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Advances in pre-harvest practices for enhancing post-harvest quality of fruits: A review

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Abstract
India, the world's second-largest fruit producer, faces significant post-harvest losses estimated at 30-40% despite an annual production exceeding 112 million metric tonnes. These losses are primarily due to poor handling and insufficient pre-harvest practices. This review explores recent advancements in pre-harvest techniques aimed at improving the post-harvest quality, shelf life and marketability of fruits. Key strategies include the use of protective tree covers, shading, fruit bagging, pruning, spacing and nutrient management (notably calcium, boron, and potassium applications). Additionally, the role of plant growth regulators (PGRs), precision irrigation, drone-based monitoring, pre-harvest sprays, integrated pest and disease management (IPDM), genetic improvements and the application of biostimulants and natural products are discussed. These interventions positively influence critical quality parameters such as firmness, sweetness, uniform ripening, and disease resistance. However, challenges such as high implementation costs, labor intensity and environmental variability limit widespread adoption. The integration of crop-specific and environmentally adaptive strategies is emphasized for maximizing post-harvest outcomes. Overall, the paper advocates for a holistic, sustainable approach to fruit production that minimizes losses and enhances India's global competitiveness in fruit exports.

Keywords: Post-harvest losses, pre-harvest techniques, fruit quality, plant growth regulators

Introduction
India holds the distinction of being the second-largest producer of fruits globally, with an impressive 112.62 million metric tonnes of fruits produced in 2023-24, covering 7.04 million hectares. During the same period, the export of fresh fruits and vegetables reached Rs. 15,039.27 crores, while processed fruits and juices contributed Rs. 6,283.76 crores to the economy (Anonymous, 2024a) [1]. Despite abundant production, an estimated 30-40% of fruits and vegetables are lost between harvest and consumption (Ranjan and Sahani 2023) [44] primarily due to issues such as poor quality, spoilage and improper handling. Since the quality of fruits cannot be substantially improved after harvest, understanding and implementing effective pre-harvest practices is crucial to ensuring optimal post-harvest quality. These practices influence various aspects of fruit development, including biochemical composition, storage behavior and intrinsic attributes such as texture, sweetness, acidity, aroma, and shelf life, as well as extrinsic attributes like color and size. This article explores recent advancements in pre-harvest practices aimed at enhancing the post-harvest quality of fruits. It highlights strategies that not only reduce food loss but also improve marketability and ensure sustainability within the fruit production sector.

Results and Discussion
Pre-Harvest Cultural Practices
A) Tree Covers and Shading
Using UV-stabilized white polymer covers (60 GSM) in pomegranate cultivation improves fruit quality by regulating light intensity, reducing sunburn, and minimizing pest incidence through the physical barrier it creates (Anonymous, 2024b) [2]. Black shade nets (50% intensity), in conjunction with foggers, enhance redness and juice recovery in fruits, likely due to the moderated temperature and humidity levels that optimize anthocyanin biosynthesis

(Kale *et al*., 2018) [15]. Emerging shading materials, such as thermo-reflective films, are under study for their ability to balance light intensity and reduce heat stress, aiming to maximize photosynthetic efficiency while mitigating abiotic stresses.

Benefits

- **Protection Against Sunburn and Hail Damage:** Protective netting systems in apple production effectively mitigate sunburn and hail damage by reducing direct solar radiation and providing a physical barrier against environmental stressors. Photo-selective nets further modulate light spectra, potentially influencing plant growth, fruit set and development. However, the effects on fruit quality appear variable and context-dependent, likely influenced by cultivar, light spectrum and local climatic conditions. This variability underscores the need for research targeting optimized net properties and site-specific recommendations (Mupambi *et al*., 2018) [28].
- **Microclimate Regulation:** Pre-harvest fruit bagging, a critical practice in Good Agricultural Practices (GAP), improves fruit visual and internal quality by reducing blemishes, sunburn, and pest damage. The practice modifies the micro-environment, which can enhance fruit development by altering light penetration, temperature and humidity around the fruit. However, inconsistencies in effects on skin color and overall quality, attributed to variations in bag material, fruit developmental stage, and environmental conditions, indicate the necessity for controlled studies to determine its cost-effectiveness and broader applicability (Sharma *et al*., 2014) [39].
- **Reduced Water Loss:** By reducing direct exposure to high temperatures, tree covers help lower transpiration rates, preserving fruit firmness and reducing postharvest weight loss. The mechanism is attributed to decreased evaporative demand and maintenance of cellular turgor under shade (Bhowmik *et al*., 2019) [4].

