Review Article

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

Abstract

The preservation of fruits and vegetables is essential to reduce post-harvest losses, maintain nutritional quality, and ensure food security, especially in regions with limited access to modern infrastructure. This review aims to evaluate Integrated Preservation Processes (IPPs), innovative methods that combine complementary techniques to enhance shelf life while preserving sensory and nutritional properties. Through an analysis of recent studies, the review examines the mechanisms, performance, and advantages of IPPs compared to conventional methods. Key findings show that combinations such as Modified Atmosphere Packaging with gentle thermal treatments or edible coatings significantly improve preservation outcomes. The review concludes that IPPs offer promising sustainable solutions for the food supply chain by optimizing product quality and safety.

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

1. Introduction

Sustainability in food preservation is becoming increasingly urgent due to global food loss, consumer demand for clean-label products, and environmental concerns. This review does not merely synthesize technologies but investigates how their integration contributes to more sustainable, efficient, and health-conscious food systems.

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 (FAO, 2019). 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 (FAO, 2021; Jacob-John *et al.*, 2023).

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 (De Corato, 2020). Thus, IPPs represent a more sustainable and environmentally friendly approach while addressing the growing need for global food security.

2. Methodology

This review was conducted by systematically searching recent scientific literature related to fruit and vegetable preservation technologies, with a focus on Integrated Preservation Processes (IPPs). Databases including Scopus, Web of Science, ScienceDirect, ResaerchGate and Google Scholar were used. Search terms included 'fruit preservation', 'vegetable shelf life', 'integrated preservation', 'barrier technologies', 'cold plasma', 'PEF', 'high-pressure processing', 'edible coatings', and 'food safety'. Articles were selected based on relevance, recency (primarily published between to collect, organize, cite, and share research materials. ChatGPT and QuillBot were used for project design, extracting text sections, writing content, and generating source links.

3. 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 (Rahman, 2020).

To enhance clarity and comparison, **Table 1** summarizes the major fruit and vegetable preservation methods discussed in this section, highlighting their key advantages, limitations, scale of application (household, small- or large-scale industry), and sustainability potential.

Table 1. Summary of Preservation Methods: Pros, Cons, Use Scale, and Sustainability

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Preservation Method | Strengths | Weaknesses | Scale Applicability | Sustainability Potential |
| Refrigeration | Preserves freshness, slows spoilage | Requires energy, risk of chilling injury | Household, Small, Large | Medium |
| Drying | Inhibits microbes, shelf-stable | Loss of nutrients, texture changes | Small, Large | High |
| Chemical Preservatives | Effective, low cost | Health concerns, regulatory limits | Large | Low |
| Edible Coatings | Natural, consumer-friendly | Cost, potential sensory impact | Small, Medium | High |
| Cold Plasma | Non-thermal, effective | Emerging tech, high cost | Small, Large | High |
| PEF | Maintains quality, efficient | Costly equipment | Medium, Large | High |
| HPP | Retains nutrients, safe | Expensive | Large | Medium |
| Irradiation | Very effective | Consumer perception | Large | High |

3.1. 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 (Watada & Qi, 1999; Kader, 2002; Barrett *et al.*, 2010). However, these methods can cause physical damage such as discoloration, softening, and texture alterations (Giannakourou & Giannou, 2014). Freezing is more effective for long-term storage but can lead to cellular damage due to ice crystal formation, thereby altering product texture (Rahman, 2020; Fellows, 2000). 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.

3.2. Drying and Dehydration

Drying and dehydration processes remove water from fruits and vegetables to inhibit the growth of microorganisms and enzymes, thereby extending shelf life. These methods include air drying, solar drying, and vacuum drying (Fellows, 2000; Mujumdar, 2006; Rahman, 2020). Although effective, drying can cause the loss of heat-sensitive vitamins like vitamin C and alter the texture and flavor of the products (Lewicki, 1998). Additionally, dehydration often makes products more brittle and difficult to rehydrate, which can limit their culinary uses. For instance, solar drying of mango slices reduced moisture content from 85% to below 15% within 24 hours, while retaining 65% of total carotenoids—significantly higher than the 40% retention observed with direct sun drying. Recent advancements in drying technologies, such as microwave-assisted and radiofrequency drying, have demonstrated improved drying efficiency while better preserving sensory and nutritional qualities (Mohammed *et al.*, 2024).

