Nano-Calcium Formulations for Improving Fruit Quality and Shelf Life of *Solanum melongena L.*

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ABSTRACT
Background: Eggplant (*Solanum melongena L.*) is a globally important solanaceous vegetable valued for its nutritional richness, dietary fiber, and phenolic antioxidant content. Despite its commercial significance, eggplant fruits are highly perishable, undergoing rapid softening, weight loss, and microbial decay during postharvest storage. Calcium plays a pivotal role in maintaining cell wall integrity and membrane stability, yet conventional calcium fertilizers suffer from poor solubility, low uptake efficiency, and antagonistic soil interactions that limit their agronomic effectiveness.
Objective: This study aimed to develop and evaluate nano-calcium formulations for enhancing fruit growth, calcium accumulation, biochemical quality, and postharvest shelf life of eggplant, in comparison with conventional calcium fertilization.
Methods: A field experiment was conducted using a Randomized Complete Block Design (RCBD) with five treatments—control, conventional calcium chloride, and low, medium, and high concentrations of a synthesized calcium-based nanoformulation—each replicated four times. Nanoparticles were characterized for particle size, zeta potential, morphology, crystallinity, and functional groups. Foliar and soil-applied nano-calcium treatments were assessed for effects on plant growth, yield, fruit firmness, calcium content, total soluble solids, vitamin C, phenolics, antioxidant activity, weight loss, decay incidence, and shelf life, with data analyzed using ANOVA and Tukey's HSD test.
Results: Medium and high nano-calcium treatments significantly improved fruit firmness, calcium accumulation, and antioxidant activity relative to the control and conventional fertilizer treatments ($P < 0.05$). Shelf life increased by approximately 40–55%, while weight loss and decay percentage were substantially reduced. Yield and biochemical quality parameters also showed marked improvement under nano-calcium application.
Conclusion: Nano-calcium formulations offer a more efficient and sustainable alternative to conventional calcium fertilizers for improving eggplant fruit quality and extending postharvest shelf life, supporting their integration into precision horticultural nutrient management systems.

Keywords: Nano-calcium, Eggplant (*Solanum melongena L.*), Calcium nanoparticles, Foliar fertilization, Fruit quality

1. Introduction
Solanum melongena L., commonly known as eggplant or brinjal, is one of the most economically significant solanaceous vegetable crops cultivated extensively across Asia, Africa, and the Mediterranean basin [1]. It contributes substantially to household nutrition and rural income generation owing to its rich content of dietary fiber, potassium, and phenolic antioxidants, particularly chlorogenic acid and anthocyanins, which confer notable health-promoting properties [2]. Despite its agronomic and nutritional importance, eggplant fruit is highly perishable, with postharvest losses frequently exceeding 25–30% due to rapid respiration, moisture loss, and microbial decay under ambient storage conditions [3].
Postharvest quality deterioration in eggplant is primarily driven by enzymatic softening, cell wall degradation, and oxidative membrane damage, processes that accelerate under inadequate mineral nutrition, particularly calcium deficiency [4]. Calcium is a structurally vital divalent cation that cross-links pectic polysaccharides within the middle lamella, forming calcium-pectate complexes that reinforce cell wall rigidity and delay senescence-associated softening [5]. Adequate calcium nutrition additionally stabilizes plasma membrane integrity, thereby limiting electrolyte leakage and reducing susceptibility to pathogen invasion during storage [6].
Conventional calcium fertilizers, such as calcium chloride and calcium nitrate, are widely used but exhibit several agronomic limitations, including high water solubility leading to leaching losses, antagonistic interactions with other cations such as potassium and magnesium, and limited translocation efficiency from roots to fruit tissues due to the low mobility of calcium in phloem tissue [7]. These constraints often necessitate repeated, high-dose applications that increase production costs and environmental nutrient loading.

The emergence of nanotechnology in agriculture has opened new avenues for precision nutrient delivery. Nano-fertilizers, engineered at the nanoscale (typically 1–100 nm), possess a high surface-area-to-volume ratio, enhanced reactivity, and the capacity for controlled and targeted nutrient release, which collectively improve nutrient use efficiency while minimizing environmental losses [8]. Nano-calcium formulations, in particular, offer improved cellular penetration through plant cuticles and stomata, enabling more efficient calcium translocation to fruit tissues compared with bulk ionic sources [9].

