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Reducing Post-Harvest Losses in Indian Strawberries: Current practices and future directions based on latest research

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Abstract

Strawberries (*Fragaria × ananassa* Duch.) are becoming an important fruit crop in India, valued for their flavor, nutrition, and market potential. Yet, because they are soft and highly perishable, a large share of the harvest is lost before reaching consumers. This review explores the main causes of post-harvest losses and highlights both research insights and practical solutions that can reduce waste. The focus is on critical stages such as harvesting, field handling, pre-cooling, packaging, storage, and transport. Studies show that picking fruit at the right stage of ripeness, removing field heat quickly, and storing fruit at near 0°C can slow down spoilage and extend shelf life. Modern techniques like modified atmosphere packaging, biodegradable films, edible coatings, and safe treatments using natural or physical methods also show promise in preserving quality. For farmers, simple practices—such as careful handling, proper grading, and using affordable on-farm coolers—can make a big difference. Building stronger cold chain systems, including cooperative storage hubs and reliable refrigerated transport, is equally important for wider impact. The findings suggest that the best results come from combining scientific advances with farmer-friendly practices. This integrated approach can lower post-harvest losses, improve farmer incomes, and deliver fresher, better-quality strawberries to consumers, while supporting sustainability and reducing food waste.

Keywords: Strawberry; Post-Harvest Losses; Cold Chain Management; Packaging Innovations; Edible Coatings; Sustainable Farming Practices

1. Introduction

Strawberries (*Fragaria × ananassa* Duch.) are becoming increasingly important in India, valued for their taste, nutritional benefits, and market potential. At the same time, their delicate nature makes them highly perishable, leading to heavy post-harvest losses—often 40–50%—before reaching consumers. These losses not only reduce farmer incomes but also limit consumer access to fresh, high-quality fruit and waste valuable resources.

This review looks at the main reasons behind these losses in India and discusses both current handling practices and promising new approaches to reduce waste. It highlights critical steps such as proper harvesting, rapid removal of field heat, cold chain management, innovative packaging, and the use of edible coatings or safe biological and physical treatments. The discussion also considers the social and economic challenges that often prevent farmers, especially smallholders, from adopting these methods.

By bringing together research findings and practical solutions, the review argues that combining advanced technologies with farmer-friendly, affordable practices is the most effective way forward. The goal is to outline a clear path for

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reducing post-harvest losses in strawberries, improving farmer livelihoods, ensuring consumers receive better-quality fruit, and supporting broader goals of food security and sustainability.

2. Background: Strawberry Cultivation and Post-Harvest Challenges in India

2.1. Current Status of Strawberry Production in India

India has emerged as a notable producer of strawberries, with cultivation concentrated in states like Maharashtra, Himachal Pradesh, Uttarakhand, Punjab, Haryana, and the North Eastern states. The adoption of modern cultivation techniques, including protected cultivation in polyhouses and greenhouses, has expanded the geographic reach and increased yield potential. While production figures have grown, the industry faces inherent limitations due to the fruit's delicate nature. Production is often seasonal, leading to gluts in peak periods and scarcity otherwise. Varieties grown are often selected for yield and local adaptation, but post-harvest attributes like firmness and shelf life may not always be prioritized.

2.2. Magnitude and Causes of Post-Harvest Losses

Post-harvest losses for fruits and vegetables in developing countries like India are substantial, often estimated to be as high as 50%. For strawberries, the magnitude of loss is particularly high due to their fragility, high respiration rate, and susceptibility to mechanical damage and decay-causing microorganisms. Losses occur at multiple stages, including harvesting, sorting, packaging, transportation, storage, and retail [1]. Primary causes include inappropriate harvesting practices, lack of proper pre-cooling facilities, inadequate temperature management throughout the supply chain, mechanical injury during handling and transport, physiological deterioration, and pathological breakdown [1,2,3]

2.3. Specific Challenges in the Indian Context

India's diverse climate, ranging from temperate to tropical, presents unique challenges. High temperatures and humidity in many growing regions accelerate ripening and decay. The fragmented nature of the supply chain, involving numerous smallholder farmers, local aggregators, wholesalers, and retailers, complicates the implementation of standardized post-harvest protocols. Limited access to and awareness of appropriate technologies, lack of robust cold chain infrastructure, poor road connectivity in rural areas, and insufficient training for farmers and handlers contribute significantly to high post-harvest losses . Economic constraints often prevent investment in necessary equipment and infrastructure, from farm-level pre-coolers to refrigerated transport.

