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Postharvest Quality Preservation and Shelf-Life Extension of Apples Through Edible Coatings and Natural Preservative Treatments

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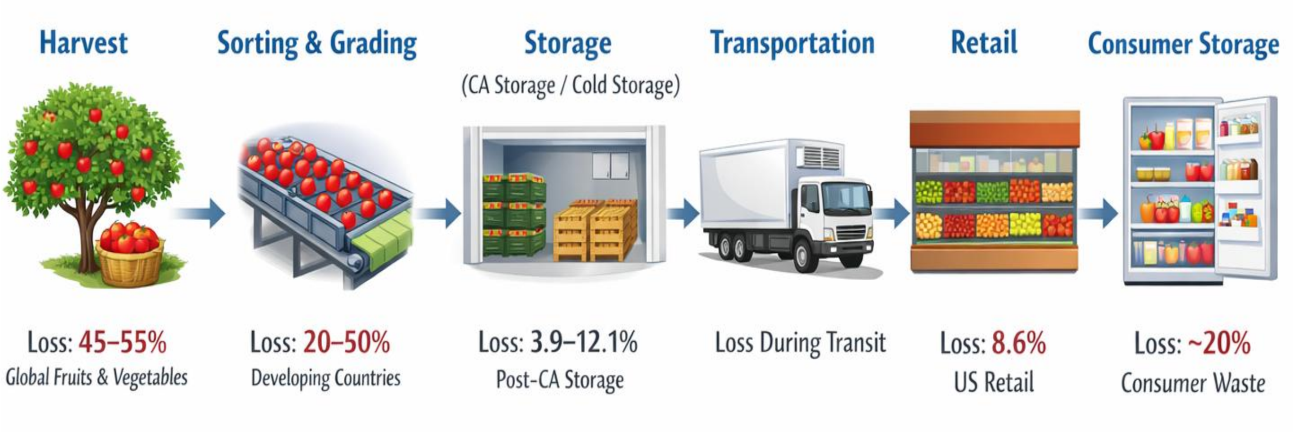
Abstract: *Apples (Malus domestica), a leading temperate fruit crop valued for their nutritional and sensory qualities, experience substantial postharvest losses (8.6–50%) driven by rapid climacteric respiration, ethylene biosynthesis via the Yang cycle, transpiration-induced weight loss, enzymatic browning mediated by polyphenol oxidase (PPO), and microbial decay (primarily anthracnose and stem-end rot). Edible coatings formulated from polysaccharides (chitosan, starch, alginate, pectin), proteins (whey protein, zein), lipids (carnauba wax, beeswax), and composite blends create a semi-permeable barrier that modulates internal atmosphere, reduces* O_2 *availability and* CO_2 *accumulation, slows ethylene production and respiration, limits moisture loss, delays cell-wall degradation by polygalacturonase and pectin methylesterase, and inhibits enzymatic browning and pathogen growth. Incorporation of natural bioactive agents' essential oils (cinnamon, oregano), nisin, lysozyme, ascorbic acid, and citric acid transform these coatings into active packaging systems with enhanced antimicrobial and antioxidant properties. Advanced application technologies, including electrostatic spraying, electrospraying, and nano-emulsions, improve uniformity, adhesion, and controlled release. Research demonstrates significant shelf-life extension (up to 21 days), retention of firmness, titratable acidity, ascorbic acid, total phenolics, and visual appeal, while reducing weight loss, browning index, and decay incidence. This review underscores edible coatings as a sustainable, consumer-friendly alternative to synthetic fungicides and plastic packaging, offering a practical solution to minimize postharvest waste, enhance market value, and support circular-economy principles in the global apple industry.*

Keywords: *Apple postharvest, edible coatings, shelf-life extension, chitosan, starch, whey protein, essential oils, enzymatic browning, modified atmosphere, natural preservatives, firmness retention, sustainable packaging*

I. Introduction

The global production of apples (Malus domestica) occupies a central role in the temperate fruit industry, driven by high consumer demand for their nutritional profile, which includes essential vitamins, dietary fibers, and polyphenolic antioxidants. However, the economic viability of apple production is perpetually challenged by significant postharvest losses that occur between the orchard and the final consumer (Singh et al., 2025). These losses are not merely quantitative but also qualitative, involving the deterioration of texture, flavor, and aesthetic appeal (Alam et al., 2024). Within the current global food system, it is estimated that approximately one-third of all food produced is lost or wasted, with fruits and vegetables experiencing even higher rates of 45% to 55%, translating to 1.2 to 2 billion tons of wasted biomass annually (Porat et al., 2018). Postharvest losses of apples occur at multiple stages of the supply chain, from harvesting to household consumption. The major points of quality deterioration and loss distribution are illustrated in figure 1.

