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P(ISSN) : 3007-0031

E(ISSN) : 3007-004X

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Calcium Chloride Treatments for Postharvest Shelf-Life Extension in Mango (Mangifera indica)

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Publisher: EDUCATION GENIUS SOLUTIONS

Review Type: Double Blind Peer Review

ABSTRACT

This review comprehensively examines the role of calcium chloride (CaCl₂) treatments in extending the postharvest shelf life of mango (*Mangifera indica* L.), a highly perishable climacteric fruit of significant economic and nutritional value. Rapid ripening, driven by elevated ethylene production and respiration rates, limits mango shelf life and contributes to substantial postharvest losses in tropical regions. Calcium chloride has emerged as an effective and economical intervention due to its critical role in maintaining cell wall integrity, stabilizing membranes, and regulating enzymatic and physiological processes associated with fruit ripening. The review highlights the biochemical mechanisms underlying calcium–pectin interactions, particularly the formation of calcium-pectate cross-links that enhance tissue firmness and reduce the activity of cell wall-degrading enzymes such as polygalacturonase and pectin methylesterase. Additionally, CaCl₂ treatments modulate ethylene biosynthesis and respiration, thereby delaying ripening and senescence. Various application methods, including pre-harvest foliar sprays, postharvest dips, and vacuum infiltration, are discussed with respect to their effectiveness and limitations. The influence of calcium treatments on fruit quality attributes such as total soluble solids, titratable acidity, vitamin C, and phenolic content is also evaluated. Furthermore, the integration of CaCl₂ with other technologies such as chitosan coatings and thermal treatments demonstrates synergistic effects in enhancing storage life and reducing physiological disorders like jelly seed and spongy tissue. Despite its benefits, improper application may lead to adverse effects such as lenticel damage and altered sensory properties. Future perspectives emphasize the potential of nanotechnology and molecular approaches to improve calcium delivery and utilization. Overall, CaCl₂ treatment represents a promising strategy for reducing postharvest losses and improving mango quality when applied under optimized conditions.

Keywords: Calcium chloride; Mango (*Mangifera indica*); Postharvest physiology; Shelf-life extension; Ethylene regulation; Cell wall stability; Fruit ripening; Chitosan; Physiological disorders; Antioxidants

1. Introduction

The mango (*Mangifera indica* L.), colloquially revered as the king of fruits, represents a cornerstone of tropical pomology and a vital component of the global horticultural trade. Its high concentration of vitamins A and C, distinct organoleptic profile, and economic significance for developing nations make its postharvest preservation a priority for agricultural researchers and industry stakeholders alike (Hepler, 2005). However, the mango is a highly perishable climacteric fruit, characterized by a rapid surge in autocatalytic ethylene production and a concomitant spike in respiration shortly after harvest. This physiological transition triggers a suite of metabolic changes, including starch-to-sugar conversion, cell wall degradation, and the loss of organic acids, which collectively result in a limited shelf life often restricted to 4 to 8 days at ambient temperatures (Prasanna et al., 2007).

The magnitude of postharvest loss in the mango sector is a significant challenge to food security and economic stability in tropical regions, where losses can reach 40% to 45% due to inadequate cold chain infrastructure and improper handling. These losses are not merely quantitative but also qualitative, as the rapid softening and susceptibility to pathogens like *Colletotrichum gloeosporioides* diminish marketability (Niazi, 2022). Within this context, the exogenous application of calcium chloride (CaCl₂) has emerged as a scientifically robust and cost-effective strategy to mitigate these losses.

Calcium is a secondary plant nutrient essential for maintaining the structural integrity of cell walls and membranes, regulating enzymatic activities, and slowing the physiological processes that lead to senescence (White & Broadley, 2003).

