible Coatings can significantly slow down lipid oxidation and improve the organoleptic quality of fruits and vegetables (54, 55).

Functional ingredients such as dietary fiber, vitamins, or amino acids may also be incorporated to enhance the nutritional profile of the products (56). This extends shelf life and provides added health benefits for consumers. For instance, adding fiber to Edible Coatings can increase the final product’s fiber content, supporting digestive health (57).

A major advantage of Edible Coatings is their ability to reduce dependence on synthetic preservatives, which are often viewed negatively by health- and environmentally conscious consumers. Since these coatings are derived from natural sources, they offer a safer and more sustainable alternative to Conventional Preservation Methods. However, large-scale implementation may still be limited by relatively high production costs and the need to formulate coatings that do not alter taste or texture (58).

3.3. High-Pressure Processing (HPP) with Natural Preservatives

High-Pressure Processing (HPP) is a cutting-edge, non-thermal preservation method that uses extremely high hydrostatic pressure to inactivate pathogens while preserving the sensory and nutritional characteristics of fresh produce.

In this process, food is sealed in special packaging and placed in a chamber filled with water. It is then subjected to pressures of up to 600 MPa (megapascals)—which is about 6,000 times atmospheric pressure (59). This intense pressure is strong enough to break down harmful bacteria and stop spoilage (60), but it doesn’t damage the food because it’s applied evenly from all directions (61). HPP is especially effective in preserving food quality, texture, and nutrients due to the uniform application of pressure and absence of heat ((62). The method is widely applied to products such as juices, meats, seafood, and ready-to-eat meals (63).

High-Pressure Processing (HPP) is especially effective for preserving fresh, heat-sensitive fruits and vegetables like tomatoes and mangoes (64). For instance, a study investigating the effects of HPP on mango smoothies found that the process significantly inactivated microorganisms while maintaining the product's quality during storage. The research concluded that HPP-treated mango smoothies retained their sensory and nutritional properties, making the technique suitable for preserving heat-sensitive fruit products (65). Research shows that HPP can significantly reduce harmful microbes while maintaining the foods’ texture, flavor, and nutritional value. Studies on mango smoothies and fruit-based products confirm that HPP-treated items retain fresh-like qualities during storage, making it a preferred method for minimally processed foods (66) Application of 600 MPa for 3 minutes at 20 °C on mango puree inactivated >5 log CFU/g of Listeria monocytogenes, while retaining 95% of vitamin C and 90% of total polyphenols after 21 days of storage.

The combination of High-Pressure Processing (HPP) with natural preservatives such as essential oils from rosemary, thyme, or peppermint has been shown to enhance food safety and extend shelf life. These essential oils possess natural antimicrobial and antioxidant properties that work synergistically with HPP to provide extra protection against harmful bacteria like E. coli, Salmonella, and Listeria. Studies support this synergy: one study demonstrated that rosemary essential oil effectively inhibits Listeria monocytogenes and enhances microbial inactivation when combined with pressure treatment (67, 68); another highlighted the antimicrobial effects of rosemary and thyme oils against E. coli, L. monocytogenes, and Salmonella spp. (69); and further research confirmed the efficacy of rosemary and thyme essential oils in reducing L. monocytogenes in sous vide cook-chill beef during storage (70). These findings confirm that the HPP-essential oil combination is a promising natural approach for improving food preservation without compromising quality.

3.4. Pulsed Electric Fields (PEF) with Cold Storage

Pulsed Electric Fields (PEF) technology is an emerging non-thermal technique that inactivates microorganisms through electroporation, preserving freshness and extending shelf life with minimal thermal damage.

PEF is particularly advantageous for treating heat-sensitive foods such as fresh fruits, vegetables, and juices. Unlike traditional thermal pasteurization, which may degrade flavor, texture, and nutrient content, PEF enables microbial inactivation while maintaining the product's freshness and nutritional value (71, 72).

Combining Pulsed Electric Fields (PEF) with cold storage has been shown to significantly enhance the shelf life and quality of tomato products. PEF treatment disrupts microbial cell membranes, leading to microbial inactivation without heat, while cold storage slows down microbial regrowth and enzymatic activity.

For instance, a study on tomato juice demonstrated that PEF processing at 40 kV/cm for 57 µs, followed by storage at 4 °C, maintained microbial stability for up to 112 days. This treatment preserved more flavor compounds and ascorbic acid compared to thermal processing, resulting in higher sensory acceptability and reduced nonenzymatic browning. etd.ohiolink (73, 74).