Figure 1: Apple Postharvest Supply Chain and Loss Points



In the specific context of apples, losses are distributed across the supply chain. In the United States, retail-level losses are estimated at 8.6%, while consumer-level waste can reach 20% (Buzby et al., 2011). In developing nations, the lack of robust cold chain infrastructure and modern storage technologies results in postharvest losses ranging from 20% to 50% (Kaur & Watson, 2024). These figures underscore a profound inefficiency in the use of land, water, and energy resources. Reducing these losses, often termed the "hidden harvest," is essential for global food security and aligns with the circular economy approach by minimizing agricultural waste through the use of protective edible coatings and natural bioactive substances (Minor et al., 2020).

Table 1: Estimated Postharvest Loss Percentages of Apples and Global Produce

Region/Category	Estimated Loss Percentage (%)	Key Drivers of Loss
Global Fruits and Vegetables	45 - 55	Handling, lack of cold chain, spoilage
Developing Nations	20 - 50	Storage infrastructure, transit

		delays
US Retail (Apples)	8.6	Over-ripening, aesthetic rejection
US Consumer (Apples)	20.0	Domestic storage conditions, senescence
Post-CA Storage (Gala/Fuji)	3.9 - 12.1	Fungal decay, physiological disorders

2. Physiological and Biochemical Mechanisms of Senescence

Apples are climacteric fruits, meaning their ripening is marked by a distinctive surge in respiration and the autocatalytic production of ethylene (C2H4). This physiological burst triggers a cascade of biochemical modifications that gradually transition the fruit from its peak maturity into senescence (Anwar et al., 2018). The primary factors contributing to this decline include transpiration-induced water loss, the depletion of internal energy reserves via respiration, and the enzymatic degradation of cell wall structures (Ali et al., 2025).

2.1 Respiration, Ethylene Biosynthesis, and the Yang Cycle

The metabolic activity of harvested apples is driven by respiration, where sugars and organic acids are oxidized to produce energy, CO2, and water. High respiration rates lead to a rapid depletion of these substrates, resulting in flavor loss and the softening of the fruit (Brizzolara et al., 2020). Ethylene acts as the primary orchestrator of these changes, regulating the expression of genes involved in softening, color transformation, and volatile production (Thewes et al., 2019).

Ethylene biosynthesis follows the Yang cycle, starting with L-methionine, which is converted to S-adenosyl-L-methionine (SAM). Two critical enzymes then regulate the production of ethylene: 1-aminocyclopropane-1-carboxylate synthase (ACS) and 1-aminocyclopropane-1-carboxylate oxidase (ACO) (Yip et al., 1996). ACS catalyzes the conversion of SAM to 1-aminocyclopropane-1-carboxylic acid (ACC), which is generally considered the rate-limiting step, although ACO has been identified as a secondary limiting factor under specific developmental conditions (Boeckx et al., 2019). Edible coatings (ECs) extend shelf life primarily by creating a modified atmosphere around the fruit, which lowers internal O2 levels and elevates CO2. Because ACO requires O2 for its activity, this modified atmosphere directly inhibits the final step of ethylene production, thereby delaying the climacteric peak and slowing down the maturation process (Büchele et al., 2023).

2.2 Moisture Loss and Transpiration Kinetics

Apples possess a high moisture content, typically between 75% and 95%. Postharvest weight loss is predominantly a consequence of transpiration, where water vapor migrates from the fruit's internal tissues to the surrounding environment through lenticels, the cuticle, or mechanical injuries (Hassan et al., 2025). A weight loss of as little as 3% to 5% can result in visible shriveling and a loss of crispness, significantly reducing market value (Lufu et al., 2024). Edible coatings serve as a physical barrier that blocks these pathways, significantly reducing the vapor pressure deficit and maintaining tissue turgor (Umeohia et al., 2024).

2.3 Enzymatic Browning and Structural Degradation

In fresh-cut apple products, enzymatic browning is the most significant deterrent to consumer acceptance. Slicing ruptures cellular membranes, allowing polyphenol oxidase (PPO) to interact with phenolic substrates and O2, forming brown-colored melanins (Fan, 2023). Simultaneously, the loss of firmness is driven by the breakdown of insoluble protopectin into soluble pectin by enzymes like polygalacturonase (Tarawneh et al., 2025). These biochemical changes not only diminish the sensory quality of the apple but also create an environment conducive to microbial growth (Arnold et al., 2023).