3. Critical Steps in Post-Harvest Handling

3.1. Optimizing Harvesting and Field Handling

The timing and method of harvest directly impact the post-harvest life of strawberries. Strawberries are non-climacteric fruits, meaning they do not ripen significantly after being detached from the plant. Therefore, they must be harvested at the optimal stage of maturity for consumption or intended use. Harvesting at the 'red stage' often yields the greatest number of marketable fruit and least weight loss compared to the 'dark red' stage [4]. Harvesting should occur during the cooler parts of the day, typically early morning. Fruits should be handled gently, ideally picked with a short piece of stem attached, and placed directly into the final retail containers to minimize subsequent handling and reduce mechanical damage [1]. Field heat removal immediately after harvest is a crucial initial step.

3.2. Importance of Pre-cooling and Temperature Management

Pre-cooling rapidly removes field heat from harvested strawberries, slowing down respiration, enzymatic activity, and microbial growth, thus extending shelf life. Studies show precooling increases the percentage of marketable fruits [5]. Various pre-cooling methods exist, including forced-air cooling, hydrocooling, and room cooling, with forced-air cooling being effective for packaged strawberries. Maintaining a consistent low temperature (near 0°C) and high relative humidity (90-95%) throughout the supply chain is paramount for preserving strawberry quality. Temperature fluctuations can lead to condensation, which promotes decay and accelerates ripening. Cold storage significantly prolongs the post-harvest life compared to storage at higher temperatures.

3.3. Efficient Sorting and Grading Techniques

Sorting and grading remove damaged, diseased, or overripe fruits, preventing the spread of decay during storage and transport and ensuring product uniformity and quality for consumers. Damaged fruits respire more rapidly and release ethylene, which negatively affects healthy fruits. Grading based on size, shape, colour, and ripeness stage allows for segregation of fruits for different market channels or storage durations. Manual sorting and grading are common in India, but they can be slow and may still involve excessive handling. Automation through optical sorting technology offers a more efficient and less damaging alternative, although its adoption requires significant investment [6]. Standardized grading criteria, often based on national or international quality standards, are essential for market access and price realization.

4. Storage and Packaging Technologies for Shelf-Life Extension

4.1. Controlled Atmosphere and Modified Atmosphere Packaging (MAP)

Storage under controlled atmosphere (CA) or modified atmosphere packaging (MAP) significantly extends the shelf life of strawberries by altering the gaseous environment around the fruit. CA storage involves maintaining specific concentrations of oxygen (O_2) and carbon dioxide (CO_2) at low temperatures. MAP involves sealing fruits in packaging materials with specific permeability properties, which naturally creates a modified atmosphere through the fruit's respiration [7]. Passive MAP uses materials like low-density polyethylene (LDPE) film. Active MAP involves flushing the package with a desired gas mixture (e.g., low O_2, high CO_2) before sealing [7]. High CO_2 levels (e.g., 15-20%) inhibit fungal growth, which is a primary cause of post-harvest decay in strawberries. These technologies reduce respiration rate, delay senescence, and maintain firmness and visual appeal, offering better results compared to unpackaged controls .

4.2. Exploring Active Packaging Systems

Active packaging incorporates components into the packaging material or within the package headspace to interact with the fruit or the surrounding environment, further extending shelf life and maintaining quality. Examples include oxygen scavengers, ethylene absorbers, and antimicrobial release systems. Oxygen scavengers reduce O_2 levels below what passive MAP can achieve, further suppressing respiration and oxidation. Ethylene absorbers, such as potassium permanganate, remove ethylene produced by the fruit, delaying ripening and senescence. Antimicrobial agents embedded in the packaging or released into the headspace can inhibit the growth of molds and bacteria responsible for decay. These systems offer enhanced preservation capabilities beyond passive MAP, addressing specific challenges like microbial spoilage effectively.

4.3. Role of Innovative and Biodegradable Packaging Materials

Traditional plastic packaging materials, while effective, raise environmental concerns. Research explores innovative packaging materials that offer improved functionality or environmental benefits. Perforated plastic packaging affects fruit storage and quality, with specific perforation levels proving optimal for maintaining quality at certain harvest stages [4]. Polyethylene terephthalate (PET) packages show less mass loss and better retention of acidity and firmness during storage at 0°C compared to other options. Expanded polystyrene (EPS) packaging with a PVC film also yields better results than no packaging. Beyond conventional plastics, there is growing interest in biodegradable and compostable packaging materials derived from renewable resources like starch, cellulose, or polylactic acid (PLA). These materials aim to reduce environmental impact while providing adequate protection and potentially incorporating active components like natural antimicrobials or antioxidants to improve preservation.

5. Post-Harvest Treatments and Preservation Methods

5.1. Application of Edible Coatings and Films

Edible coatings and films offer a promising method to extend the shelf life of strawberries by providing a semi-permeable barrier that modifies the internal atmosphere of the fruit, reduces water loss, and can carry antimicrobial or antioxidant compounds. These coatings are made from various natural polymers, including polysaccharides (like chitosan, starch, cellulose derivatives), proteins (like whey protein, soy protein), or lipids (like waxes, fatty acids). Chitosan coating, for example, reduces respiration rate and weight loss, maintains higher firmness and protective enzyme activities, and reduces decay, keeping the cell membrane relatively intact [8]. The application methods are relatively simple, involving dipping, spraying, or brushing. These coatings can also serve as carriers for post-harvest fungicides, calcium salts, or other beneficial compounds, offering multi-functional preservation.

