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Sustainable food preservation techniques for reducing postharvest losses and food waste

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Abstract

Postharvest losses and food waste remain major challenges for global food security, economic stability, and environmental sustainability. Every year, a significant proportion of perishable foods such as fruits, vegetables, dairy, and meat are lost due to spoilage, inadequate storage, and inefficient handling, contributing to resource wastage and greenhouse gas emissions. Sustainable food preservation techniques offer effective solutions to mitigate these losses by extending shelf life, maintaining nutritional and sensory quality, and minimizing environmental impact. This review explores current and emerging preservation strategies, including novel thermal and non-thermal processing technologies, bioprocessing and fermentation approaches, and innovative packaging systems such as modified atmosphere, active, intelligent, and nanotechnology-based packaging. Emphasis is placed on the integration of these methods to achieve synergistic effects, reduce chemical additive usage, and promote sustainable postharvest management. Furthermore, challenges related to scalability, energy efficiency, regulatory compliance, and consumer acceptance are discussed, alongside future perspectives for the development of smart and sustainable food preservation systems. By combining technological innovation with sustainable practices, it is possible to reduce food waste, enhance food safety, and contribute to resilient and environmentally responsible food systems.

Keywords: Postharvest losses; Food waste reduction; Sustainable food preservation; Novel thermal processing; Non-thermal processing

1. Introduction

Globally, nearly one-third of all food produced for human consumption is either lost or wasted, representing an estimated 1.3 billion tons per year ^[1]. These losses not only exacerbate food insecurity but also contribute to significant environmental and economic burdens, including wasted water, land resources, and greenhouse gas emissions associated with production and disposal ^[2]. Postharvest losses are particularly critical for highly perishable commodities such as fruits, vegetables, dairy, and meat products, where spoilage can occur rapidly due to microbial growth, enzymatic degradation, or physical damage during handling, storage, and transportation ^[1].

Traditional food preservation methods, including refrigeration, freezing, drying, and conventional thermal processing, have been widely used to mitigate spoilage and extend shelf life. While these methods are effective in reducing microbial contamination and slowing deterioration, they are often associated with high energy consumption, increased operational costs, and in some cases, compromised nutritional and sensory quality ^[2]. Heat-sensitive nutrients, such as vitamins, antioxidants, and bioactive compounds, may be partially lost during conventional thermal treatments, while prolonged cold storage can lead to textural and flavor degradation in certain foods, sustainable food preservation techniques have emerged as critical tools for minimizing postharvest losses while maintaining nutritional quality, food safety, and environmental responsibility. Advances in novel thermal and non-thermal processing technologies, bioprocessing and fermentation methods, and innovative packaging solutions provide opportunities to reduce spoilage, decrease chemical additive use, and extend shelf life. Moreover, the integration of these technologies into a multi-hurdle approach can achieve synergistic effects, improving food stability and quality throughout the supply chain ^{[1][2]}. Such

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innovations are essential not only for reducing postharvest losses and food waste but also for building resilient and sustainable

food systems capable of meeting the demands of a growing global population.

Table 1: Summary of Novel Thermal and Non-Thermal Processing Techniques

Technology	Principle	Key Benefits	Applications	Limitations / Challenges
Microwave Heating (MW)	Dielectric heating using electromagnetic waves	Rapid volumetric heating; preserves nutrients and bioactive compounds; reduces processing time	Ready-to-eat meals, soups, beverages, low-moisture foods	Uneven heating in heterogeneous foods; requires process optimization
Radio Frequency Heating (RF)	Dielectric heating using radio waves	Uniform heating; nutrient retention; fast processing	Juices, liquid foods, low-moisture products	Equipment cost; dielectric properties must be matched to food
Ohmic Heating	Electrical current passed through food	Uniform internal heating; improves microbial inactivation; preserves proteins	Soups, sauces, purees, liquid foods with particulates	Requires sufficient conductivity; electrode corrosion potential
High-Pressure Processing (HPP)	Application of hydrostatic pressure (100-600 MPa)	Non-thermal microbial inactivation; retains fresh-like qualities; nutrient preservation	Juices, seafood, ready-to-eat meals	High equipment cost; batch processing limitations
Pulsed Electric Fields (PEF)	Short high-voltage pulses disrupt microbial membranes	Non-thermal microbial inactivation; retains sensory and nutritional quality	Liquid foods, juices, dairy	High capital cost; limited to liquid or semi-liquid foods
Ultraviolet (UV) Treatment	UV-C light inactivates microorganisms	Surface decontamination; minimal thermal damage; energy-efficient	Juices, water, fresh produce	Limited penetration; effective only on surfaces

