



Optimizing Apple Quality through Modern Postharvest Handling and Storage Practices

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Abstract: *Postharvest losses in apples represent a significant economic and sustainability challenge, with fungal pathogens and physiological disorders contributing to up to 25% loss in stored fruit. This review explores modern strategies to optimize apple quality by preserving firmness, flavor (sugars, acids, and volatile aroma compounds), and nutritional value (polyphenols and antioxidants) while minimizing synthetic chemical use. Key foundational practices include rapid or gradual precooling and ethylene inhibition with 1-methylcyclopropene (1-MCP). Advanced atmospheric storage technologies, particularly Dynamic Controlled Atmosphere monitored by chlorophyll fluorescence (DCA-CF), enable precise low-oxygen management, achieving superior firmness retention, reduced physiological disorders, and markedly better preservation of aroma volatiles compared to ultra-low oxygen (ULO) or 1-MCP treatments. Non-chemical alternatives, such as chitosan-based edible coatings incorporating essential oils or probiotics, effectively control postharvest decay while aligning with consumer demand for low-residue produce. Emerging digital tools, including hyperspectral imaging and AI-driven predictive models, facilitate non-destructive quality assessment and dynamic storage management. These integrated approaches enhance economic returns through extended market windows, improve energy efficiency, and support sustainable, residue-free apple production.*

Keywords: *Apple postharvest quality, Dynamic Controlled Atmosphere (DCA), 1-Methylcyclopropene (1-MCP), edible coatings, chitosan, essential oils, volatile aroma compounds, chlorophyll fluorescence, physiological disorders, artificial intelligence, non-destructive assessment, firmness, flavor preservation*

