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Post-Harvest Management of Pomegranate (*Punica granatum* L.): Technologies for Quality Retention and Market Success

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Pomegranate (*Punica granatum* L.) has emerged as a high-value horticultural crop due to its nutritional richness, antioxidant properties and expanding global trade. Despite its economic importance, postharvest losses caused by physiological deterioration, moisture loss, microbial decay and inadequate cold chain management remain significant constraints. This review synthesizes current scientific literature on harvest maturity, postharvest physiology, cold storage, controlled atmosphere (CA), modified atmosphere packaging (MAP), edible coatings, minimal processing of arils, disease management, packaging innovations and market integration strategies. Emphasis is placed on scientifically validated technologies that enhance shelf life, preserve physicochemical and nutraceutical quality and support commercial success. Integrated approaches combining temperature management, atmosphere modification, sanitation and innovative packaging systems are shown to be most effective. Research gaps and future directions for cultivar-specific optimization and scalable postharvest solutions are discussed.

Keywords: Pomegranate, postharvest technology, controlled atmosphere, modified atmosphere packaging, edible coatings, arils, cold chain, postharvest diseases.

Introduction

Pomegranate is one of the oldest cultivated fruit crops and has gained renewed global prominence because of its functional food properties and increasing export demand. The fruit is valued for its attractive arils, balanced sweet-acid taste and high levels of phenolics and anthocyanins (Pareek *et al*., 2015). However, maintaining fruit quality from harvest to consumer remains challenging due to mechanical damage, water loss, chilling injury and postharvest pathogens. Postharvest management determines market acceptability and profitability. Studies indicate that inadequate storage conditions and poor handling can result in substantial quantitative and qualitative losses (Arendse *et al*., 2014). Therefore, integrated postharvest strategies are essential for sustaining quality during domestic distribution and export.

Postharvest Physiology

Pomegranate is classified as a non-climacteric fruit, exhibiting low respiration and minimal ethylene production compared to climacteric fruits (Pareek *et al*., 2015). Despite this, quality deterioration occurs rapidly under unfavourable conditions. Water loss through transpiration leads to peel shrinkage, reduced firmness and decreased visual appeal. Anthocyanins and phenolic compounds contribute significantly to antioxidant activity and consumer preference. These compounds are relatively stable under refrigerated conditions but degrade under high temperatures or mechanical injury (Palumbo *et al*., 2024). Chilling injury may occur in some cultivars when stored below optimal temperatures, manifesting as peel browning and internal discoloration (Arendse *et al*., 2014). Therefore, storage protocols must consider cultivar sensitivity.

Pomegranate Fruit Physiology After Harvest

After harvest, pomegranate fruit remain metabolically active, undergoing respiration, water loss, biochemical changes and susceptibility to external stresses. As a non-climacteric fruit, pomegranate does not exhibit a dramatic peak in respiration and ethylene evolution, but metabolic reactions continue in response to environmental stimuli, temperature fluctuations and physical damage. The interplay of respiration and oxidative processes drives changes in aril colour, firmness and biochemical constituents such as anthocyanins and tannins, highly valued for their antioxidant properties. Chilling injury under low temperatures often manifests as rind browning, surface pitting and internal discoloration, significantly reducing marketability (Amodio *et al*. 2023). One of the most studied physiological disorders in pomegranate is chilling injury, which occurs when fruit are stored below their tolerance threshold (typically <5-7 °C). Chilling injury not only affects the skin but can alter fatty acid composition and antioxidant systems in the peel and arils, undermining quality attributes consumers seek. Research by Maghoumi, Amodio, Cisneros-Zevallos and Colelli elucidated that oxidative stress and membrane dysfunction lie at the heart of chilling injury, with ensuing changes in protein and enzyme activity that influence the development of browning and other defects (Amodio *et al.* 2023).

Harvest Maturity and Handling

Harvest timing critically influences postharvest performance. Optimal maturity is determined by peel coloration, aril colour, TSS and TSS:TA ratio (Pareek *et al*., 2015). Over-mature fruits are prone to cracking and microbial infection, while immature fruits have inferior flavour. Mechanical injuries during harvest serve as entry points for pathogens such as *Botrytis cinerea* and *Alternaria* spp. (Mincuzzi *et al*., 2023). Gentle harvesting, padded containers and field sorting significantly reduce infection incidence. Rapid precooling after harvest minimizes respiration and extends storage life.

Cold Storage and Relative Humidity

Refrigerated storage is the most effective technique for prolonging pomegranate shelf life. Optimal storage temperatures range between 5°C and 7°C for many cultivars, with relative humidity maintained at 90-95% to minimize weight loss (Arendse *et al*., 2014, Pareek *et al*., 2015). Low temperatures reduce metabolic activity and delay deterioration. However, prolonged exposure to very low temperatures may induce chilling injury symptoms in sensitive cultivars (Arendse *et al*., 2014). Maintaining cold chain continuity during transportation and marketing is essential for preserving quality.

Controlled Atmosphere (CA) Storage

Controlled atmosphere storage further enhances shelf life by modifying O_2 and CO_2 concentrations. Studies have demonstrated that low O_2 (3-5%) combined with moderate CO_2 (5-10%) effectively reduces respiration rate and maintains firmness and acidity (Matityahu *et al*., 2016). CA storage also preserves antioxidant enzyme activity and slows senescence processes (Matityahu *et al*., 2016). However, excessive CO_2 levels may lead to off-Flavors or internal disorders. Therefore, cultivar-specific CA optimization is necessary.