Table 2: Summary of Bioprocessing and Fermentation Techniques

Technique	Mechanism	Key Benefits	Applications	Limitations / Challenges
Fermentation (Lactic Acid Bacteria)	Microbial metabolism produces acids, bacteriocins, ethanol	Natural preservation; improves nutrient bioavailability; functional/probiotic benefits	Yogurt, kefir, kimchi, kombucha	Requires controlled conditions; starter culture management
Enzyme-Assisted Bioprocessing	Enzymes modify food components	Enhances digestibility, nutrient release, flavor, and texture	Plant-based foods, cereal products, dairy	Cost of enzymes; process optimization required
Multi-Microbial / Co-Fermentation	Use of multiple microbial strains	Enhanced flavor, texture, and nutritional profile; natural preservation	Fermented foods and beverages	Complex management; risk of inconsistency
Combined Fermentation + Mild Thermal/Packaging	Synergistic hurdle approach	Extends shelf life; maintains quality and safety	Perishable fruits, beverages, dairy	Requires precise coordination of steps

Table 3: Summary of Innovative and Sustainable Packaging Technologies

Technology	Mechanism / Principle	Key Benefits	Applications	Limitations / Considerations
Modified Atmosphere Packaging (MAP)	Alters surrounding gas composition (O ₂ , CO ₂ , N ₂)	Slows microbial growth and oxidation; extends shelf life; reduces chemical preservatives	Fresh produce, meat, seafood, bakery products	Requires optimized gas composition and package integrity
Active Packaging	Incorporates antimicrobial agents, oxygen/moisture scavengers	Maintains freshness; reduces spoilage; extends shelf life	Dairy, meat, beverages	Food compatibility; regulatory approval
Intelligent Packaging	Sensors or indicators monitor quality (pH, microbial load, temperature)	Real-time quality monitoring; reduces waste; improves traceability	Perishable foods, ready-to-eat meals	High cost; sensor accuracy; consumer understanding
Biodegradable Packaging	Polylactic acid, starch-based polymers, biopolymers	Reduces plastic waste; environmentally friendly; maintains barrier properties	Dairy, beverages, bakery	Mechanical strength; water sensitivity; cost
Nanotechnology-Based Packaging	Nanomaterials improve barrier and mechanical properties; antimicrobial	Extends shelf life; enables smart sensing; reduces spoilage	Dairy, beverages, meat	Safety concerns; nanoparticle migration; regulatory compliance

2. Novel Thermal and Non-Thermal Processing Techniques

Emerging thermal and non-thermal processing technologies provide targeted, energy-efficient alternatives to conventional methods, enabling improved food safety and quality while minimizing nutrient loss and environmental impact ^[3]. Unlike traditional thermal processing, which relies on prolonged exposure to high temperatures, these novel approaches offer precise control over processing conditions, reducing energy consumption and preserving the functional and sensory attributes of foods.

2.1 Microwave and Radio Frequency Heating

Microwave (MW) and radio frequency (RF) heating utilize electromagnetic energy to achieve rapid volumetric heating, allowing foods to be heated uniformly and efficiently. These techniques significantly reduce processing time, which helps retain heat-sensitive nutrients such as vitamins C and B-complex, antioxidants, and bioactive compounds ^[4]. MW and RF heating are particularly suitable for ready-to-eat meals, beverages, soups, sauces, and low-moisture foods. Studies have demonstrated that these methods not only improve microbial

inactivation but also maintain the color, texture, and flavor of processed foods compared to conventional heating [3]. Challenges remain in achieving uniform heating in heterogeneous food matrices, requiring careful process optimization to prevent cold spots that could compromise safety.