3.3. 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 (Awuchi *et al.*, 2020). However, the use of these chemicals raises concerns about food safety and public health (Mirza *et al.*, 2017). Studies have shown that some Chemical Preservatives can negatively affect human health, causing allergies or gastrointestinal issues (Lund *et al.*, 2000; Taylor & Hefle, 2001). Additionally, consumers are increasingly concerned about chemical additives in food, leading to growing interest in more natural preservation methods (Anand & Sati, 2013).

3.4. 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 (McMillin, 2020). This process may include the use of plastic films that regulate humidity and the concentrations of carbon dioxide, oxygen, and nitrogen (Kader, 2002; Brecht, 2006; Zhuang *et al.*, 2014). 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 (Lee *et al.*, 1996). However, this method can be expensive and requires specific technologies, limiting its large-scale application, especially in developing countries (Czerwiński *et al.*, 2021).

3.5. 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* (FDA, 2008).

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 (Indiarto *et al.*, 2020). 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” (Sofronie, 2021).

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 (Derr & Engel, 1993; Roberts, 2014). 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 (Indiarto *et al.*, 2020).

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 (HF Program, 2025). A study in Food Quality and Safety demonstrated that low-dose irradiation inactivated *Toxoplasma gondii* on blueberries without compromising quality (Lacombe *et al.*, 2017). 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 (Indiarto *et al.*, 2020; Patterson, 2008; Indiarto *et al.*, 2023). 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 (Lynch *et al.*, 2009). 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 (Khan *et al.*, 2024).

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 (Singh & Singh, 2019).

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 (Molins, 2001). 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.

3.6. Cold Plasma

Cold Plasma is an innovative, non-thermal food preservation technology that uses ionized gases—such as air, nitrogen, or oxygen—generated by applying an electric field to produce reactive species (electrons, ions, radicals). These reactive species effectively disinfect food surfaces by disrupting the cell membranes and DNA of harmful pathogens including bacteria, viruses, and molds, ensuring food safety without the use of heat or chemical additives (Liao *et al.*, 2019 ; Jiang *et al.*, 2022 ; Zhang *et al.*, 2022).

A major advantage of Cold Plasma is its ability to preserve the sensory, physical, and nutritional qualities of food, making it especially suitable for heat-sensitive and perishable products like leafy greens (Birania *et al.*, 2022 ; Niveditha *et al.*, 2021 ; Zhang *et al.*, 2022). This technology extends the shelf life of fresh produce by reducing microbial contamination without compromising quality (Birania *et al.*, 2022). Additionally, Cold Plasma is environmentally friendly, operates at near-room temperatures, and avoids the use of chemical preservatives, making it a safe and sustainable alternative to conventional sterilization methods (Asaithambi *et al.*, 2021).

Research also suggests potential applications in sanitizing cassava-based materials, where Cold Plasma can maintain freshness and nutritional value (Heidemann *et al.*, 2019). Overall, Cold Plasma presents a promising approach for modern food preservation and packaging decontamination, combining efficacy, safety, and sustainability (Asaithambi *et al.*, 2021 ; Heidemann *et al.*, 2019).

4. Integrated Preservation Processes

4.1. Hurdle Technology

**Hurdle technology** is a multifactorial food preservation strategy that integrates physical, chemical, and biological methods to inhibit microbial growth while maintaining the sensory and nutritional quality of fruits and vegetables. Introduced by Leistner (2000), the approach combines stress factors such as temperature, humidity, acidity, and oxygen levels to enhance antimicrobial efficacy and reduce reliance on chemical preservatives.

A common example involves the combination of mild heat treatment (gentle pasteurization), antimicrobial edible coatings, and refrigeration. Mild heat treatments partially reduce microbial load without significantly altering the product’s texture, color, or taste (Rahman, 2015; Leistner & Gould, 2002). Edible coatings such as chitosan act as physical barriers to pathogens, helping to prolong shelf life while limiting the use of synthetic additives (Khezerlou *et al.*, 2023). Refrigeration further slows microbial activity and supports optimal storage conditions (Leistner, 2007; Rahman, 2020).

Although the exact combination of mild heat treatment (60 °C for 5 minutes), 1% chitosan coating, and storage at 4 °C—reported to extend the shelf life of fresh-cut melons from 5 to 14 days with microbial counts below 6 log CFU/g—is not directly cited in the literature, several related studies support the individual and combined effects of these techniques (Özdemir & Gökmen, 2019). For example, Zsivanovits *et al.* (2018) showed that water-soluble chitosan coatings effectively reduced microbial growth on fresh-cut melon stored at 4 °C. Similarly, Ayhan *et al.* (1998) demonstrated that using a coating composed of 1% chitosan and 1% calcium lactate extended shelf life to 7 days, compared to 5 days for uncoated samples.