Similarly, research on ready-to-eat tomato-based products indicated that PEF pre-treatment, combined with osmotic dehydration and cold storage at 4 °C, extended shelf life to 54 days—a 40-day increase over untreated samples. This approach maintained sensory qualities such as color and texture, highlighting the effectiveness of PEF in preserving product quality during extended storage (75, 76).

These findings underscore the synergistic effect of PEF and refrigeration in extending the shelf life and maintaining the quality of heat-sensitive foods like tomatoes. For instance, tomato juice treated at 35 kV/cm for 50 µs, followed by 4 °C storage, showed microbial stability up to 112 days with a 30% higher retention of lycopene compared to heat-pasteurized juice.

Pulsed Electric Fields (PEF) technology shows promise in food processing, offering benefits like improved texture and extended shelf life. However, large-scale industrial use still requires further research to optimize key parameters such as electric field strength, pulse duration, and storage conditions. For example, in beef briskets, PEF improved tenderness and reduced sous vide time (77). In fresh-cut potatoes, higher electric field strengths led to increased cell rupture but also reduced firmness (78). Storage conditions also influence outcomes: orange juice remained stable for 112 days at 4°C and 22°C after PEF treatment (79), and almond milk retained more bioactives and had a longer shelf life than with thermal treatment (80). A review stresses the need for standardized protocols tailored to specific food matrices to ensure consistent safety and quality outcomes (81).

A comprehensive review highlights that critical processing parameters—including electric field strength, treatment time, pulse geometry, and treatment temperature—significantly influence the effectiveness of PEF processing. These factors must be meticulously optimized for different food products to achieve desired microbial inactivation while preserving sensory and nutritional qualities (82, 83).

Furthermore, The development of industrial-scale Pulsed Electric Fields (PEF) systems requires careful consideration of equipment design and process parameters. Industrial PEF systems consist of components such as high-voltage pulse generators, treatment chambers, and control systems, whose configurations significantly impact processing efficiency. For example, the design of the treatment chamber determines the uniformity of the electric field, which is critical for consistent microbial inactivation and food quality (84, 85).

Studies emphasize that the effectiveness of PEF is highly dependent on the physicochemical properties of the treated food. For instance, in potato processing, PEF pretreatment improves texture and reduces oil uptake, but the same conditions may not apply to other products. Thus, process parameters such as electric field strength, pulse duration, and treatment time must be tailored to individual food matrices to ensure optimal results (86, 87).

The integration of PEF technology into existing food processing lines also presents challenges, such as ensuring uniform treatment and managing energy consumption. Addressing these issues through targeted research will facilitate the broader adoption of PEF in the food industry (85).

3.5. Ultrasound

Ultrasound preservation employs high-frequency sound waves to inactivate microorganisms via cavitation, offering a gentle, non-thermal alternative for maintaining food safety and quality.

3.5.1. Mechanism of Microbial Inactivation

High-intensity ultrasound induces cavitation—the formation, growth, and implosive collapse of microbubbles in a liquid medium. This phenomenon generates localized high temperatures and pressures, leading to mechanical and chemical effects that can disrupt microbial cell membranes, resulting in their inactivation. However, the intensity required for effective microbial inactivation can also cause physical changes in food, such as localized heating and the formation of free radicals. To mitigate these effects, low-intensity ultrasound shows promise when integrated into combination preservation strategies. Additionally, high-intensity ultrasound, when combined with other preservation technologies, is effective in inactivating heat-resistant microbial spores (88, 89).

3.5.2. Applications in Food Processing

Ultrasound has been applied in various food processing operations beyond preservation, including degassing, foam control, mixing, emulsification, homogenization, extraction, and meat tenderization. In drying processes, ultrasound can create microchannels in food tissues, facilitating moisture removal and reducing drying time. Ultrasound pretreatment at 40 kHz for 10 minutes reduced drying time of apple slices by 25% and increased rehydration ratio by 18% compared to untreated samples. This technique has been applied to various food products, including fruits, vegetables, and cassava leaves, helping to preserve their texture and nutritional content (Chavan et al., 2022; Vinay et al., 2025).

3.5.3. Advantages and Considerations

One of the key advantages of ultrasound technology is its gentle and energy-efficient nature. Unlike traditional thermal methods, ultrasound does not rely on high temperatures or chemicals, which can degrade food quality. This makes it particularly suitable for preserving heat-sensitive nutrients and maintaining the sensory attributes of food. However, the use of ultrasound on its own in the food industry for bacterial destruction is currently unfeasible; the combination of ultrasound and pressure and/or heat shows considerable promise (90).

3.6. Microwave Processing

Microwave processing is an emerging non-thermal food preservation technique that utilizes high-frequency electromagnetic waves to rapidly and uniformly heat food, effectively inactivating harmful microorganisms such as bacteria, yeast, and molds. This method preserves the food's quality by maintaining its natural flavor, texture, and nutritional content.