Motivated by the need for sustainable and efficient postharvest quality management strategies, this study investigates the synthesis, characterization, and agronomic performance of nano-calcium formulations applied to *Solanum melongena L.* The specific objectives were to: (i) synthesize and characterize a stable nano-calcium formulation; (ii) evaluate its effects on vegetative growth and fruit yield; (iii) quantify improvements in fruit firmness, calcium accumulation, and biochemical quality; and (iv) assess the extent of shelf-life extension relative to conventional calcium fertilization. The findings are expected to contribute toward the development of nanotechnology-based nutrient management strategies for sustainable vegetable production.

2. Related Work

Nano-fertilizers have attracted substantial research interest as tools for improving nutrient use efficiency in horticultural crops. Studies on nano-zinc, nano-iron, and nano-silica formulations have demonstrated enhanced micronutrient uptake and improved stress tolerance in tomato, pepper, and cucumber crops [10, 11]. These findings established a foundation for extending nanoformulation strategies to macronutrients such as calcium, which plays a comparatively underexplored but physiologically critical role in fruit quality determination [12].

Calcium nutrition in vegetable crops has been extensively linked to disorders such as blossom-end rot in tomato and pepper, conditions arising from localized calcium deficiency in rapidly expanding fruit tissues [13]. Comparable calcium-related physiological disorders have been reported in eggplant, manifesting as reduced fruit firmness and accelerated postharvest softening [14]. Research on nano-calcium formulations, including calcium carbonate nanoparticles and chitosan-calcium nanocomposites, has shown superior foliar absorption and translocation efficiency compared with conventional calcium salts in leafy and fruiting vegetables [15].

Postharvest physiology research on eggplant has identified fruit firmness loss, seed browning, and calyx desiccation as primary quality-limiting factors during storage [16]. Firmness retention has been closely correlated with cell wall calcium content, as calcium cross-linking of de-esterified pectins delays polygalacturonase-mediated cell wall degradation [17]. Controlled-release nano-fertilizer systems, often employing polymeric or mineral encapsulation matrices, have been developed to synchronize nutrient release with crop physiological demand, thereby reducing application frequency and nutrient wastage [18].

Nanoparticle uptake in plants occurs via foliar stomatal and cuticular pathways or root-mediated apoplastic and symplastic transport, with particle size, surface charge, and formulation chemistry strongly influencing absorption efficiency [19]. Several studies have documented that nano-calcium application enhances antioxidant enzyme activity, including catalase and superoxide dismutase, thereby mitigating oxidative stress associated with postharvest senescence [20]. Comparative studies on strawberry and mango have reported significant increases in shelf life and reduced decay incidence following nano-calcium treatment relative to conventional calcium chloride dips [21].

Sustainable nutrient management frameworks increasingly emphasize precision-targeted fertilization to minimize environmental nutrient losses while maximizing crop productivity [22]. Despite these advances, research specifically addressing nano-calcium application in *Solanum melongena L.* remains limited, with existing studies primarily focused on postharvest dip treatments rather than integrated foliar-soil agronomic application strategies [23]. This represents a critical research gap, as pre-harvest nano-calcium biofortification may offer more durable and systemic improvements in fruit calcium status than postharvest surface treatments alone. The present study addresses this gap by evaluating an integrated nano-calcium application strategy across the eggplant crop cycle.

3. Proposed Nano-Calcium Formulation Strategy

3.1. Formulation Design and Synthesis

The nano-calcium formulation was designed as a calcium carbonate nanoparticle suspension stabilized with a biodegradable chitosan coating to enhance colloidal stability and cuticular adhesion. Nanoparticles were synthesized via a controlled precipitation method, wherein calcium chloride and sodium carbonate precursor solutions were combined under continuous ultrasonication to control nucleation and prevent particle agglomeration. The chitosan coating additionally imparts a positive surface charge, promoting electrostatic interaction with the negatively charged plant cuticle and cell wall surfaces, thereby facilitating enhanced adhesion and penetration.

3.2. Mechanism of Calcium Release and Transport

Following foliar or soil application, the nanoformulation undergoes gradual dissolution, releasing calcium ions in a controlled manner that aligns with plant physiological demand rather than the rapid ionic dissociation characteristic of conventional calcium salts. Foliar-absorbed nanoparticles traverse the cuticle via stomatal and ectodesmatal pathways, entering the apoplastic continuum before symplastic transport into mesophyll and, ultimately, phloem-associated tissues supplying developing fruit. Soil-applied nanoparticles interact with root epidermal cells, where controlled dissolution supplies calcium ions for xylem-mediated translocation.