I. Introduction

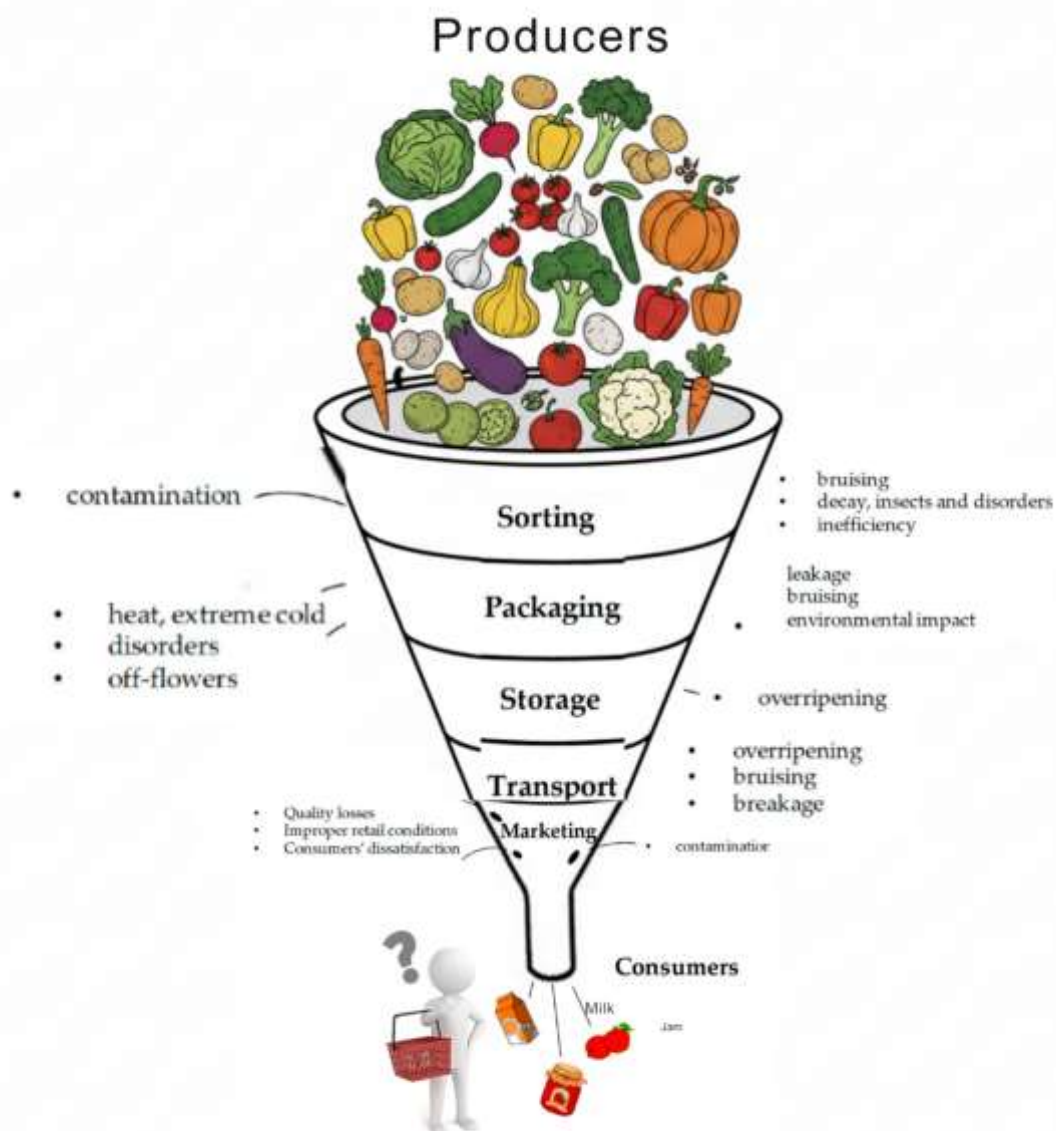
The global apple industry relies heavily on efficient postharvest logistics to ensure continuous supply and meet pervasive consumer demand for year-round fresh produce. In high value markets, such as the United States, fresh fruit production contributes significantly to the economy, valued at U.S.\$20.6 billion in 2023. The sheer magnitude of this investment necessitates highly efficient and sophisticated postharvest systems designed to maximize market longevity and minimize waste (Kaur et al., 2024). A persistent and major challenge in this sector is the magnitude of postharvest loss, which compromises both economic return and resource sustainability. These losses are primarily attributed to a combination of physiological disorders and pathological decay caused by fungal and bacterial diseases (Grau et al., 2024). Fungal pathogens, in particular, are responsible for devastating losses that can reach up to 25% of stored fruit, underscoring the critical need for advanced intervention strategies. Furthermore, when fruit unfit for the fresh market is diverted for processing, contaminants such as mycotoxins produced by these pathogens pose additional risks to food safety. The increasing consumer expectation for high quality fruit with low synthetic chemical residue levels requires innovative research and tools to move beyond traditional decay control (Bidyalakshmi et al., 2025).

Apple quality is a complex, multi-dimensional construct that extends far beyond external appearance. A comprehensive evaluation involves assessing high external quality (color, absence of blemishes) alongside desirable internal characteristics, specifically sweetness, acidity, firmness, and volatile aroma compounds (Ji et al., 2023). The target market dictates

the specific quality thresholds applied. For the fresh market, the highest standards are mandated for both external appearance and internal characteristics. Conversely, apples destined for processing (juices, ciders, or sauces) may be acceptable with lower external quality standards, but they must maintain high internal quality to ensure the desired final product taste, texture, and aroma (Calugar et al., 2021). Postharvest practices are critical because genetic and pre-harvest environmental factors (temperature, sunlight, soil quality) establish the potential quality, but proper handling and storage practices determine whether that optimal quality is delivered to the consumer (Thokar et al., 2022).

This review systematically examines the evolution of postharvest technology, detailing the biological mechanisms of deterioration and synthesizing the advancements in atmospheric control, non-chemical preservation, and digital management (Liu et al., 2025). The progression moves from understanding the fundamental metabolic challenges to evaluating cutting-edge technological solutions, including Dynamic Controlled Atmosphere (DCA) storage and Artificial Intelligence (AI) integration, providing a comprehensive assessment for horticultural scientists and industry stakeholders. The inherent high economic value combined with significant loss potential necessitates technology adoption (e.g., DCA, AI) to minimize waste and ensure product availability when market prices are optimal (Fatorachian et al., 2025).