5.2. Review of Chemical and Biological Treatments from Research

Research explores various chemical and biological treatments to control post-harvest decay and maintain strawberry quality. Chemical treatments, such as dipping in solutions containing calcium salts (e.g., calcium chloride) or organic acids, can improve fruit firmness and reduce decay. However, public concern regarding chemical residues drives research into safer alternatives. Biological control agents, including beneficial yeasts and bacteria, compete with or inhibit the growth of decay-causing pathogens on the fruit surface. Studies also investigate the use of plant extracts, essential oils, or natural compounds with antimicrobial properties. For instance, melatonin, a ubiquitous molecule in plants, delays senescence and exerts antioxidant effects, improving post-harvest preservation when applied exogenously . These treatments offer targeted approaches to reduce spoilage, often complementing other methods like cold storage and packaging.

5.3. Utilizing Physical Treatments for Preservation

Physical treatments offer non-chemical means of preserving strawberry quality. These include heat treatments (like hot water dipping or vapor heat), irradiation (UV-C or gamma irradiation), and pulsed light. Heat treatments can reduce microbial load on the fruit surface and induce heat shock proteins that enhance stress tolerance, but precise temperature and duration are critical to avoid fruit damage. UV-C irradiation can reduce surface microorganisms and stimulate the fruit's natural defense mechanisms, improving disease resistance. Pulsed light treatments utilize short bursts of high-intensity light for microbial inactivation. While these methods hold promise, optimizing parameters to ensure efficacy without negatively impacting sensory quality (flavor, texture, color) remains an area of active research [1]. Mechanical treatments, such as gentle handling and innovative packaging designs that minimize contact and vibration, also mitigate physical damage during transit [9,10].

6. Supply Chain Integration and Cold Chain Logistics in India

6.1. Assessment of Current Cold Chain Infrastructure

India's cold chain infrastructure has seen development in recent years, but significant gaps persist, particularly in connecting production centers to markets for highly perishable commodities like strawberries. While refrigerated storage facilities exist in some locations, the crucial "last mile" connectivity, including refrigerated vehicles for transport from farms to collection centers and from wholesale markets to retailers, remains weak or non-existent in many areas [11]. This leads to temperature breaks during transit, compromising the quality of temperature-sensitive fruits like strawberries. Assessing the current state reveals a need for integrated cold chain solutions that encompass farm-level pre-cooling, refrigerated transport, and cold storage at aggregation points and retail outlets to ensure continuous temperature management from harvest to consumption [11,12].

6.2. Strategies for Optimizing Transportation and Distribution

Optimizing transportation and distribution for strawberries involves minimizing transit time, maintaining optimal temperature and humidity, and reducing mechanical damage. Using refrigerated trucks is essential for longer distances, but smaller, insulated vehicles with coolants can serve for shorter hauls from farms to collection centers. Proper stacking and securing of packaged fruits within vehicles reduce movement and physical injury during transit [9]. Efficient logistics planning, including consolidation of loads and optimization of routes, decreases transit time. Collaboration among farmers, transporters, wholesalers, and retailers can streamline the supply chain and facilitate the adoption of cold chain practices. Developing regional collection centers with pre-cooling and cold storage facilities can help consolidate produce and prepare it for longer-distance transport.

6.3. Leveraging Technology for Supply Chain Visibility and Monitoring

Technology plays a role in improving supply chain efficiency and reducing losses. Temperature sensors and data loggers can monitor conditions during transport and storage, providing real-time data and alerts if temperatures deviate from the optimal range. GPS tracking devices allow for monitoring the location and progress of shipments. These technologies improve transparency and accountability within the supply chain. Furthermore, leveraging digital platforms for market linkages can reduce intermediaries and speed up the movement of produce from farms to consumers, shortening the supply chain and reducing the time window for potential losses [13]. Implementing traceability systems using QR codes or RFID tags allows for tracking the origin and journey of specific batches of strawberries, enhancing food safety and quality control.

7. Recent Research Findings and Future Perspectives

7.1. Advances in Novel Preservation Technologies

Recent research explores novel technologies for strawberry preservation. Beyond conventional MAP and edible coatings, studies investigate the use of nanomaterials for improved packaging properties, such as enhanced barrier function or controlled release of antimicrobial agents. Plasma technology, ozone treatment, and electrolyzed water are being explored as surface disinfection methods to reduce microbial load without leaving harmful residues. Acoustic technologies and pulsed electric fields are investigated for their potential to improve cell membrane stability and reduce deterioration. Research also delves into the application of natural compounds like melatonin, demonstrating its potential to extend shelf life by enhancing antioxidant activity . These advancements offer potential for more effective and environmentally friendly preservation methods.