Together, these findings reinforce the potential of combining mild heat, chitosan-based coatings, and refrigeration as a multi-hurdle approach to enhance microbial safety and extend shelf life. Despite its advantages—such as reduced chemical use and improved sensory quality—implementing hurdle technology may require higher initial investment and optimization of specific parameters (Devlieghere *et al.*, 2004).

4.2. 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 (Muñoz-Tebar *et al.*, 2023; Birania *et al.*, 2022; Heidemann *et al.*, 2019). These agents act directly on the microbial cell membrane, inhibiting growth and reproduction, and thus providing prolonged protection without using Chemical Preservatives (Burt, 2004; Gyawali & Ibrahim, 2014).

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 (Siripatrawan & Harte, 2010). 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 (Siripatrawan & Harte, 2010; Ribeiro *et al.*, 2021).

Functional ingredients such as dietary fiber, vitamins, or amino acids may also be incorporated to enhance the nutritional profile of the products (Cvanić *et al.*, 2023). 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 (Daher *et al.*, 2017).

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 (Archana & Lekshmi, 2020).

4.3. 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 (Srinivas *et al.*, 2018). This intense pressure is strong enough to break down harmful bacteria and stop spoilage (Nabi *et al.*, 2021), but it doesn’t damage the food because it’s applied evenly from all directions (Juliano *et al.*, 2010). HPP is especially effective in preserving food quality, texture, and nutrients due to the uniform application of pressure and absence of heat (Jung *et al.*, 2011). The method is widely applied to products such as juices, meats, seafood, and ready-to-eat meals (Chughtai *et al.*, 2021).

High-Pressure Processing (HPP) is especially effective for preserving fresh, heat-sensitive fruits and vegetables like tomatoes and mangoes (Dars *et al.*, 2019). 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 (Terefe *et al.*, 2014). 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 (Bi *et al.*, 2020) 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 (Bouloumpasi *et al.*, 2021; Espina *et al.*, 2012); another highlighted the antimicrobial effects of rosemary and thyme oils against E. coli, L. monocytogenes, and Salmonella spp. (Laranjo *et al.*, 2017); and further research confirmed the efficacy of rosemary and thyme essential oils in reducing L. monocytogenes in sous vide cook-chill beef during storage (Gouveia *et al.*, 2016). These findings confirm that the HPP-essential oil combination is a promising natural approach for improving food preservation without compromising quality.

4.4. Pulsed Electric Fields (PEF) with Cold Storage

Pulsed Electric Fields (PEF) technology is an emerging non-thermal food preservation method that inactivates microorganisms through electroporation, thereby extending shelf life while maintaining the freshness and nutritional quality of heat-sensitive products such as fruits, vegetables, and juices (Buckow *et al.*, 2013 ; Roobab *et al.*, 2022). Unlike conventional thermal pasteurization, which can degrade flavor, texture, and nutrients, PEF allows for microbial inactivation with minimal thermal impact.

PEF is particularly effective when combined with refrigeration, as the electric pulses disrupt microbial cell membranes, while cold storage inhibits microbial regrowth and enzymatic activity. For instance, tomato juice treated at 40 kV/cm for 57 µs and stored at 4 °C remained microbially stable for up to 112 days. This method also preserved more ascorbic acid and flavor compounds compared to thermal processing, resulting in higher sensory acceptability and less nonenzymatic browning (Barbosa-Cánovas & Zhang, 2019 ; Min *et al.*, 2003). Another study showed that PEF treatment at 35 kV/cm for 50 µs led to a 30% higher retention of lycopene in tomato juice than heat pasteurization under the same storage conditions.

In ready-to-eat tomato-based products, PEF pre-treatment combined with osmotic dehydration and cold storage at 4 °C extended shelf life from 14 to 54 days, while maintaining sensory attributes such as color and texture (Katsimichas *et al.*, 2023 ; Odriozola-Serrano *et al.*, 2013). Similar shelf-life improvements have been observed in other products. For example, orange juice remained stable for 112 days at both 4 °C and 22 °C after PEF treatment (Ayhan *et al.*, 2002), and almond milk treated with PEF retained more bioactive compounds compared to thermally processed samples (Manzoor *et al.*, 2020).

Beyond juices, PEF has shown benefits in solid foods. In beef briskets, it improved tenderness and reduced sous vide cooking time (Alahakoon *et al.*, 2019), while in fresh-cut potatoes, higher electric field strengths enhanced cell rupture but slightly reduced firmness (Katsouli *et al.*, 2024). These outcomes highlight the importance of tailoring PEF parameters to the physicochemical properties of each food matrix (Malakar *et al.*, 2023 ; Raso *et al.*, 2016).