Modified Atmosphere Packaging (MAP)

MAP has been extensively investigated for both whole fruit and fresh-cut arils. Caleb *et al.* (2012) described MAP as an effective technique for slowing respiration and reducing microbial growth in fresh produce. For pomegranate arils, active MAP systems using selective permeability films significantly extend shelf life under refrigerated conditions (Rokalla *et al*., 2022). Silicone membrane packaging and other breathable films have also demonstrated improved moisture retention and reduced decay incidence (Caleb *et al*., 2012).

Film permeability must balance oxygen diffusion with carbon dioxide accumulation to prevent anaerobic respiration.

Edible Coatings

Edible coatings act as semi-permeable barriers to moisture and gases. Chitosan is widely studied due to its antimicrobial and film-forming properties. Kumar *et al*. (2021) reported that chitosan films enriched with pomegranate peel extract improve barrier properties and inhibit microbial growth. Application of chitosan coatings reduces weight loss, delays colour degradation and enhances storage life. Integration of coatings with MAP offers synergistic benefits.

Minimal Processing of Arils

Ready-to-eat arils represent a rapidly growing market segment. However, arils are highly perishable due to exposed tissues and higher respiration rates. Rokalla *et al*. (2022) demonstrated that active MAP significantly extends aril shelf life under refrigeration. Strict hygiene during aril extraction, rapid cooling and proper packaging are essential to prevent microbial contamination. Shelf life is typically shorter than whole fruit, requiring precise cold chain management.

Post-Harvest Treatments

Various post-harvest treatments help enhance pomegranate storage life and quality:

- **Thermal Treatments:** Heat conditioning and intermittent warming have been successfully applied to reduce chilling injuries and preserve flavour compounds during cold storage. Research shows that controlled heat treatments prior to storage can improve anthocyanin retention and maintain quality attributes.
- **Chemical Treatments:** Pre-storage treatments with substances like salicylic acid, methyl jasmonate or polyamines have been shown to boost antioxidant activity and reduce chilling injury in pomegranates.
- **Edible Coatings and Biological Treatments**

Edible coatings have gained traction as an eco-friendly, residue-free method of quality preservation. Natural polymers such as chitosan and carboxymethyl cellulose create semi-permeable barriers around the fruit surface, reducing moisture loss, gas exchange and microbial penetration. When combined with organic acids or antimicrobial agents, coatings can influence metabolic processes that preserve firmness, colour and biochemical quality over extended storage periods. Across horticultural commodities, edible coatings have shown success in reducing weight loss and limiting microbial decay by creating a protective microenvironment around the fruit. In pomegranate, such coatings can be particularly useful when integrated with MAP or CA storage to enhance overall effectiveness. Exogenous treatments using bioactive compounds like salicylic acid, methyl jasmonate, polyamines and melatonin have also been investigated to trigger stress tolerance mechanisms in pomegranate fruit before and during storage. These compounds often modulate antioxidant pathways and stabilize cell membranes, contributing to reduced chilling injury and decay (Amodio *et al.* 2023).

Postharvest Diseases

Major postharvest pathogens include *Botrytis cinerea* and *Alternaria alternata* (Mincuzzi *et al*., 2023). These pathogens infect through wounds or latent infections established preharvest. Integrated disease management includes:

- Preharvest disease control
- Gentle harvesting
- Sanitation treatments
- Biological control agents
- Temperature management

Mincuzzi *et al*. (2023) emphasized that preventive strategies are more effective than post-infection chemical treatments.

Packaging and Transportation

Packaging must provide mechanical protection, moisture control and atmosphere regulation. Advances in biodegradable films and active packaging systems enhance sustainability while maintaining quality. Cold chain logistics significantly influence export success. Temperature monitoring devices and data loggers help prevent temperature abuse during transit (Arendse *et al*., 2014).

Value Addition and Market Success

Value addition through aril packaging, juice processing and nutraceutical extraction increases profitability and reduces waste. Proper processing techniques preserve antioxidant properties and sensory attributes. Economic analyses indicate that investment in cold storage infrastructure provides high returns due to reduced rejection rates and extended marketing windows (Pareek *et al*., 2015).

Quality Assessment and Consumer Acceptance

Quality assessment protocols during post-harvest handling encompass physical, chemical and sensory attributes. Physical parameters such as weight loss, firmness and visual appearance (e.g., color and surface integrity) serve as primary indicators of market readiness. Chemical attributes, including total soluble solids, titratable acidity and antioxidant levels, reflect internal quality and nutritional value. Sensory evaluations link these objective measurements to consumer acceptability. Standardized assessment methods help stakeholders make informed decisions regarding storage adjustments, market timing and pricing strategies. Combining laboratory analysis with field evaluations enhances the reliability of post-harvest quality predictions and supports consistent delivery of high-quality produce to consumers.

Research Gaps and Future Perspectives

Future research should focus on:

1. Cultivar-specific CA and MAP optimization
2. Sustainable edible coating formulations
3. Integration of biological control agents
4. Smart packaging and sensor technologies
5. Socioeconomic evaluation of postharvest interventions

Conclusion

Postharvest management of pomegranate requires an integrated approach combining harvest maturity control, cold storage, atmosphere management, sanitation, packaging innovation and disease prevention. Cold chain maintenance remains the most critical factor in quality retention. Advanced technologies such as CA, MAP and edible coatings provide additional benefits when appropriately optimized. Continued research and infrastructure development are necessary to maximize market success and reduce postharvest losses in global pomegranate supply chains.

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