3. Edible Coating Matrices: Composition and Structural Properties

Edible coatings are formulated from a variety of biopolymers, including polysaccharides, proteins, lipids, and composite blends (Dhumal et al., 2018).

3.1 Polysaccharide-Based Biopolymers

Polysaccharides are the most widely explored materials for apple preservation due to their abundance, low cost, and excellent gas barrier properties (Pillai et al., 2024).

- **Chitosan:** A cationic polymer derived from the deacetylation of chitin, chitosan is prized for its intrinsic antimicrobial and antifungal properties (Ali et al., 2025).

It forms a semipermeable film that effectively regulates gas exchange (O2 and CO2), thereby reducing the respiration rate (Zhao et al., 2021).

- **Starch derivatives:** Sago, potato, and corn starches are frequently utilized. Sago starch exhibits superior film-forming properties compared to low-amylose starches. Research has demonstrated that a blend of 5% sago starch and 0.5% soy oil can maintain the quality of fresh-cut apples for 12 days at 4 degrees C (Srivastav et al., 2025). Potato starch has been identified as exceptionally effective for color retention, achieving a significantly lower browning index compared to other polysaccharide bases (Shoukat et al., 2025).
- **Alginate and Pectin:** These hydrophilic polymers are often used for fresh-cut produce. Sodium alginate requires cross-linking with divalent cations like calcium (Ca2+) to form a stable, water-insoluble gel (Wang et al., 2025). This cross-linking not only improves the structural integrity of the coating but also provides supplemental calcium to the fruit tissue, which reinforces the cell wall and maintains firmness (Sharma et al., 2025).

3.2 Protein-Based Biopolymers

Proteins offer excellent gas barrier properties under low relative humidity and possess higher nutritional value than polysaccharides (Wang & Rhim, 2025).

- **Whey Protein:** A byproduct of the dairy industry, whey protein isolate (WPI) forms transparent, odorless coatings with high barrier efficacy. Research on Golden Delicious apples indicates that WPI coatings can reduce weight loss from 6.8% to 5.75% and delay the conversion of starch to sugars (Tarawneh et al., 2025).
- **Zein:** This corn-derived protein is unique due to its hydrophobic nature, making it a more effective moisture barrier than most other proteins. Coatings comprising zein and nisin have successfully extended the shelf life of Granny Smith apples to 21 days at 15 degrees C (Ali et al., 2023).

3.3 Lipid-Based Biopolymers

Lipids, including beeswax, carnauba wax, and shellac, are primarily used to combat moisture loss. While they provide superior moisture retention and a desirable surface gloss, they are often less effective as gas barriers and can be brittle if used alone (Shellhammer & Krochta, 2018). Modern approaches involve emulsifying these lipids into polysaccharide matrices to create composite coatings that leverage the strengths of both material types (Kumari et al., 2026).

Table 2: Comparison of Major Biopolymer Categories for Apple Coatings

Biopolymer Category	Representative Materials	Primary Advantage	Limitation
Polysaccharides	Chitosan, Alginate, Sago Starch	Superior gas barrier (O2, CO2)	High water vapor permeability
Proteins	Whey Protein, Zein, Soy Isolate	Excellent aroma barrier; nutritional	Fragile; humidity sensitive
Lipids	Beeswax, Carnauba, Shellac	Superior moisture barrier	Brittle; may cause anaerobic stress
Composites	Starch-Lipid, Protein-Lipid	Balanced gas/moisture barrier	Complex formulation process

4. Natural Preservative Treatments and Active Ingredients

The functionalization of edible coatings through the incorporation of natural bioactive substances represents the vanguard of active packaging (Trajkovska Petkoska, et al., 2021). The incorporation of natural bioactive compounds converts edible coatings into active packaging systems with antimicrobial properties. The major antimicrobial mechanisms of these natural preservatives are illustrated in figure 2.

4.1 Essential Oils (EOs) and Plant Extracts

Essential oils from plants such as oregano and cinnamon leaf are rich in volatile compounds like carvacrol and cinnamaldehyde. These compounds exhibit potent antimicrobial activity by disrupting the cytoplasmic membranes of bacteria and fungi (Ali et al., 2025). For Braeburn apples, a chitosan coating infused with 0.1% cinnamon leaf EO was found to be the most effective formulation for maintaining quality and inhibiting microbial growth (Ali et al., 2025).