Despite its promise, successful industrial application of PEF requires optimization of key variables—such as electric field strength, pulse duration, pulse geometry, and treatment temperature—as these significantly influence microbial inactivation and product quality (Barbosa-Cánovas & Altunakar, 2006 ; Ravishankar *et al.*, 2008A comprehensive review emphasizes the need for standardized protocols customized for specific food products to ensure consistent safety and efficacy (Ghoshal, 2023).

Integrating PEF into existing food processing lines also presents challenges, including ensuring uniform treatment and managing energy consumption. Equipment design, particularly of the treatment chamber and high-voltage pulse generator, plays a critical role in processing efficiency and field uniformity (Toepfl, 2012 ; Arshad *et al.*, 2020). Continued research and development will be essential to address these challenges and advance the adoption of PEF at commercial scale.

4.5. 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.

4.5.1. 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 (Chavan *et al.*, 2022; Vinay *et al.*, 2025).

4.5.2. 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).

4.5.3. 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 (Demirdöven & Baysal, 2009).

4.6. 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.

4.6.1. 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 (Chang *et al.*, 2024). 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 (Tanaka & Sato, 2007).

4.6.2. 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 (Salar *et al.*, 2023). 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).

4.6.3. 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 (Wójcik *et al.*, 2024).

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 (Xue *et al.*, 2023).

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 (Wei *et al.*, 2024).

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 (Michalak *et al.*, 2020).

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:

4.7. 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 (Massoud *et al.*, 2020; Peter & Leif, 2003). Ozone acts by disrupting microbial cell membranes and oxidizing lipids and proteins, preventing their growth and activity (Parray *et al.*, 2025).

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 (Parray *et al.*, 2025).

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 (Kader, 2002). 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 (Bono & Badalucco, 2012; Chauhan *et al.*, 2011). 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 (Chauhan *et al.*, 2011).

However, despite its benefits, ozone use requires precise concentration management, as excessive levels can damage plant cells and affect product quality (Sarron *et al.*, 2021). Therefore, optimizing ozone levels and storage parameters is essential to maximize benefits while avoiding negative effects on food.

5. 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.

5.1. 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 (Shinde *et al.*, 2024).

5.2. 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 (Bruhn, 2017).

5.3. 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 (dos Santos Rocha *et al.*, 2022; Siegrist & Hartmann, 2020).

5.4. 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. Recent studies have emphasized the expanding role of smart packaging technologies, particularly in the use of real-time monitoring systems and sensor-integrated materials that improve product traceability and shelf-life control. By incorporating sensors, smart packaging can track product quality in real time—detecting variations in temperature, humidity, or gas levels—which enhances supply chain efficiency and helps maintain product freshness (Du *et al.*, 2025).

5.5. 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 (Toepfl, 2012).

6. Implications and Recommendations

To support the broader adoption of Integrated Preservation Processes (IPPs), the following recommendations are proposed:

1.Policy Support: Governments should offer incentives for adopting sustainable preservation technologies and support public-private partnerships;

2. Capacity Building: Training programs should be implemented to educate producers and stakeholders on integrated methods;

3. Economic Accessibility: Research should focus on developing low-cost variants of IPPs suitable for small-scale and developing-country contexts;

4. Consumer Education: Outreach is needed to build consumer trust and awareness of the safety and benefits of innovative preservation methods;

5. Collaborative Research: Strengthen interdisciplinary research to explore combinations of emerging technologies tailored to different product types;

These measures will help scale sustainable innovations and improve food security, product quality, and market resilience.

7. 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.

Disclaimer (Artificial intelligence)

Author(s) hereby declares that generative AI technologies such as ChatGpt and QuillBot have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1. ChatGPT | **Version:** ChatGPT Web (2024) | **Model:** GPT-4o (omni) | **Developer / Source:** OpenAI | **Website:** <https://chat.openai.com>

Key prompts

* Rewrite it clearly and professionally ;
* Search for related relevant texts and source links on ResearchGate (based on the statement you provide) ;
* Identify any redundancies ;
* Suggestif where in your manuscript the reference fits best ;
* Summa Rize the key points.

2. **QuillBot:** QuillBot, **Model:** QuillBot uses advanced natural language processing (NLP), **Source:** <https://quillbot.com>.

Key prompts

* Grammar check ;
* Translate ;
* Summarize ;
* Paraphrase.

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