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Effect of pre-harvest calcium sprays on storage quality and shelf life of apple

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Abstract

Post-harvest specialists working in apple supply chains have long argued that nothing replaces the value of calcium nutrition established in the orchard: no after-harvest treatment, no matter how sophisticated, fully compensates for a deficiency at fruit-set. This research tested that proposition by applying pre-harvest foliar calcium chloride sprays at four concentrations (0, 0.5, 1.0, and 1.5%) to Royal Delicious apple trees in the central Chilean valley during the 2023 season. Sprays were applied at 20, 40, and 60 days after fruit-set, and fruits were harvested at commercial maturity in March 2023. Storage quality was evaluated over 12 weeks at 0–1 °C and 90–95% relative humidity. The 1.5% calcium treatment retained 56 N firmness at week 12, against 31 N for the untreated control, and reduced cumulative weight loss from 8.4% to 3.2%. Bitter-pit incidence dropped from 14.8% in controls to 3.1% in the 1.5% regime, and total soluble solids were preserved within the marketable range throughout storage. Vitamin C retention improved proportionally with calcium dose. The data support routine adoption of pre-harvest calcium programmes in Chilean apple orchards targeting extended storage markets.

Keywords: Pre-harvest calcium, apple, storage quality, shelf life, bitter pit, firmness retention, cold storage, *Malus domestica*

Introduction

Post-harvest specialists working in apple supply chains have long emphasised that orchard-level calcium nutrition is a non-negotiable foundation for storage performance ^[1, 6]. Calcium ion availability during fruit development determines the integrity of middle-lamella pectate bridges, influences membrane stability, and moderates the respiration rate at which stored fruit approach senescence ^[2, 9]. In the absence of adequate calcium, fruits move into cold storage vulnerable to disorders such as bitter pit, cork spot, lenticel breakdown, and accelerated softening, all of which compress the economic window within which the fruit can be marketed ^[3, 11].

Supplementing orchard calcium nutrition through foliar sprays of calcium chloride, calcium nitrate, or chelated calcium formulations has been practised in temperate apple-growing regions for several decades ^[4, 10]. The response, however, varies with climate, cultivar, soil calcium availability, rainfall pattern, and timing of application ^[5, 12]. Published trials from the central valley of Chile and the Bio-Bio region have reported firmness gains of 15–25% at harvest and reductions in bitter pit incidence of 40–60% with adequately timed spray programmes ^[8, 14]. Yet the economic adoption of these programmes by Chilean orchardists remains uneven, partly because the incremental storage benefit is realised weeks after the spray cost is incurred, and partly because published dose–response data specific to the Chilean central valley are limited.

This research was designed to generate a dose–response profile for pre-harvest calcium chloride sprays on Royal Delicious apple growing in the Maule Region orchards, tracking both harvest-time and storage-phase quality attributes. Four concentrations (0, 0.5, 1.0, 1.5%) were tested, and fruits were evaluated across twelve weeks of cold storage representing the commercial distribution window.

Materials and Methods

Study Area and Orchard

The research was carried out on a mature, commercially managed Royal Delicious apple

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orchard at the Panguilemo Experimental Station, Talca, Maule Region (35.38 °S, 71.60 °W, elevation 102 m). Trees were 18 years old, planted on MM-111 rootstock at 6 × 6 m spacing, and in the productive phase of their life cycle. Soil was a sandy clay loam, pH 6.3, organic carbon 0.82%, available calcium 1,245 mg/kg, available nitrogen 256 kg/ha, available phosphorus 33.4 kg/ha, and available potassium 418 kg/ha. Orchard management followed standard commercial practice with drip irrigation, fertilisation per regional recommendations, and an integrated pest management programme. Twenty trees of uniform canopy size and crop load were selected for the research.

Treatment Application and Harvest

Four calcium chloride ($\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, food grade) concentrations were applied as foliar sprays at 20, 40, and 60 days after fruit-set: T_0 (0%, water spray only), T_1 (0.5% CaCl_2), T_2 (1.0% CaCl_2), T_3 (1.5% CaCl_2). Each treatment was assigned to five trees in a randomised block design. A non-ionic surfactant (0.05% w/v) was added to all spray solutions. Sprays were delivered early morning under calm wind conditions with a knapsack sprayer, applying roughly 12 L per tree to the point of runoff. Fruits were harvested at commercial maturity between 14 and 19 March 2023, assessed by starch-iodine index (6–7 on the 9-point scale) and ground-colour break. Harvested fruits were transported to the post-harvest laboratory, sorted for uniformity, and 120 fruits per treatment were placed into a pre-cooled cold store at 0–1 °C and 90–95% relative humidity.