Figure 1.1 The Apple Postharvest Supply Chain: Critical Stages and Risk Factors from Producer to Consume



2. Biological and Chemical Determinants of Apple Quality and Deterioration

2.1 Physical Quality Attributes: Texture and Firmness

Firmness is arguably the most recognizable physical determinant of apple quality and consumer acceptance. During the ripening and senescence phases, fruit firmness decreases due to the enzymatic breakdown of structural cell wall polymers, such as pectin and cellulose. The goal of long-term postharvest storage is therefore centered on effectively suppressing the enzymatic activity responsible for this softening to ensure the fruit maintains an acceptable texture profile upon removal from storage and throughout the shelf-life period. (Wang et al., 2021).

2.2 Internal Flavor Profile: Sugars, Acids, and Aroma Volatiles

Flavor in apples is a composite trait determined by taste and aroma. Optimal postharvest management requires careful navigation between metabolic suppression necessary for firmness retention and the retention of these key sensory characteristics (Pott et al., 2020)

2.2.1 Taste Balance: Sugars and Organic Acids

Taste is primarily a function of the concentration and ratio of sugars and organic acids. Consumer acceptability strongly correlates with the appropriate sugar-to-acidity ratio. Soluble solid content (SSC), which includes organic acids, inorganic salts, and sugars, is a key metric (Janiszewska et al., 2025). As the fruit matures, starch degradation increases the concentration of soluble sugars, contributing to a sweet taste. The typical SSC for mature apples, such as the Delicious cultivar, ranges from 10.8% to 12.2%. Critically, titratable acidity (TA) naturally declines gradually during ripening and prolonged storage, often resulting in a diminished and bland flavor profile (Kumar et al., 2023).

2.2.2 Aroma Compounds (VACs)

Aroma is complex, consisting of hundreds of volatile aroma compounds (VACs) specific to the cultivar. The most significant contributors to apple aroma are esters, followed by alcohols and aldehydes. In immature apples, aldehydes predominate, but as the fruit matures, these compounds are converted, resulting in an increase in alcohols and esters; the latter dominate the aroma of ripe apples (Tang et al., 2025).

The biosynthesis of these VACs is controlled by specific enzyme activities, including lipoxygenase (LOX), alcohol dehydrogenase (ADH), and alcohol acyltransferase (AAT). Storage conditions profoundly affect both organic acid and volatile concentrations. Esters, which provide the desirable fruity, fresh, and sweet notes (e.g., ethyl acetate, ethyl butyrate), are the most susceptible volatile class to loss during long-term storage. The fundamental difficulty in optimizing postharvest flavor lies in the fact that the severe metabolic suppression required for extended shelf-life retention often reduces the necessary enzymatic activity (specifically AAT) that synthesizes these volatile flavor esters (Roberts et al., 2020).

2.3 Nutritional and Health-Related Quality

Modern quality assessment also includes the retention of bioactive substances, such as ascorbic acid, total polyphenols, and overall antioxidant activity. Postharvest treatment protocols demonstrate a varying impact on these parameters. Some studies observe a decline in antioxidant capacity, while others find retention or even an increase in specific compounds in the peel (Gómez et al., 2023). However, advanced systems such as Dynamic Controlled Atmosphere (DCA) storage have shown clear benefits, maintaining significantly higher total polyphenol content and antioxidant capacity in both the flesh and peel of apples compared to traditional cold storage regimes (Thewes et al., 2023).

3. Foundational Postharvest Handling: Cooling, Temperature, and Ethylene Control

The initiation of storage involves two critical steps: rapid heat removal and immediate ethylene suppression, both of which set the trajectory for long-term quality retention (Alonso et al., 2024).