The fundamental role of calcium in plant biology is multifaceted. It serves as a structural component of the cell wall and middle lamella, acting as a cementing agent that holds cells together. Beyond its structural functions, calcium acts as a ubiquitous secondary messenger in cellular signaling, facilitating the fruit's response to environmental stressors and developmental cues (Thor, 2019). In mango, the concentration of calcium naturally fluctuates during fruit development, typically decreasing on a dry weight basis as the fruit expands into maturity. This dilution effect, coupled with the limited mobility of calcium in the phloem, often results in localized deficiencies in the mesocarp, predisposing the fruit to various physiological disorders and rapid postharvest breakdown (Ferguson, 1984). Consequently, exogenous treatments of CaCl₂, applied either as pre-harvest sprays or post-harvest dips and infiltrations, are necessary to fortify the fruit's natural defenses and extend its longevity (Singh et al., 2017).

2. Biochemical Architecture of the Mango Cell Wall and Calcium Interaction

To understand the efficacy of CaCl₂ in shelf-life extension, one must examine the biochemical architecture of the mango cell wall. The cell wall is a complex matrix comprising cellulose microfibrils, hemicellulose, and pectic substances. During ripening, the dissolution of the middle lamella and the solubilization of pectins are the primary drivers of fruit softening. Calcium ions Ca²⁺ play a critical role here by forming cross-links between the carboxyl groups of polygalacturonic acid chains in the pectic fraction (Nestby & Tagliavini, 2017).

The Egg-Box Model and Pectin Stability

The interaction between calcium and pectin is best described by the "egg-box" model, where Ca²⁺ ions reside within cavities formed by the alignment of galacturonic acid residues. These calcium-pectate bridges significantly increase the mechanical strength of the cell wall, making it more resistant to the hydrolytic enzymes that characterize the ripening phase. The formation of these bridges is a concentration-dependent process; higher exogenous applications typically lead to a greater number of calcium-pectin bonds, resulting in a firmer fruit texture (Prado et al., 2020).

In cultivars such as 'Calcuttia', treatments with 800 ppm CaCl₂ have been shown to supply adequate calcium to reinforce these pectates without causing surface injury. The reinforcement of the cell wall serves as a physical barrier not only to softening but also to moisture loss through transpiration and the invasion of microbial pathogens. Furthermore, the presence of calcium within the cell wall matrix modulates the activity of enzymes like polygalacturonase (PG) and pectin methylesterase (PME) (Parfitt et al., 2010).

Inhibition of Cell Wall Degrading Enzymes

As mango ripening progresses, a coordinated suite of enzymes targets the pectic matrix. PG and PME are the primary enzymes responsible for the cleavage and de-esterification of pectin, respectively. CaCl₂ treatments effectively reduce the activities of these enzymes, thereby preserving the structural framework of the fruit tissue (López et al., 2023).

Table 1: Effect of CaCl₂ on Ripening-Related Cell Wall Degrading Enzymes in Mango.

Enzyme	Function in Ripening	Effect of CaCl ₂	Resulting Physiological Impact
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Polygalacturonase (PG)	Hydrolysis of glycosidic bonds in pectin chains	Significant reduction in activity	Delayed depolymerization and sustained tissue firmness
Pectin Methylesterase (PME)	De-esterification of pectin, facilitating PG action	Inhibition of enzyme activity	Reduced solubility of pectic substances
\beta-galactosidase	Degradation of cell wall galactans	Downregulated activity	Slower modification of hemicellulosic components
Cellulase	Breakdown of cellulose microfibrils	Lowered activity levels	Preservation of primary cell wall architecture

Studies on fresh-cut mango and dragon fruit have demonstrated that the inhibitory effect of calcium on these enzymes is both concentration and duration-dependent. In fresh-cut 'Kent' and 'Tommy Atkins' mangoes, short dips in CaCl₂ effectively retarded softening by maintaining higher firmness through enzyme suppression. The negative correlation between fruit calcium content and PG/PME activity (e.g., $r = -0.371$ for PG) underscores the direct biochemical role of calcium in regulating these catabolic pathways (Tharanathan et al., 2006).