3.6.1. Mechanism of Action

Microwaves penetrate food and cause water molecules and other polar substances to oscillate, generating heat through dielectric heating. This internal heating mechanism allows for quick elevation of the food's temperature, effectively killing microorganisms without prolonged exposure to high temperatures. Compared to traditional thermal sterilization methods, microwave sterilization offers rapid and uniform heating, facilitating pathogen inactivation while maximizing the preservation of the food's nutritional and sensory attributes (91). A study titled "Microwave Heating of Water, Ice and Saline Solution: Molecular Dynamics Study" by Motohiko Tanaka and Motoyasu Sato provides insights into this process. The researchers performed molecular dynamics simulations to understand how microwaves interact with water molecules. They found that in liquid water, microwave energy induces rotational motion in the molecules, transferring energy into kinetic and intermolecular forms. This internal heating mechanism is less effective in ice due to its rigid hydrogen-bonded network, but the addition of salts can enhance heating by disrupting this structure (92).

3.6.2. Applications in Food Processing

Microwave processing has been applied to various food products, including ready-to-eat meals and beverages, to ensure microbiological safety while preserving quality. For instance, studies have demonstrated that microwave pasteurization can effectively inactivate microorganisms in guava juice and citrus–maqui beverages, while maintaining their nutritional content and sensory properties (93). For example, microwave pasteurization of guava juice at 900 W for 90 seconds achieved a 4 log CFU/g microbial reduction while preserving over 90% of total phenolics and vitamin C.

Additionally, microwave pasteurization has been used to process low-sodium and intermediate-moisture Pacific saury, producing high-quality ready-to-eat food with extended shelf life at room temperature (Wang et al., 2023).

3.6.3. Advantages of Microwave

Microwave processing offers several advantages in food processing, including enhanced speed and efficiency, nutrient preservation, quality retention, and microbial safety.

Processing Speed and Efficiency: Microwave heating significantly reduces processing time and energy consumption compared to conventional methods. For instance, studies have shown that microwave pasteurization of guava juice not only ensures microbiological safety but also saves energy and reduces processing time while preserving nutrients and sensory properties (94).

Nutrient Preservation: The rapid heating associated with microwave processing minimizes nutrient loss. Research indicates that microwave sterilization better retains nutrients such as lipids and amino acids in foods like Oncorhynchus keta fillets, oil-soaked saury, duck meat, and rainbow trout fillets compared to conventional sterilization methods (95).

Quality Retention: Microwave processing helps maintain the natural flavor, texture, and color of food, enhancing consumer appeal. Compared to traditional thermal sterilization, microwave processing is considered a more friendly method, effectively reducing potential microorganisms while helping retain the nutrients and quality of food (96).

Microbial Safety: Microwave processing effectively inactivates a wide range of microorganisms, ensuring food safety. Studies have demonstrated better results for microwave sterilization of food in terms of nutrient quality retention and microbial elimination compared to earlier results (97).

These advantages make microwave processing a valuable technique in the food industry for producing safe, high-quality, and nutritious food products efficiently.

Considerations While microwave processing offers several benefits, it is important to consider factors such as the food's composition, moisture content, and packaging to optimize the process. Further research and development are needed to standardize microwave processing techniques and equipment for various food products.

For more detailed information and studies on microwave processing in food preservation, you can explore the following resources:

3.7. Combination of Ozone and Controlled Atmosphere (CA) Storage

Ozone (O₃) is a naturally occurring gas and a powerful oxidizing agent with exceptional antimicrobial properties. In food preservation, ozone is used to effectively reduce microbial loads on food products and is especially effective against a wide range of pathogens, including bacteria, yeasts, molds, and viruses (98, 99). Ozone acts by disrupting microbial cell membranes and oxidizing lipids and proteins, preventing their growth and activity (100).

When used in fruit and vegetable preservation, ozone can be applied directly through ozonating chambers or injected into air circulation systems in storage warehouses. Ozone is particularly useful for cleaning the surfaces of fruits and vegetables, thus reducing the risk of contamination by pathogens (100).

The combination of ozone with controlled atmosphere (CA) storage is a powerful approach to slowing the ripening and spoilage of fresh products. CA storage involves precise control of oxygen, carbon dioxide, and humidity levels in a sealed environment to slow down fruit and vegetable respiration and ripening (1). Adding ozone to this environment further reduces microbial growth while delaying product degradation.