3.1 Pre-Storage Cooling Strategies

Rapid removal of field heat is essential for slowing metabolic processes immediately after harvest. Several pre-cooling technologies are utilized in the apple industry. Forced Air Pre-Cooling (FAPC) achieves rapid cooling by using powerful fans to create a pressure difference, forcing cold air over and through the fruit stacks (Alabi et al., 2023). Natural Convection Pre-Cooling (NCPC) relies on passive air circulation and is commonly used for apples and citrus. Vacuum Pre-Cooling (VPC) lowers the pressure in a chamber, causing water to rapidly evaporate, removing heat this method offers speed, high efficiency, and low energy consumption, although it is more commonly applied to leafy vegetables (Makule et al., 2023).

Despite the focus on engineered speed, thermal management is not solely dictated by mechanical efficiency. A key shift in recent recommendations involves moving away from universally rapid cooling toward gradual cooling for certain cultivars. This deliberate, stepwise approach is increasingly advised for apple cultivars known to be sensitive to chilling, as it helps mitigate the development of physiological disorders (Boudichevskaia et al., 2020).

Furthermore, apple cultivars are classified into groups based on their chilling sensitivity (storage at 0 to 1 °C or greater than 1 °C). Atmospheric modification alters thermal tolerance; research indicates that Controlled Atmosphere (CA) recommendations are, on average, approximately 0.9 °C higher for apples compared to refrigerated air (RA) recommendations for the same cultivar. This suggests that low O₂ conditions stabilize metabolism enough to safely permit storage at a slightly warmer temperature, which also offers the potential for energy savings (Wright et al., 2015).

3.2 Chemical Ethylene Inhibition: 1-Methylcyclopropene (1-MCP)

1-Methylcyclopropene (1-MCP) is a synthetic compound widely used to delay ripening and senescence. Its mechanism involves binding tightly to the ethylene receptors on the fruit surface, thereby inhibiting ethylene-mediated processes (Satekge et al., 2023).

1-MCP is highly effective in preserving physical quality. Treatment at harvest significantly maintains firmness and reduces storage rot incidence. For example, studies show that after 12 months of CA storage followed by 7 days at room temperature, rot incidence was substantially lower in 1-MCP treated apples (12%) compared to untreated fruit (31%). This reduction in storage rot has been consistently observed across various cultivars (Lee et al., 2019).

However, the efficacy of 1-MCP comes with inherent trade-offs concerning internal quality. 1-MCP treatment is known to increase the susceptibility of apples to external CO₂ injury.

Furthermore, it can lead to a higher incidence of internal disorders like core browning, particularly after six months of storage. Crucially, while 1-MCP successfully suppresses softening, its aggressive suppression of metabolic pathways disproportionately inhibits the biosynthesis of volatile esters, leading to a poorer flavor profile compared to non-chemically treated fruit (Nath et al., 2023).

4. Advanced Atmospheric Storage Systems: From ULO to DCA

4.1 Traditional Controlled Atmosphere (CA) and Ultra-Low Oxygen (ULO) Storage

Traditional Controlled Atmosphere (CA) storage operates by reducing the O₂ concentration (typically 1.5 to 3.0 kPa) and increasing the CO₂ concentration to inhibit fruit respiration and delay senescence. Ultra-Low Oxygen (ULO) storage is an extreme form of CA, reducing O₂ further (e.g., 1.5 kPa O₂ and 1.3 kPa CO₂) to severely suppress metabolism and extend shelf life. These methods utilize fixed gas compositions determined by cultivar history (Xie et al., 2024).

4.2 Dynamic Controlled Atmosphere (DCA): Precision Respiration Management

DCA represents a significant evolution from fixed-point CA storage. The technology operates on the principle of lowering the O₂ concentration to the absolute Lowest Tolerated Level (LOL) that the fruit can withstand without entering injurious anaerobic respiration. The resulting O₂ concentrations in DCA are significantly lower than ULO, typically operating in the range of 0.4 to 0.6 kPa O₂ (Thewes et al., 2021).

