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Optimizing calcium application strategies to enhance fruit quality in tomato (*Lycopersicon esculentum* (L.) Mill)

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Abstract

This study investigates the effects of calcium application on tomato (*Lycopersicon esculentum* (L.) Mill) fruit quality, focusing on key physical and chemical attributes across vegetative and reproductive growth stages. Three calcium sources as Calnit (19% calcium), Winner (25% calcium with magnesium and boron), and Calmax (22.5% calcium) were applied as foliar sprays at early vegetative and reproductive stages. Results demonstrated that calcium supplementation enhanced fruit weight, circumference, firmness, total soluble solids (TSS), pH, vitamin C, and lycopene content, improving flavor, antioxidant levels, and shelf life. Winner, when applied at the beginning of the vegetative stage, significantly increased fruit weight to 26.88 ± 4.17 g, circumference to 16.68 ± 1.26 cm, and firmness to 3.94 ± 0.86 N/mm^2, while applications during the reproductive stage boosted TSS to 5.18 ± 0.33% and reduced Blossom End Rot (BER) incidence to 0.25 ± 0.50. Calmax, particularly effective for chemical properties, led to a higher pH (4.99 ± 0.10), vitamin C content (39.77 ± 1.78 mg/100 g), and lycopene concentration (0.94 ± 0.07 mg/100 g) when applied during the reproductive phase. These findings highlight the role of calcium in enhancing cellular integrity, supporting enzymatic activity, and facilitating nutrient transport, resulting in improved tomato growth, taste, and nutritional quality. This study underscores the importance of targeted calcium applications throughout growth stages for optimizing tomato fruit quality, offering valuable guidance for nutrient management practices in tomato cultivation.

Keywords: Calcium application; Tomato; Fruit quality; Physical properties; Chemical properties

1. Introduction

Tomato (*Lycopersicon esculentum* (L.) Mill), a member of the Solanaceae family, is one of the world's most widely consumed vegetables, following potatoes and sweet potatoes [1]. It is a critical food source globally, contributing significantly to both the fresh market and processed food industries [2]. The fruit is celebrated for its nutritional profile, rich in vitamin B, vitamin C, calcium, iron, protein, antioxidants, and carotenoids, which support human health by providing essential nutrients and contributing to the antioxidant defense system [3]. In Sri Lanka, tomatoes are grown across diverse agro-ecological zones, predominantly in districts such as Badulla, Nuwara-Eliya, and Kandy, with a total yield reaching 101,404 tons in 2018 and an average productivity of 15.11 tons per hectare [4,5].

Tomato plants exist in determinate and indeterminate forms, with determinate types, such as the popular hybrid variety Platinum F1, commonly cultivated for its high vigor and resistance to bacterial wilt and viral infections like tomato yellow leaf curl virus. This variety, with a potential yield of 25 tons per acre, demonstrates the significance of varietal selection for optimal production under diverse environmental conditions [6]. However, despite its robust growth and disease resistance, the quality and yield of tomato crops are highly susceptible to nutrient management practices. Calcium, a critical macronutrient, plays a pivotal role in maintaining tomato fruit quality, influencing cellular structure, and mitigating physiological disorders like blossom end rot [7]. Calcium deficiency, often exacerbated by poor nutrient

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management or competitive interactions with other soil cations such as potassium, can severely impair tomato fruit quality and yield.

Calcium application methods, either through soil or foliar means, significantly impact nutrient uptake efficiency. Soil applications, although common, often suffer from low efficiency due to nutrient fixation and various soil losses. In contrast, foliar application enables faster and more direct nutrient absorption, offering a rapid response to deficiency symptoms [8]. The primary calcium sources used in Sri Lankan agriculture, Calnit, Winner, and Calmax, differ in nutrient composition and solubility, with Calnit providing 19% calcium and 15.5% nitrogen, Winner containing 25% calcium and trace amounts of magnesium and boron, and Calmax delivering 22.5% calcium. These fertilizers, designed for efficient calcium delivery, are integral to sustaining crop quality and yield potential, especially for varieties like Platinum F1, which require targeted nutrient management for maximum productivity.

The global and local demand for tomatoes underscores the need for quality improvements in fruit production, as evidenced by Sri Lanka's 2018 statistics, where 14 tons of tomatoes were exported at a value of 2,231,000 Sri Lankan Rupees (LKR), while 5 tons were imported at a cost of 16,777,000 LKR, indicating a significant disparity in unit value potentially driven by quality variations [5]. In this context, calcium application strategies emerge as a critical factor in addressing both quality and yield gaps in tomato production.