Challenges

- **Potential Impact on Photosynthesis:** Shading can induce low-light stress, adversely affecting photosynthetic efficiency and overall fruit physiology. For example, research on 'Hongdeng' sweet cherry demonstrated that shading impairs photosystem function, reduces nutrient accumulation, and alters fruit composition. Transcriptomic analyses further reveal significant changes in carbon metabolism, organic acid metabolism and stress-resistance pathways under shaded conditions. These findings emphasize the need for breeding programs focused on low-light-tolerant cultivars and refining shading practices to minimize adverse effects while preserving desired fruit traits (Tang *et al*., 2023) [48].
- **Cost of Installation:** The adoption of high-quality shade nets and covers is often constrained by their high initial costs, particularly for small-scale farmers. While these technologies offer substantial benefits in terms of yield and quality, their economic feasibility needs to be assessed through long-term studies incorporating cost-benefit analyses and evaluating their performance under diverse agro-climatic conditions (Sharma *et al*., 2014) [39].

B) Thinning, Pruning, and Spacing

a) **Thinning of Grapes:** Somkuwar *et al*. (2014) [42] recommended thinning grape clusters to 27/vine for improving fruit quality and yield. Thinning reduces competition for resources like nutrients, water and light, allowing for better fruit size and uniformity.

b) **Plant Spacing in Acid Lime:** Pawar *et al*. (2022) [32] highlighted the efficacy of 6x6 m spacing combined with integrated nutrient management for better fruit growth and yield. Proper spacing optimizes light interception and air circulation, reducing disease incidence and enhancing photosynthesis.

c) **Pruning of Guava:** Kumar *et al*. (2020) [18] concluded that pruning guava trees from the top at 30 cm increased fruit yield, weight, diameter and quality. This practice promotes balanced vegetative and reproductive growth by redistributing plant resources.

d) **Drone-Based Monitoring:** Recent innovations in drone-based monitoring systems using RGB, multispectral, hyperspectral, thermal and LiDAR sensors enable real-time assessment of fruit crops for improved yield, quality and food safety. These technologies support precision management in large orchards by optimizing thinning and spacing, reducing labor costs and offering insights through advanced imaging and analytics, while highlighting the need for standardization and integration with other precision agriculture tools. Goswami *et al*. (2024) [11].

Benefits

- **Improved Fruit Size and Uniformity:** Fruit thinning in Kym Green Bush (KGB) trained sweet cherry trees enhanced fruit quality. Foliar application of $CaCl_2$ during Stage I improved firmness, while applications at later stages reduced cracking susceptibility (Matteo *et al*., 2022) [24]. Thinning minimizes competition for nutrients, ensuring uniform fruit development.
- **Artificial Bud Extinction (ABE):** Early crop load reduction in 'Scilate' apples to ~6 fruit/cm² Limb cross-sectional area (LCSA) improved fruit quality, return bloom and yield, showing the importance of precise crop load management (Sidhu *et al*., 2022) [40].
- **Enhanced Nutrient Allocation**: Ethephon and carbaryl applications in apples inhibited fruit growth and redirected assimilates, demonstrating the role of thinning in optimizing nutrient distribution (Ward and Marini, 1999) [52].
- **Reduced Disease Incidence:** Well-spaced and thinned trees reduce canopy density, lowering humidity and fungal infection risks (Singh *et al*., 2021) [41].

Challenges

- **Labor-Intensive:** Manual thinning and spacing increase production costs (Wertheim, 2000) [54].
- **Risk of Over-Thinning:** Excess thinning reduces overall yield despite improving fruit quality (Ward and Marini, 1999) [52].

Best Practices

- Thin fruits during early developmental stages to optimize resource allocation (Singh *et al*., 2021) [41].
- Follow spacing guidelines tailored to the crop for maximum growth (Ward and Marini, 1999) [52].

C) Bagging Practices

a) **Bananas:** Non-woven bagging enhanced shelf life, reduced weight loss, and minimized bruising (Magar *et al.*, 2023) [20]. Bags create a controlled microenvironment, reducing physical and physiological stress.

b) **Pomegranates:** Parchment bagging reduced cracking, increased juice content, and lowered pest incidence (Gethe *et al.*, 2023) [8]. It acts as a barrier to pests and weather extremes, improving fruit quality.

c) **Biodegradable Alternatives:** Eco-friendly bags reduce production costs and environmental impact while maintaining fruit quality.

Benefits

- **Protection from Pests and Diseases:** Bagging acts as a physical barrier, minimizing pest infestations and fungal infections (Lalel *et al.*, 2003) [19].
- **Improved Appearance:** Bagged fruits show fewer blemishes and better skin color, increasing market value (Wang *et al.*, 2014) [51].
- **Reduction in Chemical Use:** Physical barriers reduce pesticide dependence, promoting sustainable farming (Sharma *et al.*, 2014) [39].