4.2.1 Monitoring Method: Chlorophyll Fluorescence (DCA-CF)

The critical advancement in DCA is the use of real time monitoring to determine the LOL, which is highly variable depending on cultivar, maturity, and pre-harvest conditions. The most widely adopted monitoring technique is Chlorophyll Fluorescence (DCA-CF). This method monitors the chlorophyll response to low O₂ stress. O₂ is gradually reduced until the sensor software detects a spike in chlorophyll fluorescence, which is indicative of hypoxic stress. The storage atmosphere set-point is then dynamically adjusted to an O₂ partial pressure just above this detected LOL. This dynamic monitoring allows the system to maximize metabolic suppression safely throughout the entire storage period, continually adapting to the fruit's changing needs (Torregrosa et al., 2020).

4.2.2 Biochemical and Quality Benefits

DCA-CF systems consistently demonstrate superior quality maintenance compared to traditional CA systems. Apples stored using DCA-CF protocols show significantly higher flesh firmness and total soluble solids. Furthermore, DCA-CF effectively reduces the incidence of physiological disorders, notably superficial scald, by potentially suppressing the oxidation of the volatiles implicated in its development (Donadel et al., 2023).

The superiority of DCA stems from its ability to induce a mild, customized hypoxic stress that enhances beneficial secondary metabolites. This metabolic stability is reflected in the

retention of antioxidant compounds and polyphenols (Li et al., 2024). Studies examining polyamines (PAs) and 4-aminobutyrate (GABA) accumulation under DCA/CA conditions suggest that although total PA levels may not be elevated by 1-MCP, the dynamic environment of low O₂ and CO₂ affects the complex interconversion of free and conjugated PA forms. The observed linear accumulation of GABA during storage, linked to the stimulation of glutamate decarboxylase activity, suggests a beneficial stress response pathway is active under optimal atmospheric control (Al-Khayri et al., 2024).

4.3 Comparative Efficacy: DCA vs. 1-MCP + ULO

A key functional difference between DCA and 1-MCP lies in their impact on volatile compounds. While 1-MCP effectively blocks the ethylene receptor, leading to metabolic dormancy, DCA maintains the fruit just above the anaerobic limit, allowing for minimal yet sufficient metabolic activity, including the biosynthetic pathways for aroma volatiles (Zhu et al., 2020).

Comparative trials demonstrate that DCA storage technology preserves apple aroma compounds much better than combined 1-MCP + ULO treatment, resulting in a significantly higher total amount of aroma compounds (often 2- to 4-fold greater). Specifically, 1-MCP exposure severely inhibits the biosynthesis of straight-chain esters, which are vital for characteristic apple flavor. The DCA method, therefore, is advantageous as it avoids chemical treatment, aligns with low-residue consumer preference, and preserves flavor integrity over long-term storage (Qin et al., 2025).

Table 4.1 Comparative Efficacy of Advanced Atmospheric Storage Technologies on Apple Quality

Technology	Key Mechanism	Typical O ₂ Level (kPa)	Flavor Preservation (Aroma)	Firmness Maintenance	Physiological Disorder Mitigation	Key Trade-offs
ULO (Ultra-Low O ₂)	Fixed Metabolic Arrest	1.0 - 1.5 ⁹	Moderate	High	Good (Low Decay)	Chilling Injury Risk, Fixed setpoint limitations
1-MCP Treatment	Ethylene Receptor Blockage	Air / CA / ULO	Low (Severe inhibition of ester biosynthesis)	Highest	Reduced Rot ¹⁵	Increased risk of CO ₂ injury and core