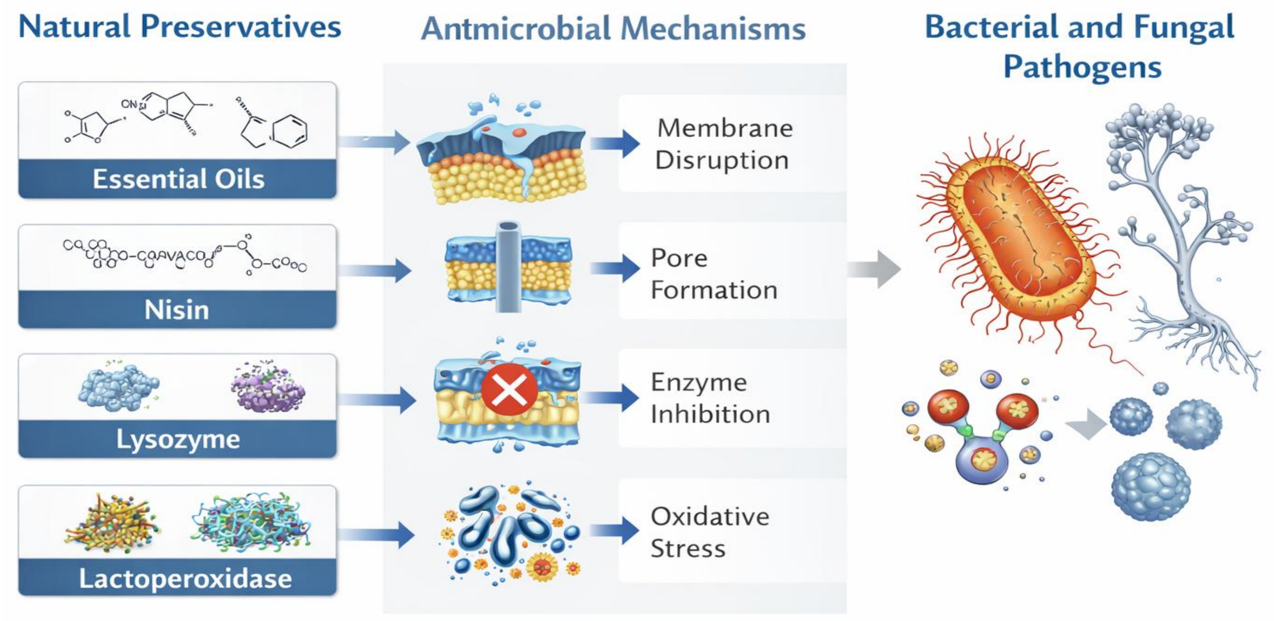
4.2 Bacteriocins and Biopreservative Enzymes

- **Nisin:** A polycyclic antimicrobial peptide produced by Lactococcus lactis, nisin is an FDA-approved bio-preservative (Cava-Roda et al., 2021). It functions by forming pores in the cell membranes of Gram-positive bacteria. In Granny Smith apples, zein coatings incorporated with nisin achieved significant reductions in microbial counts (Brandes et al., 2024).
- **Lysozyme and Lactoperoxidase:** These enzymes are increasingly used in active coatings due to their strong antimicrobial properties. These enzymes are safe, stable, and highly compatible with biopolymer matrices like alginate and whey protein (Yousefi et al., 2022).

4.3 Antioxidants and Anti-browning Agents

To address enzymatic browning, coatings are frequently enriched with organic acids such as ascorbic acid and citric acid. These compounds act by lowering the surface pH or by reducing quinones produced by PPO back into phenols (AL-abbasy et al., 2021). Research has shown that 1% ascorbic acid, synergized with potato starch and calcium chloride, can maintain the visual appearance and firmness of apple slices for 15 days (Moon et al., 2020).

Figure 2: Antimicrobial Mechanisms of Natural Preservatives



5. Innovative Application Technologies

The efficiency of an edible coating is determined by its composition and the method of application, which influences film thickness and uniformity (Kocira et al., 2021).

5.1 Traditional Dipping and Spraying

The dipping method involves immersing the apple in the coating solution for 5 to 30 seconds. While simple and effective for irregular surfaces, it often leads to excessive material consumption and can result in thick coatings that may induce anaerobic respiration (Singh et al., 2025).