2.2 Ohmic Heating

Ohmic heating, also known as Joule heating, involves passing an electrical current directly through the food, which acts as a resistive medium and generates heat internally. This method ensures rapid and uniform heating, minimizing thermal gradients and hot/cold spots that are common in conventional processing [4]. Ohmic heating is particularly effective for liquid foods and particulate-laden products such as soups, sauces, and purees, enhancing microbial inactivation while preserving protein functionality, vitamins, and other heat-sensitive nutrients. Moreover, the shorter processing time reduces energy consumption, making ohmic heating a sustainable alternative for industrial-scale food processing [5]. Limitations include the need for sufficient electrical conductivity in the food matrix and potential electrode corrosion during prolonged use.

2.3 Non-Thermal Techniques

Non-thermal food processing methods, including high-pressure processing (HPP), pulsed electric fields (PEF), and ultraviolet (UV) treatment, inactivate spoilage and pathogenic microorganisms without significant heat exposure. HPP applies hydrostatic pressures of 100-600 MPa to foods, disrupting microbial cell membranes while preserving vitamins, antioxidants, and bioactive compounds [3]. PEF involves the application of short bursts of high-voltage electric fields, which permeabilize microbial cell membranes, leading to rapid inactivation while maintaining fresh-like qualities [4]. UV treatment is an effective surface decontamination method for liquid foods, juices, and fresh produce, reducing microbial load with minimal thermal damage [5]. Non-thermal methods are increasingly adopted for perishable products where maintaining nutritional quality, color, and texture is critical. Additionally, these techniques typically require less energy than conventional thermal processes, supporting sustainability objectives in food processing.

Collectively, these novel thermal and non-thermal technologies provide a foundation for developing sustainable, energy-efficient food preservation strategies that reduce nutrient loss, enhance microbial safety, and contribute to longer shelf life, thereby helping to mitigate postharvest losses and food waste.

3. Bioprocessing and Fermentation

Bioprocessing techniques, including fermentation and enzyme-assisted processes, utilize microorganisms or specific enzymes to enhance food safety, nutritional quality, and shelf life [6]. Fermentation is a natural preservation method in which microorganisms such as lactic acid bacteria metabolize carbohydrates, producing organic acids, bacteriocins, ethanol, and other metabolites that inhibit spoilage and pathogenic organisms [7]. These microbial metabolites not only improve microbial safety but also contribute to flavor, aroma, and functional properties of foods.

In addition to preservation, fermentation can enhance nutrient bioavailability by reducing antinutritional factors such as phytates, oxalates, and tannins, thereby improving the absorption of essential minerals such as iron, calcium, and zinc [6]. Fermented foods, including yogurt, kefir, kimchi, and

kombucha, also serve as functional foods by providing probiotics that promote gut health, immune function, and overall wellness. Advances in controlled fermentation, such as optimized starter cultures, enzyme technology, and bioreactor design, have improved product consistency, safety, and scalability, making fermentation a sustainable and versatile strategy for postharvest management of perishable foods [7][8]. The integration of fermentation with other preservation techniques, such as mild thermal processing or modified atmosphere packaging, can further enhance shelf life while maintaining nutritional and sensory quality. This combined approach aligns with the principles of sustainable food processing, reducing the reliance on synthetic preservatives and minimizing postharvest losses.

4. Innovative and Sustainable Packaging Technologies

Packaging plays a critical role in complementing food processing methods by protecting products from microbial contamination, oxidation, and physical damage while extending shelf life and reducing food waste [8]. Recent innovations focus on sustainability, functionality, and real-time monitoring of food quality.

4.1 Modified Atmosphere Packaging (MAP)

Modified Atmosphere Packaging (MAP) works by altering the composition of gases surrounding the food product, typically reducing oxygen levels and increasing carbon dioxide or nitrogen concentrations. This modification slows microbial growth and oxidative reactions, thereby extending shelf life and reducing spoilage [9]. MAP is widely used for fresh produce, meat, seafood, and bakery products. By maintaining product quality without extensive chemical preservatives, MAP contributes to safer, cleaner-label foods and reduces environmental impact associated with waste.

4.2 Active and Intelligent Packaging

Active packaging incorporates antimicrobial agents, oxygen scavengers, or moisture absorbers into packaging materials to actively preserve food quality. Intelligent packaging integrates sensors, freshness indicators, or RFID tags to monitor parameters such as pH, temperature, or microbial activity, providing real-time feedback on food condition [8]. These innovations not only enhance food safety but also minimize waste by allowing timely consumption and informed distribution decisions.