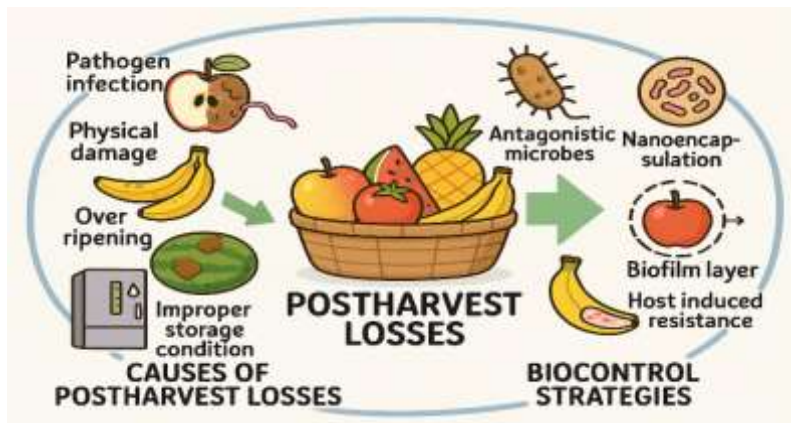
) ⁹			browning ¹⁵
DCA-CF	Dynamic Metabolic Triage	0.4 - 0.8 (Just > LOL) ⁹	High (2-4x better than 1-MCP+ULO) ⁹	High	Excellent (Reduced scald/disorders) ¹⁸	High initial capital and complexity of monitoring ¹⁷

5. Non-Atmospheric Quality Preservation and Bio-Coatings

5.1 Addressing Pathological Decay

Pathological decay remains a principal driver of postharvest losses. Fungal pathogens such as *Penicillium expansum* (Blue Mold) and *Botrytis cinerea* (Grey Mold) are prevalent worldwide. *P. expansum* causes deterioration in appearance, texture, and taste, rendering the fruit unsuitable for fresh consumption. (Wang et al., 2023). *B. cinerea* is a major cause of postharvest losses, occasionally reaching up to 5% during storage. The industry has historically relied on synthetic chemical fungicides, but consumer demand for high-quality, low-residue fruit necessitates the development of innovative, non-chemical disease management solutions (Chikte et al., 2024).

Figure 5.1 Mechanisms of Postharvest Loss and Emerging Biocontrol Interventions: From Pathogens to Nano-Encapsulation



5.2 Edible Coatings: Chitosan and Polysaccharides

Edible coatings represent a promising, ecologically friendly alternative to traditional packaging and chemical treatments. Chitosan, a cationic polysaccharide derived from renewable sources, is a preferred biopolymer for these applications due to its non-toxic, biodegradable nature.

Chitosan coatings function as passive barriers that retard water loss, helping to maintain fruit hydration. Furthermore, they actively inhibit the growth of spoilage microorganisms, significantly extending the shelf-life of both whole and fresh cut apples. By slowing the metabolic and physical changes, chitosan application positively affects quality metrics by helping to preserve the soluble solid content (SSC) and titratable acidity (Lin et al., 2020).

5.3 Integrating Active Compounds (Essential Oils and Probiotics)

The current trend is to transition edible coatings from passive barriers to active systems that deliver functional ingredients (Nunes et al., 2023).

5.3.1 Essential Oils (EOs) for Antifungal Control

Integrating essential oils (EOs) into the coating matrix provides enhanced antifungal capabilities. Studies have shown that chitosan coatings combined with EOs such as thyme effectively inhibit *B. cinerea* infection (e.g., reducing infected wounds by 48% compared to untreated controls). Similarly, chitosan encapsulated with clove EO reduced *Penicillium* infections in 'Golden Delicious' apples by 62%. These results demonstrate the potential of encapsulated EOs for controlling major postharvest diseases during storage (Soppelsa et al., 2023).

5.3.2 Probiotic Functionality

Polysaccharide based coatings, such as those made from alginate or chitosan, can also serve as carriers for beneficial microorganisms, advancing functional food concepts. For instance, an alginate coating carrying *Bifidobacterium lactis* and *Lactobacillus rhamnosus* retained the microbiological and nutritional properties of fresh apples while ensuring the beneficial bacteria could reach the human small intestine (Li et al., 2024).