3. Physiological Regulation and Ethylene Biosynthesis

The climacteric nature of the mango necessitates a strategy that addresses the hormonal drivers of ripening. Ethylene acts as the master regulator of the metabolic transitions from a mature green stage to an eating-ripe stage. This pathway is tightly regulated by two key enzymes: 1-aminocyclopropane-1-carboxylate synthase (ACS) and 1-aminocyclopropane-1-carboxylate oxidase (ACO) (Sakimin, 2011).

Suppression of the Ethylene Pathway

CaCl₂ treatments have been shown to significantly lower ethylene production rates and delay the onset of the ethylene climacteric. This suppression occurs through multiple mechanisms. Calcium ions may stabilize the membranes where ACO is localized, thereby impairing its functional efficiency. Additionally, calcium serves as a signaling molecule that can influence the transcriptional regulation of ACS and ACO genes (Alonso-Salinas et al., 2024).

In cultivars like 'Amrapali', postharvest CaCl₂ treatments noticeably delayed ripening by reducing ethylene production. For 'Namdokmai' mango slices, 1% and 2% CaCl₂ dips had a comparable inhibitory effect on ethylene production, preventing the dramatic increase seen in untreated controls. By maintaining lower ethylene levels, CaCl₂ postpones the activation of ripening-associated genes responsible for color change, aroma development, and sugar accumulation (Zhang et al., 2017).

Respiration and Metabolic Quiescence

The respiration rate of a harvested fruit is an index of its metabolic activity and potential shelf life. Mangoes exhibit a typical climacteric respiration peak, which coincides with rapid quality deterioration. Calcium application reduces the peak respiration rate and slows the overall rate of CO₂ evolution (Kuldeep et al., 2025).

The reduction in respiration is partly attributed to the stabilization of mitochondrial membranes and the maintenance of cellular compartmentalization. By slowing down the consumption of oxygen and the production of carbon dioxide, CaCl₂ keeps the fruit in a state of relative metabolic quiescence. In 'Calcuttia' mangoes, 800 ppm CaCl₂

was found to be the optimal level for supplying enough calcium to reinforce cell wall pectates without impairing the necessary gas exchange through the fruit surface (Brecht et al., 2026).

4. Methodologies for Exogenous Calcium Application

The effectiveness of CaCl₂ is highly dependent on the mode of application and the developmental stage at which the fruit is treated. Researchers have explored pre-harvest foliar sprays, post-harvest dips, and more advanced techniques such as vacuum and pressure infiltration (Mazumder et al., 2021).

Pre-harvest Foliar Sprays

Pre-harvest treatments aim to build up the endogenous calcium status of the fruit while it is still attached to the tree. This is particularly important because calcium moves primarily through the xylem via the transpiration stream; as the fruit matures, its transpiration rate decreases relative to the leaves, leading to a natural decline in calcium import (Al-Saif et al., 2025).

Table 2: Comparative Performance of Pre-harvest CaCl₂ Foliar Sprays on Mango Ripening and Shelf Life.