4.3 Biodegradable and Nanotechnology-Based Packaging

Biodegradable packaging materials, such as polylactic acid (PLA), starch-based polymers, and other biopolymers, offer environmentally friendly alternatives to conventional plastics [9]. Nanotechnology-based packaging further enhances barrier properties, mechanical strength, and antimicrobial activity, enabling the development of smart packaging solutions capable of detecting spoilage or extending shelf life. While promising, the use of nanoparticles requires careful evaluation of food safety and regulatory compliance to prevent potential migration into food.

Together, these innovative packaging strategies, especially when combined with advanced processing and bioprocessing techniques, provide a holistic approach to reducing postharvest losses, minimizing food waste, and promoting sustainable food systems.

5. Integration of Techniques for Sustainable Food Preservation

The concept of **hurdle technology** emphasizes the combination of multiple preservation strategies to achieve synergistic effects, improving food safety, quality, and shelf life while minimizing the intensity of individual treatments^[10]. By integrating thermal or non-thermal processing with bioprocessing and innovative packaging, food manufacturers can effectively reduce microbial load, inhibit spoilage, and maintain nutritional and sensory attributes. For example, a fruit product may undergo mild ohmic heating to inactivate spoilage microorganisms, followed by storage in a modified atmosphere or biodegradable packaging to slow oxidative reactions and microbial regrowth.

Such integrated approaches offer several advantages. First, the reduced intensity of each individual treatment helps preserve heat-sensitive nutrients, antioxidants, and bioactive compounds. Second, the combination of hurdles enhances microbial safety by targeting multiple spoilage mechanisms simultaneously, thereby reducing reliance on chemical preservatives. Third, energy consumption is lowered by optimizing each step rather than relying on a single intensive processing method. Collectively, these strategies contribute to more sustainable postharvest management, reducing food losses, minimizing waste, and promoting environmentally responsible production systems^[11, 12].

6. Challenges and Future Directions

Despite the promising potential of sustainable preservation techniques, several challenges remain in their widespread adoption. High capital investment and equipment costs can limit implementation, particularly for small and medium-sized enterprises. Regulatory hurdles related to the approval of novel processing technologies, nanomaterials in packaging, and multi-hurdle approaches can delay commercialization. Consumer acceptance is also a key factor, as unfamiliar processing methods may be perceived as unsafe or unnatural^[10]. Future research should focus on several critical areas to advance sustainable food preservation. Developing integrated, multi-hurdle systems that combine thermal, non-thermal, bioprocessing, and packaging strategies can maximize efficacy while minimizing negative impacts on nutritional and sensory quality. Long-term studies are needed to assess the nutritional, microbiological, and safety implications of these technologies under real-world conditions. Increasing the use of renewable and biodegradable materials for packaging is essential to reduce environmental impact and support circular food systems. Finally, public awareness campaigns and educational initiatives are vital to improve consumer acceptance and adoption of sustainable preservation practices^[11, 12-19]. These challenges, the food industry can move toward resilient, efficient, and environmentally responsible food supply chains.

7. Conclusion

Sustainable food preservation techniques provide effective strategies for mitigating postharvest losses and reducing food waste, while simultaneously maintaining nutritional quality, safety, and sensory attributes. Novel thermal and non-thermal processing methods, including microwave, ohmic, high-pressure, and pulsed electric field treatments, offer precise and energy-efficient alternatives to conventional processing. Bioprocessing and fermentation enhance food safety, nutrient bioavailability, and functional properties, while innovative packaging solutions—such as modified atmosphere, active, intelligent, and biodegradable or nanotechnology-based

materials—further extend shelf life and reduce environmental impact.

The integration of these approaches through multi-hurdle strategies creates synergistic benefits, improving microbial safety, preserving nutrients, and minimizing the need for chemical preservatives. However, widespread adoption requires continued research, technological optimization, regulatory support, and consumer engagement to ensure efficacy, safety, and public acceptance. By embracing these sustainable preservation strategies, the food industry can build resilient, efficient, and environmentally responsible supply chains, contributing to global food security, improved nutrition, and reduced ecological footprint.

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