3.3. Physiological Basis for Fruit Quality Enhancement

At the cellular level, calcium ions delivered via the nanoformulation cross-link de-esterified pectic acid residues within the middle lamella, forming stable calcium-pectate networks that reinforce cell wall rigidity and reduce susceptibility to enzymatic degradation. Concurrently, calcium stabilizes plasma membrane phospholipid bilayers by bridging phosphate head groups, thereby reducing membrane permeability and electrolyte leakage during senescence. These combined effects delay fruit softening, reduce moisture loss, and enhance resistance to postharvest pathogen colonization.

3.4. Advantages over Conventional Calcium Fertilizers

Compared with conventional calcium fertilizers, the proposed nanoformulation offers a substantially higher surface-area-to-volume ratio, improving cellular penetration and translocation efficiency. The controlled-release mechanism minimizes leaching losses and reduces application frequency, while the chitosan coating provides additional antimicrobial protection against postharvest decay-causing pathogens. These combined attributes position nano-calcium as an agronomically and environmentally superior alternative to bulk calcium salts.

Table 1: Comparison of conventional calcium fertilizers and nano-calcium formulations.

Fertilizer Type	Particle Size	Ca Availability	Uptake Efficiency	Advantages	Limitations
Calcium chloride (conventional)	Bulk (>1 μm)	High, rapid release	Low–moderate	Low cost, widely available	Leaching loss, antagonism, low mobility
Calcium nitrate (conventional)	Bulk (>1 μm)	High, rapid release	Moderate	Dual N-Ca supply	Salinity risk, volatile release
Nano-calcium (chitosan-coated $CaCO_3$)	45–80 nm	Controlled, sustained	High	Enhanced penetration, controlled release, antimicrobial coating	Higher synthesis cost, requires standardization

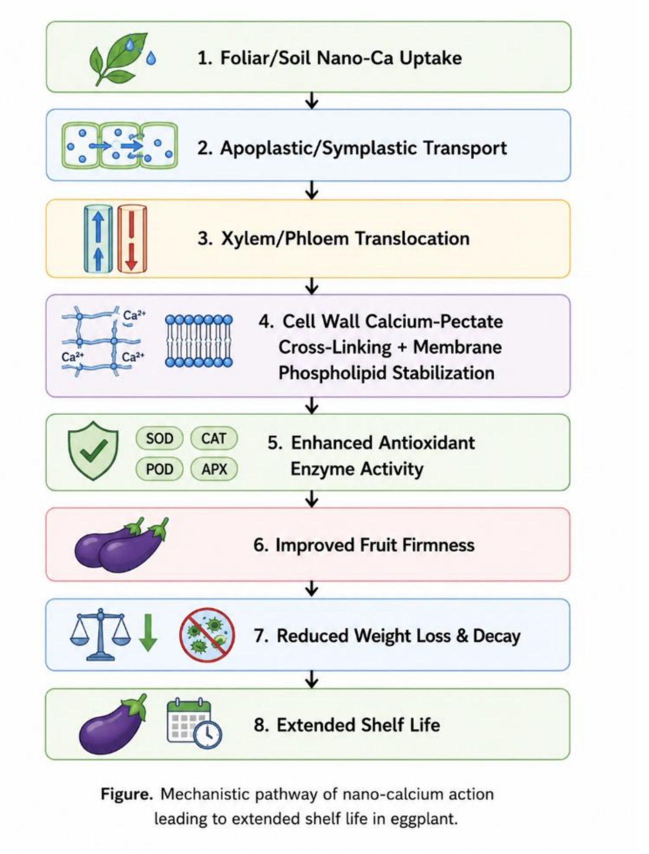

Fig 1: Proposed mechanism of nano-calcium-mediated enhancement of fruit shelf life in eggplant

4. Materials and Methods

4.1. Experimental Design

A field experiment was conducted at a research farm using a Randomized Complete Block Design (RCBD) comprising five treatments replicated four times, resulting in twenty experimental plots. Treatments included an untreated control, a conventional calcium chloride fertilizer application, and three concentrations (low, medium, high) of the synthesized nano-calcium formulation, applied through combined foliar and soil delivery routes at key phenological stages.

4.2. Plant Material and Growth Conditions

A locally adapted, high-yielding eggplant cultivar was used as the test materia*L*. Seedlings were raised in a nursery and transplanted at the four-to-five true-leaf stage into sandy-loam soil with a pH of 6.5–7.0, moderate organic matter content, and adequate drainage. Irrigation was managed through a drip system to maintain consistent soil moisture, and standard agronomic practices, including weed and pest management, were uniformly applied across all treatment plots to isolate the effects of calcium treatment.