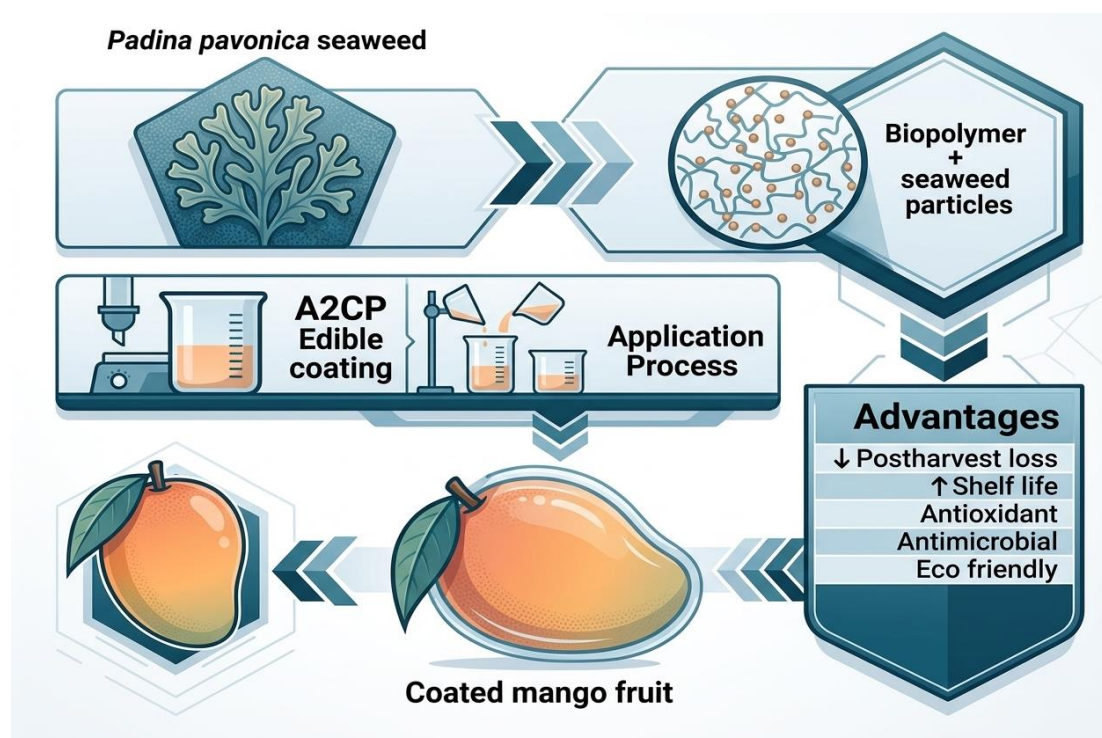
Cultivar	Application Timing	Concentration	Key Findings
'Mallika'	15 and 30 days before harvest	3.0% (combined with 1% Chitosan)	Extended shelf life by 6 days; minimal weight loss
'Alphonso'	15 and 30 days before harvest	1.50%	Significantly increased ripening time (13.6 days) and shelf life (20.6 days)
'Totapuri'	15 and 30 days before harvest	1.50%	Ripening delayed to 19.89 days; shelf life extended to 25.89 days
'Amrapali'	10 and 20 days before harvest	1.50%	Enhanced fruit length, weight, and overall organoleptic quality

Research consistently indicates that sprays applied earlier in the development (e.g., 30 days before harvest) are more successful than those applied immediately before picking. This is because the calcium has a longer window to be integrated into the growing cell wall matrix. Furthermore, pre-harvest calcium can reduce the abscission rate, potentially increasing total yield (Owen-Smith et al., 2019).

Post-harvest Dips and Infiltration

Post-harvest applications focus on rapid fortification. Simple dipping for durations ranging from 1 to 30 minutes is the most common commercial method. However, the mango's thick, waxy cuticle and limited number of lenticels can act as a significant barrier to calcium diffusion (Phorbee et al., 2023).

Figure: 2 Overview of *Padina pavonica* Seaweed-Based Edible Coating (A2CP) on Mango Fruit: Extraction, Application, and Postharvest Advantages



To overcome this, vacuum and pressure infiltration are used to force the solution into the fruit tissue. Vacuum infiltration at -20 kPa to -33 kPa has shown varying degrees of success. In 'Carabao' mangoes, 6% CaCl_2 vacuum infiltration delayed ripening for 4 days, though it also increased skin shriveling. In 'Thilina' tomatoes, which serve as a comparative model for climacteric fruit, vacuum infiltration was the most effective mode for extending shelf life and increasing total calcium in both the inner and outer pericarp. The stem-end scar has been identified as a primary pathway for solution entry during infiltration (Becker et al., 2012).

However, the risk of injury is a major constraint for infiltration methods. Studies on 'Kensington' and 'Sensation' mangoes found that vacuum infiltration at -33 kPa with 4% CaCl_2 failed to extend shelf life and caused significant lenticel damage. This suggests that the optimal concentration and pressure must be precisely calibrated for each cultivar to avoid physiological stress (Gosa et al., 2019).