7.2. Understanding Genetic and Pre-harvest Factors

While post-harvest handling is critical, the inherent quality and shelf life potential of strawberries are significantly influenced by genetic factors and pre-harvest practices. Breeding programs are increasingly focusing on developing varieties with improved post-harvest attributes, such as a firmer texture, a slower ripening rate, greater resistance to bruising, and natural resistance to common post-harvest diseases [10, 14]. For instance, Japanese breeding efforts improved pectin structure related to fruit texture [10]. Pre-harvest factors like nutrient management (e.g., calcium application can influence firmness [15]), irrigation practices, pest and disease control in the field, and even the stage of maturity at harvest (as highlighted in [4] and [7]) play a substantial role in determining how well the fruit will store and transport. Integrating pre-harvest management with post-harvest protocols offers a holistic approach to quality retention.

7.3. Socio-economic Aspects and Adoption of Technologies

The successful implementation of improved post-harvest management practices in India depends heavily on socio-economic factors. Farmer awareness and education regarding the importance of proper handling, pre-cooling, and cold chain are fundamental [16,17]. The cost-effectiveness and accessibility of new technologies for smallholder farmers determine their adoption rates. Government policies, subsidies, and extension services play a role in disseminating knowledge and providing financial or infrastructural support. Establishing farmer cooperatives or producer organizations can facilitate collective investment in shared resources like pre-cooling units or refrigerated transport. Understanding the economic benefits of reduced losses incentivizes farmers and other stakeholders to adopt improved practices, contributing to increased income and livelihood security [18,19].

8. Analysis of Economic and Social Implications

8.1. Impact on Farmer Income and Livelihoods

Reducing post-harvest losses directly increases the marketable quantity of strawberries, leading to higher income for farmers. When fewer fruits are lost due to spoilage or damage, farmers sell a larger proportion of their harvest. Improved quality resulting from better handling and storage can also command higher prices, especially in premium markets or for export [20]. The economic benefits of loss reduction can significantly improve farmer livelihoods, contributing to rural prosperity and reducing poverty. Investment in post-harvest infrastructure and training, while requiring initial capital, yields returns through increased sales and reduced waste. This fosters a more sustainable and profitable agricultural practice for strawberry growers.

8.2. Contribution to Food Security and Quality

Reducing post-harvest losses of strawberries contributes to overall food security by making more food available for consumption from the same level of production [18, 19, 21]. It means that the resources (land, water, labor, inputs) used to produce the lost food are not wasted. Furthermore, proper post-harvest management preserves the nutritional quality of strawberries, ensuring that consumers receive fruits rich in vitamins and antioxidants. Maintaining quality also enhances consumer confidence and encourages consumption of healthy fruits. By ensuring that strawberries reach consumers in good condition, post-harvest management supports dietary diversity and improves public health outcomes, especially in regions where access to nutrient-rich foods might be limited [19].

8.3. Sustainability Considerations of Post-Harvest Practices

Adopting efficient post-harvest management practices aligns with sustainability goals. Reduced losses mean less food waste, which in turn reduces the environmental footprint associated with production (water usage, energy, emissions from farming inputs) and disposal of spoiled produce. Energy consumption in cold chains needs careful consideration; optimizing energy efficiency in refrigeration and transport is vital. The choice of packaging materials, favoring recyclable or biodegradable options [22], minimizes environmental impact. Sustainable practices also involve social equity, ensuring that technologies and benefits are accessible to smallholder farmers and that labor practices throughout the post-harvest chain are fair. A holistic approach considers economic viability, social equity, and environmental responsibility in implementing post-harvest solutions for strawberries.

9. Conclusion

Post-harvest management poses a significant challenge for the strawberry industry in India, primarily due to the fruit's high perishability and existing infrastructure gaps. High losses occur across the supply chain, diminishing farmer income and wasting valuable resources. Implementing critical steps such as optimizing harvesting time, rapid pre-cooling, careful sorting, and maintaining a continuous cold chain are fundamental to mitigating these losses. Advanced packaging technologies, including MAP and active packaging, along with post-harvest treatments like edible coatings, offer effective means to extend shelf life and maintain quality. Integrating improved practices requires addressing infrastructural limitations, particularly in cold chain logistics, and leveraging technology for better monitoring and visibility. Future efforts should focus on adopting novel preservation techniques, developing varieties with enhanced post-harvest traits, and ensuring the socio-economic feasibility of these technologies for widespread adoption among Indian farmers. By reducing losses, India can significantly enhance food security, improve farmer livelihoods, and promote sustainability within its burgeoning strawberry sector.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no conflict of interest relevant to this work.

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