5.4 Navigating the Flavor Interference Challenge

While EOs offer significant fungicidal benefits, their volatile nature presents a challenge to sensory quality. EOs may interfere with the fruit's characteristic volatile aroma compounds (VACs), potentially altering the native flavor profile of the apple variety. To address this, future development focuses on utilizing nanoemulsion technology. These intelligent edible coatings can adjust their permeability or provide a targeted, controlled release of bioactive compounds, such as citrus or lemongrass essential oils, minimizing high surface concentrations that disrupt the fruit's intrinsic aroma while maintaining preservative effects (Siddiqui et al., 2023).

6. The Digital Transformation: Precision Postharvest Management

The integration of digital technologies, particularly spectroscopy and machine learning, is moving postharvest apple management from static, batch-based decisions toward dynamic, predictive, and item-specific control (Fallik et al., 2020).

6.1 Non-Destructive Quality Assessment (NDQA)

The traditional methods of quality assessment are often slow and destructive. There is an urgent commercial need for efficient, non-destructive assays to assess the internal nutritional qualities of apple fruits for accurate grading, marketing, and industrial development (Anjali et al., 2024).

Hyperspectral Imaging (HSI) technology, often combined with Visible-Near Infrared (Vis-NIR) spectroscopy, has gained wide recognition as an effective nondestructive testing method in the fruit and vegetable sector. These optical techniques capture detailed spectral data across multiple wavelengths, which correlate with internal chemical properties such as sugar content (SSC) and acidity. When coupled with deep learning frameworks, such as the CNN-BiGRU-Attention architecture, Vis-NIR spectroscopy can effectively and accurately grade apples based on their internal quality parameters (Grabska et al., 2023).

6.2 Artificial Intelligence and Machine Learning (AI/ML) Integration

Recent strides in artificial intelligence and machine learning (AI/ML) are catalyzing a profound metamorphosis across the entire food value chain, elevating the pace and precision of postharvest operations (Agrawal et al., 2025).

6.2.1 Predictive Diagnostics and Sorting

ML models are applied to various pre- and postharvest tasks, including yield prediction, fruit maturity assessment, and automated sorting and grading. A critical application involves predictive diagnostics for storage disorders (Qin et al., 2025). For instance, computer vision models like Mask R-CNN have demonstrated high performance in analyzing time-sequenced images of postharvest apples, achieving a mean Average Precision (mAP) of 98.81% for general apple detection and 43.60% for the detection of postharvest decay zones. This capacity for early and precise identification of decay zones is promising for improving food storage processes in precision agriculture (Kar et al., 2025).

6.2.2 Dynamic Management Optimization

The deployment of AI shifts management protocols significantly. By providing high-resolution data on the quality of individual fruit or pallets, AI enables storage managers to move away from treating large volumes of fruit identically. Instead, high-risk cohorts (e.g., those predicted to develop disorders) can be identified and diverted for earlier sale or processing, while robust batches can be held for extended periods (Pathmanaban et al., 2023). This predictive capacity allows for the dynamic optimization of storage duration for each batch, maximizing financial returns by enabling sales during periods of high market demand. The ultimate vision involves integrating AI to manage complex systems like DCA, allowing for real-time, dynamic adjustments of temperature and atmosphere based on predicted disorder susceptibility and market dynamics (Darema et al., 2023).

7. Economic and Environmental Sustainability of Modern Practices

7.1 Economic Justification of Advanced Storage

Investment in advanced postharvest technology is fundamentally driven by economic viability. Without storage infrastructure, most producers are forced to sell their apples during the harvest season when supply is highest and market prices are consequently very low (Kaur et al., 2024). Investing in sophisticated cold storage facilities, particularly those employing advanced atmospheric controls, allows producers to postpone sales, providing the opportunity to access higher market prices later in the year. The economic justification for technology like DCA lies in its ability to extend the storage period significantly while delivering superior quality, thus maximizing revenue per unit of fruit by minimizing quality-related losses and maximizing the time window for optimal pricing. (Krupa et al., 2022)

7.2 Energy Efficiency and Sustainability

Improving the energy efficiency of the postharvest sector is a critical component of achieving long-term sustainability. Advanced technologies contribute to energy savings by allowing for adjusted temperature regimes. As noted previously, the stability afforded by controlled atmospheres (CA and DCA) often permits storage temperatures to be maintained at a slightly higher level than traditional refrigerated air (RA) storage (Soppelsa et al., 2023). Storing fruit at higher tolerated temperatures, when compared to deep cold CA, can lead to reduced energy consumption for the cooling systems, contributing to a smaller environmental footprint. Factors such as cold room design, insulation, and the efficiency of cooling and ventilation equipment are also key determinants of overall energy use (Zhu et al., 2020).