4.3. Nano-Calcium Characterization

The synthesized nanoformulation was characterized using dynamic light scattering (DLS) for particle size distribution and zeta potential determination, scanning and transmission electron microscopy (SEM/TEM) for morphological assessment, X-ray diffraction (XRD) for crystallinity analysis, and Fourier-transform infrared spectroscopy (FTIR) for functional group identification. Mean particle size ranged between 45 and 80 nm, with a zeta potential of approximately +28 mV, indicating good colloidal stability.

4.4. Data Collection

Vegetative growth parameters (plant height, leaf area) and yield-related traits (fruit length, diameter, weight, total yield) were recorded at physiological maturity. Fruit quality parameters, including calcium content (atomic absorption spectroscopy), fruit firmness (penetrometer), total soluble solids (refractometry), titratable acidity, vitamin C (titrimetric method), total phenolics (Folin–Ciocalteu assay), and antioxidant activity (DPPH radical scavenging assay), were assessed. Postharvest shelf life, cumulative weight loss, and decay percentage were monitored under ambient storage conditions over a 14-day evaluation period.

4.5. Statistical Analysis

Data were subjected to one-way analysis of variance (ANOVA), and treatment means were separated using Tukey's Honestly Significant Difference (HSD) test at a significance level of $P < 0.05$. All statistical analyses were performed using GraphPad Prism software, with results expressed as mean ± standard deviation across four replications.

Table 2: Experimental design and treatment parameters.

Treatment	Ca Concentration	Application Method	No. of Applications	Growth Stage	Duration	Replications
T1 – Control	0 mg/L	None	0	—	Full cycle	4
T2 – Conventional $CaCl_2$	2000 mg/L	Foliar spray	3	Vegetative–fruiting	Full cycle	4
T3 – Nano-Ca (Low)	250 mg/L	Foliar + soil	3	Vegetative–fruiting	Full cycle	4
T4 – Nano-Ca (Medium)	500 mg/L	Foliar + soil	3	Vegetative–fruiting	Full cycle	4
T5 – Nano-Ca (High)	750 mg/L	Foliar + soil	3	Vegetative–fruiting	Full cycle	4

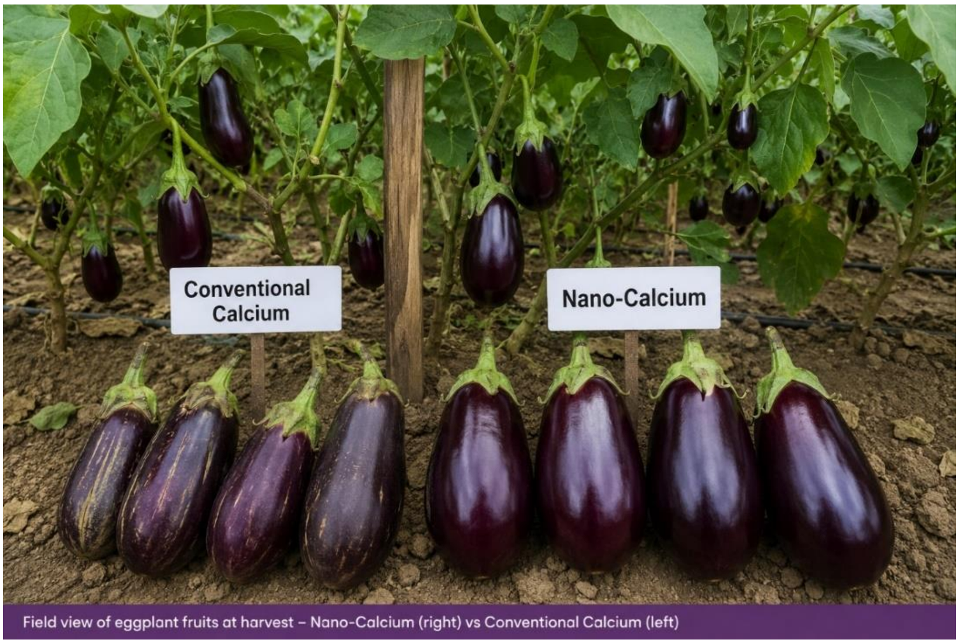

Fig 2: Field view of eggplant (*Solanum melongena L.*) fruits at physiological maturity under nano-calcium and conventional calcium treatments, illustrating differences in fruit size, skin gloss, and calyx condition at harvest.