Challenges

- **Labor Requirements:** Bagging is labor-intensive, limiting feasibility for large farms (Lalel *et al.*, 2003) [19].
- **Material Costs:** High-quality biodegradable bags can be expensive (Wang *et al.*, 2014) [51]

Best Practices

- Use breathable, biodegradable bags to avoid moisture buildup and mold (Singh *et al.*, 2021) [41].
- Bag fruits early after pollination or fruit set to protect against damage and pests (Wang *et al.*, 2014) [51].

Nutrient Management

a) **Calcium and Boron:** Pre harvest application of chelated calcium (0.2%) and boric acid (1%) in Pomegranate improve fruit size, juice content, and reduce cracking. Calcium strengthens cell walls, while boron aids in sugar transport and cell division (Mane, 2019) [21].

- Foliar application of calcium-organo mineral (Ca-OM) suspension improved fruit quality and storage life in red currants, particularly in 'Lvovyanka,' 'Vika,' and 'Gazel' cultivars. While it did not affect leaf Ca or TSS, Ca-OM increased berry Ca content, TSS, density, and resistance to abscission and disease, extending shelf life by 3-7 days and highlighting its potential for yield and postharvest enhancement of different berry. (Panfilova *et al.*, 2024) [59].

b) **Potassium and Calcium:** Potassium enhances sugar content and osmotic balance, while calcium prevents disorders like blossom-end rot by improving cell wall integrity (Evans, 2021) [6].

- Polyhalite, a natural mineral fertilizer, significantly improved the yield, quality and shelf life of MD2 pineapples when applied post-anthesis, with a 12.8% increase in fruit weight at 660 kg/ha. Besides supplying potassium, it also enhanced nutrient content (Ca, Mg, S) and fruit sensory attributes, making it a promising alternative to conventional KCl-based fertilizers in pineapple cultivation. (Ong *et al.*, 2025) [29].

c) **Nano-Fertilizers:** Emerging nano-technologies improve nutrient efficiency and reduce environmental impact by enhancing targeted nutrient delivery.

Benefits

- **Improved Fruit Firmness:** Calcium applications maintain firmness by fortifying cell walls, reducing disorders like bitter pit in apples (White & Broadley, 2003) [56].
- **Enhanced Antioxidant Activity:** Micronutrients like zinc and boron improve antioxidant levels, boosting stress resistance during storage (Hussain *et al.*, 2019) [12].
- **Extended Shelf Life:** Potassium improves sugar content, enhancing taste and storability (Marschner, 2012) [23].
- **Reduction of Disorders:** Balanced magnesium reduces splitting and softening in citrus and bananas (Fageria *et al.*, 2002) [7].

Challenges

- Over-application of nitrogen causes excessive vegetative growth and reduces fruit firmness (Tahir *et al.*, 2018) [46].
- Nutrient imbalances may lead to cracking or uneven ripening.

Best Practices

- Apply calcium chloride ($CaCl_2$) or calcium nitrate as foliar sprays during fruit development.
- Use chelated zinc and boron for improved uptake and reduced losses.

Plant Growth Regulators (PGRs)

a) **Improvement of mango shelf life:** Taduri *et al.* (2017) [45] found that pre-harvest sprays of GA_3 @ 75 ppm combined with $CaCl_2$ @ 1.5% improved shelf life in mangoes. GA_3 delays senescence by reducing ethylene biosynthesis, while $CaCl_2$ enhances cell wall integrity, improving firmness and reducing postharvest decay.

b) **Fruit quality in mango cv. Amrapali:** Patel *et al.* (2023) [30] reported that foliar application of 3000 ppm salicylic acid five weeks after full bloom, combined with $CaCl_2$@ 1.0% 15 days prior to harvest, maximized fruit firmness, TSS, carotenoids, ascorbic acid and reduced titratable acidity. Salicylic acid enhances antioxidant activity and stress resistance, while $CaCl_2$ strengthens cell walls for better quality retention.

Benefits

Delayed Ripening and Senescence

- 1-Methylcyclopropene (1-MCP) blocks ethylene receptors, delaying ripening in climacteric fruits like apples and bananas, extending shelf life (Watkins, 2006) [53].
- 1-MCP also enhances firmness and color, with encapsulated formulations providing sustained ethylene inhibition.
- Gibberellic acid (GA_3) delays senescence, improves firmness and reduces cracking by maintaining cellular structure (Zoffoli *et al.*, 2009) [58].