7.3 Integrated Management for Low Residue

The convergence of biological and atmospheric controls aligns with critical consumer and regulatory demands for sustainability. The successful application of non-chemical approaches such as Dynamic Controlled Atmosphere, gradual cooling protocols, and synergistic bio coatings (chitosan and essential oils) provides viable pathways for reducing reliance on synthetic chemical fungicides. This integrated management strategy satisfies the objective of quality preservation while simultaneously promoting sustainable, environmentally friendly, and low-residue domestic fruit production. (Thewes et al., 2021).

8. Conclusion and Future Research Outlook

8.1 Synthesis of Optimized Quality Pathway

Optimizing postharvest apple quality demands an integrated, multi-disciplinary approach that systematically controls the metabolic environment, mitigates decay, and leverages digital precision. The modern paradigm emphasizes proactive, customized care: implementing gradual cooling for chilling-sensitive varieties, utilizing Dynamic Controlled Atmosphere (DCA-CF) to maintain the lowest non-injurious O₂ level, and employing synergistic non-chemical treatments such as chitosan combined with essential oils for decay control. (Grau et al., 2024). This integrated approach ensures the optimal preservation of texture, and, critically, retains the volatile aroma compounds and nutritional value (polyphenols, antioxidants) that fixed-rate chemical inhibitors often compromise (Calugar et al., 2021).

8.2 Future Research Directions

First, further investigation into the biochemical signals and metabolic pathways induced by DCA storage is warranted, particularly concerning polyamines and GABA accumulation. Understanding how mild hypoxic stress upregulates these protective and regulatory compounds will allow for the exploitation of beneficial stress responses to maximize quality retention across different cultivars. (Fatorachian et al., 2025).

Second, the advancement of non-destructive quality assessment technologies must continue. Research should aim to refine AI models for real-time, predictive adjustment of DCA set-points. (Roberts et al., 2020). Integrating AI (such as Mask R-CNN derived diagnostics) with the DCA-CF system could allow the storage atmosphere to be dynamically customized not only to the LOL but also to the predicted pathological risk of a specific batch, enabling truly paradigm-shifting, long-term management solutions. (Xie et al., 2024).

Third, sophisticated solutions for non-chemical decay control require novel delivery mechanisms. Research should concentrate on developing nano-encapsulation and nanoemulsion techniques for bioactive compounds (EOs and probiotics). This will allow for targeted, effective delivery of antimicrobial agents while successfully avoiding the flavor interference associated with high surface concentrations of volatile compounds. (Alabi et al., 2023).

Conclusion

Optimizing postharvest apple quality requires an integrated, multidisciplinary strategy that combines precise metabolic control, non-chemical decay management, and digital precision technologies. Dynamic Controlled Atmosphere with chlorophyll fluorescence monitoring (DCA-CF) emerges as a superior method for long-term storage, delivering excellent firmness and physiological disorder suppression while preserving volatile aroma compounds and nutritional value far better than traditional chemical (1-MCP) or fixed-atmosphere approaches. Complementing DCA with gradual cooling protocols and bioactive edible coatings (e.g., chitosan plus essential oils) provides effective, low-residue alternatives to synthetic fungicides. Future advancements should prioritize real-time AI integration for dynamic storage adjustments, deeper understanding of beneficial stress metabolites (polyamines, GABA), and refined nano-delivery systems for active coatings to eliminate flavor interference. Adoption of these modern practices enables extended storage duration, reduced waste, higher economic returns, and alignment with consumer preferences for high-quality, sustainable fresh apples.

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