5. Results and Performance Evaluation

Vegetative growth parameters improved progressively with increasing nano-calcium concentration. Plant height and leaf area under the high nano-calcium treatment (T5) were significantly greater than the control and conventional fertilizer treatments ($P < 0.05$), reflecting enhanced calcium-mediated cell wall extensibility and meristematic activity. Fruit yield followed a similar trend, with medium and high nano-calcium treatments producing 22–31% higher yield than the control and 12–18% higher yield than conventional calcium fertilization.

Fruit calcium content increased substantially under nano-calcium treatment, with T5 exhibiting nearly double the calcium concentration observed in control fruits, consistent with improved translocation efficiency of the nanoformulation. Fruit firmness, a key determinant of mechanical resistance to postharvest softening, was significantly higher in nano-calcium-treated fruits, corresponding closely with elevated tissue calcium levels. Total soluble solids and vitamin C content also increased significantly, indicating improved biochemical maturation and antioxidant capacity.

Shelf-life evaluation revealed that nano-calcium-treated fruits maintained marketable quality for significantly longer durations than control and conventionally fertilized fruits, with the high-concentration treatment extending shelf life by approximately 50–55%. Cumulative weight loss and decay percentage were correspondingly reduced, reflecting improved membrane integrity and reduced pathogen susceptibility. Antioxidant activity, assessed via DPPH radical scavenging capacity, was significantly enhanced in nano-calcium treatments, suggesting a strengthened enzymatic and non-enzymatic antioxidant defense system that mitigates oxidative damage during storage.

Table 3: Fruit quality and shelf-life performance across treatments.

Parameter	T1 Control	T2 Conventional Ca	T3 Nano-Ca Low	T4 Nano-Ca Medium	T5 Nano-Ca High
Firmness (N)	8.2 ± 0.4a	10.1 ± 0.5b	11.4 ± 0.6c	13.2 ± 0.5d	14.8 ± 0.6e
Ca content (mg/100 g)	18.5 ± 1.1a	26.3 ± 1.4b	31.2 ± 1.6c	38.7 ± 1.8d	45.1 ± 2.0e
TSS (°Brix)	4.1 ± 0.2a	4.6 ± 0.2b	4.9 ± 0.3bc	5.3 ± 0.2cd	5.6 ± 0.3d
Vitamin C (mg/100 g)	9.8 ± 0.5a	11.4 ± 0.6b	12.6 ± 0.6c	14.3 ± 0.7d	15.9 ± 0.8e
Weight loss (%, 14 d)	18.6 ± 1.0e	14.2 ± 0.9d	12.1 ± 0.8c	9.4 ± 0.6b	7.3 ± 0.5a
Shelf life (days)	6.5 ± 0.4a	8.2 ± 0.5b	9.1 ± 0.5c	10.4 ± 0.6d	11.8 ± 0.6e
Decay (%, 14 d)	34.5 ± 1.8e	24.6 ± 1.5d	20.3 ± 1.3c	14.7 ± 1.0b	10.2 ± 0.8a
Antioxidant activity (% DPPH inhibition)	42.1 ± 2.0a	48.9 ± 2.2b	53.4 ± 2.3c	59.6 ± 2.5d	65.2 ± 2.6e
Yield (t/ha)	22.4 ± 1.2a	25.1 ± 1.3b	26.8 ± 1.4bc	28.7 ± 1.5cd	29.6 ± 1.6d

Values represent mean ± standard deviation (n = 4). Different superscript letters within a row indicate statistically significant differences among treatments (Tukey's HSD, $P < 0.05$).

6. Discussion

The observed improvements in fruit firmness and calcium accumulation under nano-calcium treatment are mechanistically consistent with enhanced calcium translocation efficiency afforded by the nanoscale formulation. The chitosan-coated calcium carbonate nanoparticles likely facilitated superior cuticular penetration and controlled ionic release, enabling sustained calcium supply that supports progressive calcium-pectate cross-linking within the cell wall middle lamella throughout fruit development [24]. This mechanism directly explains the significant firmness retention and delayed softening observed relative to conventionally fertilized fruit.