5. Interaction with Quality and Bioactive Compounds

CaCl_2 treatments influence the entire biochemical profile of the mango, affecting sugars, acids, and the fruit's antioxidant potential (Hossain et al., 2021).

Sugars and Total Soluble Solids (TSS)

The conversion of starch to sugars is a primary feature of mango ripening, typically leading to a rise in TSS. Calcium chloride generally slows this accumulation, indicating a retardation of the metabolic rate (Kuldeep et al., 2025).

In 'Dushehari' mangoes, 6% CaCl_2 treatment resulted in a slow and steady increase in TSS over 12 days, whereas control fruits exhibited a much more rapid rise followed by a decline as senescence set in. Higher concentrations of calcium can also lead to higher final TSS values at the point of full ripeness, as seen in calcium-infiltrated fruits which remained firmer while accumulating more sugars than controls (Punam et al., 2021).

Titrateable Acidity (TA) and Organic Acids

The degradation of organic acids, primarily citric and malic, occurs through respiration

as the fruit ripens. CaCl₂ is highly effective at preserving TA levels, which is crucial for maintaining the fruit's flavor balance (You et al., 2026).

Table 3: Impact of CaCl₂ Treatments on Titratable Acidity (TA) Preservation in Various Mango Cultivars.

Cultivar	Treatment	Acid Retention	Comparison to Control
'Amrapali'	2% CaCl ₂	0.09%	0.08% in control after 12 days
'Dushehari'	6% CaCl ₂	0.17%	0.10% in control after 12 days
'Mallika'	1.5% pre-harvest spray	0.15%	Higher than controls

The high acidity in calcium-treated fruits is an indicator of delayed ripening and reduced substrate utilization in respiration. This retention of acids contributes significantly to the overall sensory quality and prevents the "bland" taste often associated with over-ripe or poorly stored fruit (Abrol et al., 2017).

Vitamin C and Phenolic Compounds

Mangoes are valued for their antioxidant content, including ascorbic acid (Vitamin C) and various phenolics. These compounds are sensitive to postharvest degradation. CaCl₂ has been found to prevent the loss of Vitamin C and phenolic compounds by reducing oxidative stress and stabilizing cell membranes (Ntsoane et al., 2019).

In 'Amrapali' mangoes, 2% CaCl₂ significantly maintained higher levels of ascorbic acid (17.08 mg/100 g vs. 8.53 mg/100 g in control) and total phenolic content after 12 days. Furthermore, CaCl₂ enhances the activity of antioxidant defense enzymes such as catalase (CAT) and peroxidase (POD), which help scavenge reactive oxygen species (ROS) and reduce the incidence of tissue browning (Saikaew et al., 2023).

6. Hurdle Technologies and Synergistic Effects

The combination of CaCl₂ with other postharvest treatments, often termed "hurdle technology," has shown the most promising results for maximizing shelf life while maintaining fruit quality (Mazumder et al., 2021).

Chitosan and Edible Coatings

Chitosan, a biopolymer with natural antimicrobial and film-forming properties, is frequently used in combination with calcium. While CaCl₂ strengthens the internal cell structure, chitosan forms a semi-permeable coating on the fruit surface that modifies the internal atmosphere by reducing O₂ levels and increasing CO₂ (Elsabee & Abdou, 2013).

In 'Mallika' mangoes, the combination of 3% CaCl₂ and 1% chitosan extended shelf life by up to 6 days at ambient conditions compared to the control. For 'Ewaise' mangoes, this combination boosted storability for up to 40 days under cold storage, significantly reducing chemical and physical degradation. The combined application also enhances decay resistance, as chitosan inhibits fungal growth (e.g., *Colletotrichum gloeosporioides*) by disrupting microbial cell membranes, while calcium maintains the host tissue's structural resistance to penetration (Al Eryani-Raqeeb et al., 2009).