Improved Color and Size

- Auxins like NAA enhance fruit set and size by promoting cell elongation and reducing premature fruit drop (Taiz *et al*., 2015) [47].
- Cytokinins improve fruit size by stimulating cell division during early development.

Enhanced Stress Resistance

- Salicylic acid reduces chilling injury and oxidative damage in mangoes and tomatoes, enhancing storability (Srivastava & Dwivedi, 2000) [43].
- Abscisic acid (ABA) regulates sugar accumulation, improving flavor and market quality in grapes (Wheeler *et al*., 2009) [55].

Challenges

- Improper timing or overuse of PGRs may cause physiological disorders like uneven ripening or fruit cracking.
- High costs of PGRs limit their adoption by small-scale farmers.

Best Practices

- Apply ethylene inhibitors like 1-MCP near harvest to prolong shelf life in fruits intended for storage or transport.
- Use GA_3 at recommended doses during early fruit development to enhance size and delay senescence.

Irrigation Management

Benefits

Improved Fruit Firmness and Shelf Life

- Regulated deficit irrigation (RDI) during critical stages enhances fruit firmness by controlling cell enlargement and reducing disorders like cracking in cherries and citrus splitting (Marsal *et al*., 2016) [22].
- Maintaining optimal soil moisture reduces postharvest weight loss and prevents shrinkage (Intrigliolo and Castel, 2010) [13].

Enhanced Fruit Composition

Moderate water stress improves sugar concentration and acidity balance in fruits like grapes and tomatoes by stimulating osmotic adjustment (Medrano *et al*., 2015) [25].

Reduction of Postharvest Disorders

- Over-irrigation leads to water-soaked textures and decay, while optimal irrigation preserves structural integrity and resistance to postharvest diseases (Naor, 2006).

Challenges

- Over-irrigation can result in fruit softening and increased susceptibility to decay, while under-irrigation may cause smaller fruits and physiological stress.
- Monitoring water requirements involves advanced tools like tensiometers and weather-based irrigation systems, which may increase costs.

Best Practices

- Implement regulated deficit irrigation during non-critical growth periods to conserve water while improving fruit quality.
- Use drip irrigation to deliver precise water amounts to the root zone, reducing waste and enhancing efficiency.

Pre-Harvest Sprays

Benefits

- **Reduction in Weight Loss:** Preharvest chitosan sprays (PCS) and postharvest chitosan coatings (PCC) significantly improved table grape quality, reduced decay and weight loss, and modulated biochemical responses (Meng *et al*., 2008) [26]. Chitosan creates a semi-permeable film that reduces water loss and microbial activity, preserving quality and extending shelf life.
- **Reduction in Physiological Disorders and Enhanced Fruit Quality:** Calcium chloride ($CaCl_2$) sprays increased fruit calcium concentration, reducing physiological disorders like bitter pit and enhancing fruit firmness and acidity in apples and pears (Raese and Drake, 1993) [34]. Calcium stabilizes cell walls and membranes, reducing decay and improving structural integrity.
- **Protection Against Post-Harvest Decay:** Preharvest chitosan sprays at 6 gL^{-1} reduced postharvest decay, preserved strawberry quality, and slowed ripening during storage (Reddy *et al*., 2000) [35]. Chitosan's antimicrobial properties inhibit pathogen growth while enhancing the fruit's natural defense mechanisms.

Challenges

- Coating efficacy depends on fruit type, environmental conditions, and application timing.
- Over-application may negatively affect fruit texture and flavor, reducing consumer acceptance.

Best Practices

- Use biodegradable coatings tailored for specific crops and conditions.
- Apply sprays and coatings at optimal developmental stages to balance protection and natural ripening.

Integrated Pest and Disease Management (IPDM)

Benefits

- **Reduced Postharvest Losses:** IPDM reduces pest infestations and disease outbreaks during storage by combining chemical, biological, and cultural methods (Kogan, 1998) [17]. Integrated approaches break pest cycles and promote long-term resilience.
- **Improved Fruit Quality:** Effective pest and disease management ensures intact fruit structure and aesthetic value, enhancing market appeal (Reddy, 2013) [36]. Pests cause surface blemishes and internal damage, directly impacting quality.
- **Reduced Residue Levels:** Biopesticides and natural predators lower pesticide residues, promoting sustainable and safe practices (Prasad & Gill, 2018) [33]. Reduced chemical use mitigates environmental and health risks.