5.2 Electrostatic Spray Coating (ESC) and Electrospraying

ESC is a technology where coating droplets are given an electrical charge, causing them to be attracted to the grounded fruit surface. This results in a highly uniform layer with minimal material waste. Electrospraying, a related technique, utilizes an electric field to generate a stable "cone-jet" geometry, allowing for precise control over film thickness at the nano-scale (Cakmak et al., 2018).

5.3 Nano-emulsions and Nano-coatings

The integration of nanotechnology involves dispersing hydrophobic active ingredients as droplets with diameters between 10 and 100 nm. Nano-emulsions, such as those formulated with beeswax and lecithin, offer enhanced stability and improved transparency compared to macro-emulsions. These systems have demonstrated impressive results in reducing physiological weight loss and spoilage rates of apples over 15 days of storage (Hassan et al., 2025).

Table 3: Comparison of Traditional vs. Innovative Application Techniques

Application Technique	Uniformity	Material Waste	Equipment Complexity	Target Application
Dipping	Moderate	High	Low	Fresh-cut slices; lab use
Conventional Spray	Low	Moderate	Moderate	Large-scale whole fruit
Electrostatic Spray	Very High	Very Low	High	High-value

				cultivars; industrial
Electrospraying	Excellent	Very Low	Very High	Nano-active coatings; research

6. Impact on Critical Quality Attributes

The ultimate success of edible coatings is measured by their ability to maintain the physicochemical and sensory integrity of the apple (Anwar et al., 2018).

6.1 Preservation of Firmness and Texture

The loss of firmness is a primary cause of consumer rejection. In zein-coated Granny Smith apples, the application of the coating significantly delayed weight loss and maintained texture for 21 days.. In fresh-cut slices, alginate-based coatings containing dietary fibers from apple pomace have been shown to double or even triple firmness compared to controls (Boeckx et al., 2019).

6.2 Maintenance of Titratable Acidity and Total Soluble Solids

As apples ripen, titratable acidity (TA) generally declines while total soluble solids (TSS) increase due to starch hydrolysis (Umeohia et al., 2024). Edible coatings effectively slow down these metabolic transitions. For example, whey protein coatings applied to Golden Delicious apples maintained significantly higher TA and lower TSS levels over storage compared to uncoated samples (Tarawneh et al., 2025).

6.3 Color Stability and Aesthetic Appeal

Edible coatings prevent browning in cut apples by limiting O2 access to PPO (Boeckx et al., 2019). Colorimetric analysis using the CIELAB space (L*, a*, b*) is the standard for quantifying these changes. Research on starch-based coatings demonstrated that potato starch was the most effective ingredient for maintaining the L* value (lightness) and preventing the shift toward positive a* values (redness/browning) (Dhumal et al., 2018).

7. Consumer Acceptance and Market Integration

Retail trends and consumer psychology heavily influence the adoption of edible coatings in the commercial sector (Lufu et al., 2024).

7.1 Food Technology Neophobia (FTN) and Educational Interventions

Recent trends have seen major retailers remove edible food coatings from apples in response to consumer demands for "natural" products. This highlights a challenge known as Food Technology Neophobia (FTN), where consumers reject novel food technologies due to a lack of understanding (Bucher et al., 2023). However, research has shown that providing information regarding the coatings purpose specifically its role in reducing food waste significantly increases acceptance rates (Spadoni et al., 2021).

8. Conclusion

Edible coatings and integrated natural preservative treatments represent a highly effective, biodegradable, and consumer-preferred strategy to combat the substantial postharvest losses that continue to undermine the economic and nutritional value of apples worldwide. By establishing a tailored semi-permeable barrier and delivering bioactive compounds directly at the fruit surface, these technologies successfully slow climacteric respiration and ethylene production, reduce transpiration and weight loss, inhibit enzymatic browning, delay cell-wall softening, and suppress microbial decay without reliance on synthetic chemicals. Extensive evidence demonstrates consistent improvements in key quality parameters firmness, titratable acidity, ascorbic acid content, color stability, and sensory appeal while extending marketable shelf life under both ambient and refrigerated conditions. As global pressure mounts to reduce food waste, plastic packaging, and chemical residues, edible coatings offer a scalable, sustainable solution aligned with circular-economy principles and evolving consumer demand for clean-label products. Continued research focusing on multi-functional smart coatings, industrial-scale application technologies, regulatory harmonization of nanomaterials, and consumer education will accelerate commercial adoption. Ultimately, widespread implementation of these innovative postharvest technologies will enhance supply-chain efficiency, increase farmer profitability, improve global food security, and contribute meaningfully to the reduction of agricultural waste in the apple industry.

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