Thermal Treatments and Chilling Injury Mitigation

Hot water treatment (HT) is a mandatory quarantine procedure for many mango export markets but can sometimes lead to excessive softening. The addition of calcium salts to the HT bath acts as a stabilizer (Almeida Miguel et al., 2016).

Research indicates that HT combined with CaCl₂ (HT-Ca) is effective at maintaining firmness and reducing electrolyte leakage in fruit stored at chilling temperatures (Ariel-

Ayala et al., 2018). Calcium helps mitigate chilling injury (CI) by maintaining the liquid-crystalline state of membrane lipids at low temperatures, preventing the phase transition that leads to membrane rupture and pitting (Matsumoto & Ikoma, 2016).

7. Mitigation of Internal Physiological Disorders

Calcium deficiency is a primary driver of several internal disorders (IDs) that plague the mango industry. These disorders often manifest as internal flesh breakdown, spongy tissue, jelly seed, and soft nose (Shahat et al., 2024).

Jelly Seed and Spongy Tissue

Jelly seed is characterized by the disintegration of the mesocarp near the endocarp, resulting in a gelatinous, over-ripe appearance around the seed. Spongy tissue involves the development of pale, corky, and acidic patches in the pulp. Both conditions are linked to a localized imbalance of calcium in the inner mesocarp (Arya et al., 2025).

Table 4: Overview of Internal Physiological Disorders in Mango and Calcium-Mediated Mitigation.

Disorder	Clinical Presentation	Relationship with Calcium
Jelly Seed	Necrosis around the cavity; gelatinous consistency in mesocarp	Associated with significantly lower Ca concentrations in the inner mesocarp
Spongy Tissue	Starchy patches in the flesh; xylem deterioration	Prevented by increasing Ca partitioning to the fruit via nutrient management
Soft Nose	Premature ripening and softening of the distal fruit end	Linked to deficiency in the distal part of the fruit; mitigated by foliar Ca sprays
Internal Necrosis	Flesh browning resulting from cell wall and membrane degradation	Low Ca levels predispose tissues to phenolic oxidation and enzymatic browning

Studies have shown that high nitrogen levels relative to calcium (high N/Ca ratio) exacerbate these disorders, as nitrogen promotes rapid cell expansion that "dilutes" the available calcium. Strategies that enhance calcium import such as foliar sprays 2-4 weeks before harvest or drip irrigation have proven effective in reducing the incidence of these IDs in cultivars like 'Sensation' and 'Tommy Atkins' (Prasanna et al., 2007).

8. Operational Risks: Lenticel Injury and Organoleptic Changes

While the benefits of CaCl₂ are substantial, improper application can lead to negative side effects that diminish the fruit's market value (Ritenour et al., 2004).

Lenticel Damage and Skin Shriveling

Lenticel damage (LD), or "spotting," occurs when the tissue around the lenticels swells and discolors, producing brown or black spots. This can be triggered by high concentrations of CaCl₂ or the use of non-osmotically balanced solutions (Kou et al., 2015).

Interestingly, moderate salt solutions can actually *reduce* lenticel damage in very turgid fruit (e.g., fruit harvested after heavy rain) by inducing a slight moisture loss that prevents the lenticels from rupturing. Cold salt solutions of 1% to 2% have been identified as effective tools in the packline dumping bath to manage fruit turgor and minimize LD. However, if the concentration is too high (e.g., >4-6%), it may lead to severe skin shriveling and pitting, as observed in 'Kensington' and 'Carabao' mangoes (White & Broadley, 2003).

Sensory Quality and Flavor Profiles

The impact of CaCl₂ on the organoleptic profile of mango is a critical concern for

consumer acceptance. High levels of calcium can interfere with the development of typical mango volatiles, leading to a reduction in aroma. In some cases, CaCl₂ has been reported to enhance skin shriveling and lower the scores for flavor and taste (Thor, 2019).