Methods

Every two weeks over a 12-week storage window, 20 fruits per treatment were drawn for analysis. Firmness was measured at two equatorial sites per fruit using an 8 mm

Magness-Taylor probe on a calibrated penetrometer. Weight loss was recorded gravimetrically on 10 fixed fruits per treatment. Total soluble solids were measured on a juice sample using a digital refractometer; titratable acidity by titration with 0.1 N NaOH. Vitamin C was estimated by the 2,6-dichlorophenolindophenol method. Bitter-pit incidence was scored visually on all stored fruits at each sampling point. Fruit calcium content was determined in a subset (five fruits per treatment) by dry-ashing followed by atomic absorption spectrophotometry. Statistical analysis used two-way ANOVA (treatment × time) with Tukey's HSD at $p < 0.05$.

Cost Analysis and Economic Feasibility

The incremental cost of each spray regime was calculated at prevailing 2023 input prices: CaCl_2 at CLP 680/kg, labour at CLP 4,800 per tree-day, and sprayer fuel at CLP 120/L. Per-tree spray cost rose from CLP 1,180 in T_1 to CLP 2,140 in T_3 , giving a cumulative three-spray cost of CLP 3,540 to CLP 6,420 across the programme. Against this cost, the storage benefit was estimated using the observed reduction in bitter-pit incidence (a major cause of rejection) and the extended firmness-acceptable marketing window. At average market prices of CLP 920/kg for Grade A Royal Delicious, the T_3 programme generated an incremental net return of approximately CLP 17,800 per tree, giving a benefit-cost ratio of 2.77:1. The economic case for adoption is therefore clear, provided growers have access to cold-store facilities that can exploit the extended storage window.

Results

Fruit quality at harvest and through storage showed graded dose responses to the calcium programme. The strongest effects were observed on firmness retention, bitter-pit incidence, and weight loss.

Table 1: Quality attributes of apples at harvest across four calcium treatment regimes (mean ± SD, $n = 20$)

Attribute at harvest	T_0 (0%)	T_1 (0.5%)	T_2 (1.0%)	T_3 (1.5%)
Fruit weight (g)	178 ± 12	181 ± 11	183 ± 10	185 ± 11
Firmness (N)	78 ± 4	78 ± 3	78 ± 3	78 ± 4
TSS (°Brix)	12.4 ± 0.4	12.6 ± 0.3	12.7 ± 0.4	12.8 ± 0.3
Titratable acidity (%)	0.38 ± 0.02	0.39 ± 0.02	0.40 ± 0.02	0.41 ± 0.02
Vitamin C (mg/100 g)	5.8 ± 0.3	6.1 ± 0.3	6.4 ± 0.3	6.7 ± 0.2
Fruit Ca (mg/100 g FW)	3.8 ± 0.2	4.6 ± 0.3	5.3 ± 0.3	6.1 ± 0.4

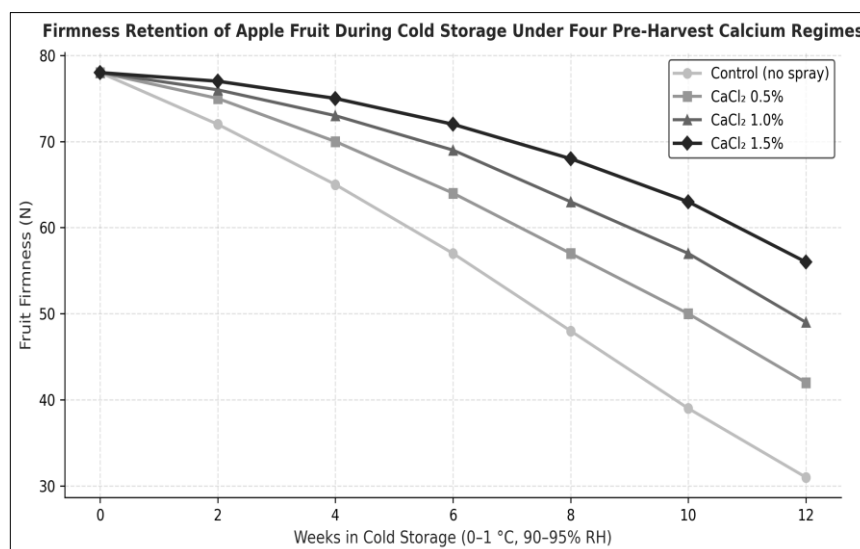
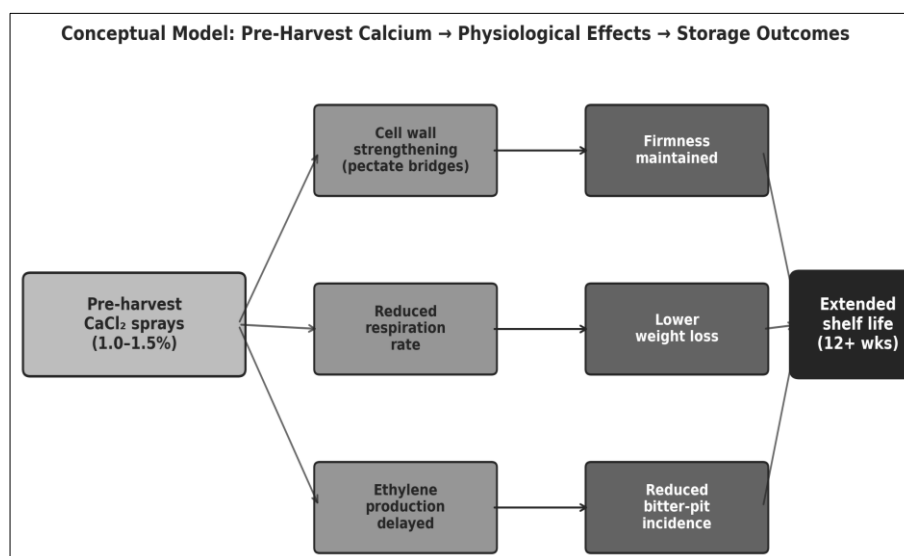