Membrane stability, a critical determinant of postharvest weight loss and decay susceptibility, appeared markedly improved under nano-calcium treatment, as reflected in reduced weight loss and decay percentages. Calcium-mediated stabilization of phospholipid bilayers likely reduced membrane permeability and electrolyte leakage, thereby limiting water loss through transpiration and reducing vulnerability to fungal and bacterial colonization. The concurrent enhancement of antioxidant activity further suggests that nano-calcium application strengthens enzymatic defense systems, mitigating reactive oxygen species accumulation associated with postharvest senescence.

These findings align with previous reports of nano-fertilizer efficacy in other horticultural crops, where nanoscale delivery systems consistently outperformed conventional ionic fertilizers in terms of nutrient use efficiency and physiological response magnitude [25]. However, the present study extends this evidence specifically to *Solanum melongena L.* through an integrated pre-harvest foliar-soil application strategy, rather than relying solely on postharvest dip treatments, thereby demonstrating durable, systemic quality improvements originating from within the developing fruit tissue.

From a practical standpoint, nano-calcium formulations offer clear advantages for commercial eggplant production, including reduced application frequency, lower cumulative fertilizer input, and extended marketable shelf life, which collectively translate into reduced postharvest losses and improved economic returns for growers and distributors. Environmentally, the controlled-release characteristics of the nanoformulation minimize leaching-associated nutrient loss, aligning with sustainable nutrient management objectives.

Nevertheless, several limitations warrant consideration. Biosafety assessment of nanomaterial residues in edible fruit tissue remains an area requiring further investigation, particularly regarding chronic dietary exposure and environmental accumulation in soil microbiota. Economic feasibility at commercial scale depends on nanoparticle synthesis cost optimization, which currently exceeds that of conventional calcium salts. Future research should prioritize large-scale multi-location field trials, long-term soil ecological impact assessments, and comprehensive food safety evaluations to validate the commercial viability and regulatory acceptability of nano-calcium formulations in vegetable production systems.

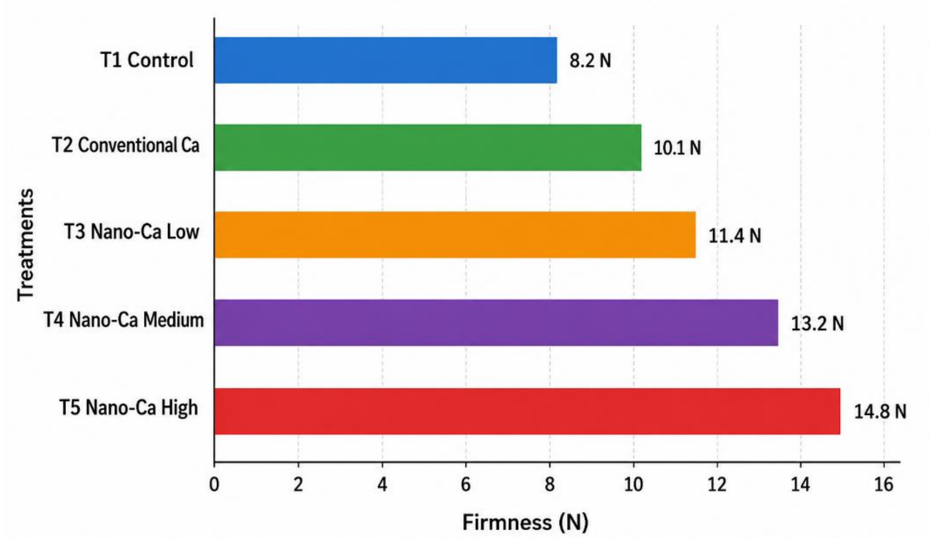

Fig 3: Comparative fruit firmness of eggplant under control, conventional calcium, and nano-calcium treatments (relative scale).

7. Conclusion

This study demonstrates that nano-calcium formulations significantly enhance vegetative growth, fruit yield, calcium accumulation, and biochemical quality of *Solanum melongena L.*, while substantially extending postharvest shelf life relative to conventional calcium fertilization. Improvements in fruit firmness and reductions in weight loss and decay incidence were attributed to calcium-mediated cell wall reinforcement and membrane stabilization, supported by enhanced antioxidant defense activity. These outcomes highlight nano-calcium formulations as a promising, resource-efficient alternative to conventional calcium fertilizers for sustainable horticultural nutrient management. Given the economic and environmental benefits demonstrated integration of nano-calcium delivery systems into commercial eggplant production merits serious consideration. Large-scale, multi-season field validation, alongside rigorous biosafety and cost-benefit analyses, is recommended before widespread agronomic adoption.

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