Consumer testing on fresh-cut mangoes indicates that while CaCl₂ is effective for retaining firmness, the concentration must be carefully managed. For 'Tommy Atkins' and 'Kent' mangoes, treatments with 0.136 M CaCl₂ were not disliked by consumers and successfully maintained texture, but the 'Kent' variety was generally preferred due to less tissue browning. The "chemical" or bitter taste sometimes associated with calcium is more prevalent when concentrations exceed the threshold required for structural stability (López et al., 2023).

9. Analytical Perspectives: Monitoring and Partitioning

Effective management of calcium status requires precise monitoring. Calcium levels vary significantly between different parts of the fruit: the skin typically has the highest concentration, followed by the outer, middle, and inner mesocarp (Prado et al., 2020).

Spatial Distribution and Sampling

To ascertain the mineral status of a mango crop, sampling must be representative. It is advised to collect fruit from the middle of the tree canopy to avoid the physiological variability introduced by sun-exposed versus shaded sides of the tree. Sun-exposed fruit often have higher transpiration rates, which can differentially influence their calcium accumulation (Singh et al., 2017).

Nutrient Ratios and Signaling

The susceptibility of mango to internal disorders is often more accurately predicted by nutrient ratios (e.g., N/Ca, K/Ca, or (Mg+K)/Ca) rather than absolute calcium levels alone. High levels of antagonistic cations like potassium (K⁺) or ammonium (NH₄⁺) can reduce calcium uptake. Furthermore, hormonal regulation plays a role in calcium partitioning; auxins are known to facilitate calcium transport into developing tissues, and inhibitors of auxin transport have been shown to reduce fruit calcium levels (Tharanathan et al., 2006).

10. Future Directions and Emerging Technologies

The landscape of postharvest mango preservation is rapidly evolving. Emerging research is focusing on nano-delivery systems and advanced molecular breeding (Singh et al., 2017).

1. **Nano-Technology:** The use of calcium-based nanoparticles or nano-encapsulated CaCl₂ within edible coatings may allow for more efficient penetration and a sustained release of calcium into the mesocarp. This could potentially reduce the concentrations needed and eliminate the risk of surface injury (Parfitt et al., 2010).
2. **Molecular Breeding:** Identifying the quantitative trait loci (QTLs) and specific genes (e.g., calcium-dependent protein kinases or calmodulin) involved in calcium-mediated stress response could lead to the development of new cultivars with inherently better calcium utilization and longer shelf lives (Kuldeep et al., 2025).
3. **Advanced Infiltration Protocols:** Refining vacuum and pressure infiltration parameters perhaps by using osmotically balanced solutions containing sugars could make these high-uptake methods commercially viable without the current risks of injury (Hossain et al., 2021).

11. Conclusion

Calcium chloride treatments play a pivotal role in enhancing the postharvest quality

and extending the shelf life of mango by targeting key physiological and biochemical processes associated with ripening and senescence. The strengthening of cell wall structure through calcium–pectin interactions, combined with the inhibition of cell wall-degrading enzymes, contributes significantly to maintaining fruit firmness. Additionally, the suppression of ethylene production and respiration rates delays ripening, allowing for prolonged storage and improved marketability. Both pre-harvest and postharvest application methods have demonstrated effectiveness, although their success depends on appropriate concentration, timing, and cultivar-specific responses. The integration of CaCl₂ with complementary technologies such as edible coatings and heat treatments further enhances its efficacy, offering a multifaceted approach to postharvest management. Moreover, calcium treatments help mitigate internal physiological disorders and preserve important quality attributes, including acidity, vitamin C, and phenolic compounds. However, excessive concentrations or improper application techniques may negatively impact fruit appearance and sensory quality, highlighting the need for optimized protocols. Future research should focus on advanced delivery systems, such as nano-formulations, and genetic approaches to improve calcium uptake and utilization in mango tissues. In conclusion, calcium chloride remains a cost-effective and scientifically validated tool for reducing postharvest losses and maintaining the quality of mango, with significant implications for food security and the horticultural industry.

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