Genetic Improvement

Benefits

- **Enhanced Shelf Life and Disease Resistance:** Breeding programs develop cultivars with longer shelf life, reduced susceptibility to pathogens, and improved postharvest traits (Klee and Giovannoni, 2011) [16]. Genomic tools like CRISPR-Cas9 accelerate targeted improvements for firmness and flavor retention (Van de Poel *et al*., 2014) [50].

- **Nutritional Enrichment:** Genetic modifications improve levels of antioxidants, vitamin C and minerals, increasing the nutritional value of fruits (Goff and Klee, 2006) [10]. Improved nutrient profiles address dietary deficiencies effectively.

Challenges

- Consumer skepticism toward GMOs may limit adoption.
- Breeding and commercialization of new varieties require substantial resources and time.

Precision Agriculture

Benefits

- **Use of Hyperspectral Imaging Technology:** Zhang *et al*. (2024) [57] demonstrated that hyperspectral imaging with machine learning models improved non-destructive quality assessment of pears. This approach provides precise predictions for traits like maturity and total soluble solids, facilitating real-time decision-making.
- **Use of Artificial Intelligence:** Machine learning algorithms, such as convolutional neural networks, enhance grape quality predictions, supporting optimal harvest timing and resource management (Patil *et al*., 2024) [31]. These methods improve efficiency and ensure high-quality wine production.
- **Optimized Resource Use:** Technologies like GPS-guided machinery and remote sensing reduce resource wastage while improving fruit quality (Bongiovanni & Lowenberg-DeBoer, 2004). Targeted application minimizes environmental impact.
- **Improved Fruit Uniformity and Quality:** Sensors and drones enable real-time monitoring, ensuring uniform ripening and optimal harvest timing (Shamshiri *et al*., 2018) [38]. Precision practices reduce variability in yield and quality.

Use of Biostimulants, Biofortification and Antioxidant Enrichment

Benefits

- **Improved Nutrient Uptake and Fruit Quality:** Biostimulants like seaweed extracts and microbial inoculants enhance nutrient uptake and improve fruit size, flavor and shelf life (Du Jardin, 2015) [5]. These compounds stimulate natural metabolic pathways.
- **Increased Nutritional Value:** Biofortification enriches fruits with essential nutrients like iron and zinc, addressing micronutrient deficiencies (Saltzman *et al*., 2013) [37]. Preharvest antioxidant applications enhance resistance to oxidative stress, improving postharvest quality (Giovanelli *et al*., 2016) [9].

Challenges

- Environmental factors influence the efficacy of biostimulants, requiring adaptive practices.
- Combining biofortification with genetic strategies ensures consistent results across different crops.

Use of Natural Products

Benefits

- **Reduced Residual Toxicity:** Biodegradable natural products like neem oil and chitosan reduce reliance on synthetic chemicals, offering safer alternatives for postharvest quality (Tripathi and Dubey, 2004) [49].
- **Antimicrobial and Antioxidant Effects:** Essential oils and natural coatings prevent microbial spoilage and maintain sensory attributes (Bautista-Baños *et al*., 2006) [3]. These products act as natural preservatives.

Challenges

- Short shelf life of natural products may necessitate frequent applications.
- Product efficacy depends on formulation and environmental conditions.

Timing of Harvest

Benefits

- **Optimal Maturity for Storage:** Harvesting at physiological maturity ensures better storage performance and flavor development (Kader, 2002) [14]. Proper timing aligns fruit quality with market preferences.
- **Improved Market Value:** Correct harvesting reduces losses during transportation and enhances consumer satisfaction (Mohamed & Al-Qurashi, 2020) [27]. Market value depends on visual and sensory appeal.

Challenges

- Environmental factors like temperature and rainfall complicate harvest timing.
- Reliance on visual maturity indicators may lead to inaccuracies.

Conclusion

The application of advanced pre-harvest practices plays a pivotal role in enhancing the post-harvest quality of fruits, contributing to reduced post harvest losses and improved marketability. By incorporating innovative techniques such as crop cover, bagging, thinning, nutrient management, plant growth regulators and irrigation optimization, the fruit industry can ensure better quality attributes like firmness, shelf life and flavor. These practices, combined with sustainable approaches like precision agriculture, genetic improvement, integrated pest management offer promising solutions to address the challenges of post-harvest loss particularly in fruit crops. However, the successful implementation of these advanced techniques with integrated approach and careful consideration of crop-specific needs, environmental conditions and economic feasibility, will helps to improve the quality of fruits by minimizing the post harvest losses. Through continued research with some time being modifications and adaptation of best practices, it is possible to achieve a more sustainable, efficient and profitable fruit production system, ultimately benefiting both producers and consumers. These strategies can strengthen India's position as a leading fruit producer and exporter.

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