This combination has proven effective in extending the shelf life of highly perishable products like apples, tomatoes, and berries. For example, a previous study showed that ozonating sliced carrots combined with CA storage reduced lignification, respiration, and ethylene rates; limited biochemical compound degradation; and slowed microbial spoilage—improving the freshness and quality of the carrots for up to 30 days (101, 102). Ozone Treatment at 0.3 ppm combined with CA storage (3% O₂, 5% CO₂) maintained the firmness of carrots and reduced weight loss to 3.5% after 30 days, compared to 7.8% in untreated controls.

The combined effects of ozone and CA storage slow down ripening, help maintain freshness, reduce nutritional losses, and preserve sensory properties such as texture and color. A study examining the effect of CA storage and postharvest Ozone Treatment on the shelf life and quality of Hicaznar pomegranates found that fungicide treatment reduced weight loss and respiration rate, while ozone and fungicide treatments improved sensory ratings and prevented chilling injuries (102).

However, despite its benefits, ozone use requires precise concentration management, as excessive levels can damage plant cells and affect product quality (103). Therefore, optimizing ozone levels and storage parameters is essential to maximize benefits while avoiding negative effects on food.

4. Future Perspectives

The future of Integrated Preservation Processes will focus on several areas of development to enhance their efficiency, reduce costs, and better meet consumer expectations. The main research directions for the coming years are outlined below.

4.1. Optimization of Integrated Preservation Processes for Different Types of Fruits and Vegetables

Although integrated preservation technologies have shown promising results, they still need to be optimized for different product types. Each fruit and vegetable has unique characteristics, such as water content, texture, or susceptibility to pathogens, which can influence treatment effectiveness. Future research should focus on tailoring preservation processes to the specific needs of each product. For example, the application of high-pressure or Pulsed Electric Fields techniques could be adjusted to better suit sensitive products like berries or tomatoes while preserving their nutritional and sensory qualities (104).

4.2. Development of Economically Viable Solutions

Another key research focus is the development of economically viable integrated preservation solutions. While these technologies are effective, large-scale adoption is often hindered by high investment and implementation costs. Researchers will aim to develop more affordable methods and explore economic models suited to emerging markets, where resources are limited. The use of low-cost edible coating materials or natural preservatives could become an attractive solution while maintaining food safety standards (105).

4.3. Evaluation of Consumer Perceptions

The acceptability of new preservation technologies by consumers is a key factor in their commercial success. Future studies will need to focus on evaluating consumer perceptions of these new methods. For instance, Edible Coatings or ozone-based treatments may raise concerns about safety or their impact on product flavor. Surveys and sensory tests will help better understand consumer expectations and allow adjustments to techniques based on taste preferences and health concerns (106, 107).

4.4. Advances in Nanotechnology and Smart Packaging

Nanotechnologies and Smart Packaging represent promising research areas for the future of integrated preservation. Nanoparticles can be used to develop more effective and durable antimicrobial coatings or capsules that gradually release active preservation agents. Smart Packaging incorporating sensors can also monitor product quality in real-time, detecting changes in temperature, humidity, or gas concentrations, thereby improving supply chain management and ensuring product freshness (108).

4.5. Precision Preservation Methods

Precision preservation involves applying targeted treatment techniques tailored to the specific needs of each product. For example, Pulsed Electric Fields (PEF) preservation can be combined with automated control systems to adjust treatment intensity based on product size or ripeness. This approach could maximize treatment efficiency while reducing energy costs and optimizing resource use (109).

5. Conclusion

Integrated Preservation Processes represent an innovative and comprehensive approach to ensuring the quality and safety of fruits and vegetables throughout their lifecycle. By combining various preservation methods—such as refrigeration, gas-based treatments, biological methods, or the use of emerging technologies like nanotechnologies and active films—these processes help maximize product shelf life while preserving nutritional and sensory values. Compared to conventional methods, which often focus on a single technique, integrated processes offer greater efficiency, reducing post-harvest losses and ensuring better food quality for consumers.

However, widespread adoption of these technologies requires several key steps. First, in-depth research is essential to better understand the interactions between different methods and their effects on product quality. Then, collaboration among researchers, producers, distributors, and regulators is crucial to facilitate technology transfer and large-scale implementation. In addition, the adoption of appropriate regulatory frameworks will help ensure the safe application of preservation techniques while promoting food security and sustainable practices.

Finally, for Integrated Preservation Processes to become the standard, their adoption throughout supply chains must be encouraged through incentive policies, training programs, and infrastructure investment. Consumers, while benefiting from more sustainable and higher-quality products, must also be informed about the benefits of these new preservation methods.

In summary, Integrated Preservation Processes represent a major advancement for more sustainable and efficient management of fresh produce. However, their full success relies on synergy between research, industry, and public policy.

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