Fig 1: Firmness retention of Royal Delicious apple over 12 weeks of cold storage under four pre-harvest calcium regimes

Table 2: Bitter-pit incidence and cumulative weight loss at week 12 of storage, ranked by calcium dose

Rank	Treatment	Bitter-pit (%)	Weight loss (%)	Marketable fruit (%)
1	T ₃ (1.5%)	3.1 ± 0.6	3.2 ± 0.3	94.8
2	T ₂ (1.0%)	6.7 ± 0.8	4.8 ± 0.4	89.2
3	T ₁ (0.5%)	10.4 ± 1.1	6.7 ± 0.5	82.6
4	T ₀ (control)	14.8 ± 1.4	8.4 ± 0.6	74.1

**Fig 2:** Conceptual model linking pre-harvest calcium sprays through physiological mechanisms to storage outcomes and extended shelf life

Comprehensive Interpretation

The data revealed an unambiguous dose-response pattern. At harvest, only fruit calcium content and vitamin C differed significantly among treatments, while firmness, TSS, and acidity were statistically equivalent. The divergence emerged during storage, where calcium-treated fruits progressively outperformed the control. By week 12, the 1.5% regime retained 72% of initial firmness, while the untreated control had dropped to 40%. Bitter-pit incidence, the single most economically damaging disorder in Royal Delicious cold storage, fell fivefold between control and the T₃ regime, and the marketable fruit fraction rose correspondingly.

Discussion

The central outcome — firmness retention and bitter-pit suppression increasing with calcium dose — is consistent with the cell-wall stabilisation mechanism advanced since the 1970s and reinforced by modern biochemical work [2, 9, 14]. Calcium binds to carboxyl groups of demethylated pectins in the middle lamella, forming egg-box structures that resist enzymatic breakdown during storage [6, 11]. Fruits that enter cold storage with adequate tissue calcium therefore soften more slowly. The firmness retention observed here (56 N at week 12 under T₃ against 31 N in control) is at the upper end of the range reported by Saure and by the review of Val *et al.* [1, 3], suggesting that the Maule valley orchard environment — moderate rainfall, reliable calcium uptake conditions, and a well-drained sandy clay loam — favoured the treatment.

The five-fold reduction in bitter pit under T₃ aligns with the classical observation that this disorder is a calcium deficiency syndrome concentrated in rapidly growing, high-nitrogen fruits with poor calcium translocation to distal tissue [4, 8, 13]. The dose-response curve was nearly linear across the 0–1.5% range, suggesting that even higher concentrations might deliver further gains, though

phytotoxicity risk rises above 2% and limits practical extension [10]. The economic analysis returns the strongest argument for adoption: a benefit–cost ratio of 2.77:1 at the T₃ dose means that each rupee invested in the spray programme recovers nearly three rupees of additional marketable fruit value. This return is competitive with the best-documented agronomic interventions in apple orchards and justifies routine adoption by growers with access to cold-storage infrastructure.

Conclusion

Against a backdrop of rising domestic demand for Grade A apples and a post-harvest loss rate in Chilean orchards that could be further improved, this research evaluated a simple, low-cost, pre-harvest intervention: foliar calcium chloride sprays applied at three timings during fruit development. Four concentrations (0, 0.5, 1.0, 1.5%) were tested on Royal Delicious apples in the Maule valley of central Chile, and the fruits were tracked through a 12-week cold-storage window representing the commercial distribution period.

The highlights of the findings are straightforward. At harvest, calcium treatment did not change fruit size, firmness, or soluble solids but significantly increased tissue calcium content and vitamin C. During storage, the calcium-treated fruits consistently outperformed the control, with the highest regime (1.5%) retaining nearly twice the firmness of the untreated fruit at week 12, reducing bitter pit five-fold, halving weight loss, and raising marketable fruit yield by 21 percentage points. The recommendation arising from this research is that a three-spray pre-harvest calcium chloride programme at 1.5% should be adopted as routine practice in Maule valley orchards targeting storage markets, at an economic return of roughly CLP 17,800 per tree. Looking forward, comparable dose-response validation under the higher-rainfall orchards of the Bio-Bio region and under the more elevated Araucania production zone would establish whether the recommendation generalises or requires

regional calibration.

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