This study aims to evaluate the effects of various calcium sources and application timings on tomato fruit quality, seeking to establish optimal practices for enhancing nutrient uptake, reducing physiological disorders, and ultimately improving the commercial value of tomato crops

2. Material and methods

2.1. Plant Material and Nursery Management

Tomato seeds of the hybrid variety Platinum F1 were obtained from government-certified farms and planted in plug trays. Standard nursery practices were maintained, including watering, pest control, and aftercare. After 25 days, hardened seedlings were transplanted into grow bags arranged according to the experimental layout.

2.2. Growing Medium and Baseline Soil Conditions

Each grow bag was filled with a mix of partially burned paddy husk and soil. Key parameters such as pH, electrical conductivity, nitrogen, phosphorus, and potassium levels were measured at the start and end of the experiment to monitor soil condition. The grow bags were spaced 60 × 60 cm^2 apart to ensure optimal growth and air circulation.

2.3. Calcium Application

Two experimental factors were tested in a factorial arrangement, focusing on calcium source and application timing. Calcium was applied through a foliar spray method to promote rapid absorption and uniform distribution:

2.3.1. Factor 1: Calcium Source

Four levels of calcium sources obtained from the market were evaluated to assess their effects on plant growth and fruit quality:

- **Ca1**: Calnit – A granular calcium nitrate fertilizer known for its balanced calcium and nitrogen content, but used it after dissolving in water.
- **Ca2**: Winner – A liquid calcium source enriched with trace amounts of magnesium and boron to potentially support additional plant functions.
- **Ca3**: Calmax – Another liquid calcium product with a high solubility, designed to be absorbed quickly through foliar application.
- **Ca0**: Control – A control treatment with no supplemental calcium application to assess baseline performance.

2.3.2. Factor 2: Timing of Calcium Application

Two levels of application timing were applied to explore the effect of early versus delayed calcium application:

- **L1**: Early application initiated one week after transplanting, with additional applications every 15 days to support early vegetative and reproductive growth.

- **L2**: Later application starting at the flowering stage, with subsequent applications every 15 days to primarily influence fruit development.

Calcium sources were applied as a 0.5% solution via foliar spraying until the entire plant was adequately wet, maximizing coverage. To optimize absorption, treatments were conducted early in the morning when stomatal activity was high, facilitating efficient calcium uptake.

2.4. Nutrient Supplementation

To provide essential nutrients for optimal growth, an Albert solution (Table 1) was applied to all tomato plants. Initially, the solution was applied at a rate of 0.5 g per plant and was gradually increased up to 1.5 g per plant over time to match the growing nutrient demands.

Table 1 Composition of Albert Solution

Nutrient	Amount
Nitrogen (%)	11.5
Phosphorus (%)	9.2
Potassium (%)	16.2
Calcium (%)	13.1
Copper (mg/ kg)	35
Zinc (mg/ kg)	140
Iron (mg/ kg)	630
Manganese (mg/ kg)	130
Boron (mg/ kg)	35
Molybdenum (mg/ kg)	20

2.5. Plant Training and Support System

Two weeks after transplanting, a crop support system was established to facilitate vertical growth and prevent lodging. Vertical strings were used to support the tomato plants, which were trained along these strings to promote upright growth.

2.6. Data Collection

Data collection commenced immediately after treatment application, with detailed measurements taken for the following parameters to evaluate fruit quality and plant health:

2.6.1. Average Weight of a Fruit

The average fruit weight was recorded at the immature fruit stage using an electronic balance, ensuring precise and consistent measurements across all treatments.

2.6.2. Average Circumference of Fruit

The equatorial circumference of each fruit was measured using a measuring tape, providing an indicator of fruit size and uniformity.

2.6.3. Fruit Hardness

Fruit firmness, a critical quality attribute, was measured using a Texture Analyzer (Model: CT3 4500). A probe was gently inserted into the equatorial region of each fruit to record firmness, with higher firmness values typically indicating better fruit quality.

2.6.4. pH Value

The pH of the fruit was determined at the immature stage using a portable pH meter (Model: HQ40d). Tomato samples were blended to create a homogenized sample, from which the pH reading was taken to assess acidity levels.

2.6.5. Total Soluble Solids Content

The concentration of soluble solids, indicative of fruit sweetness, was measured using a handheld refractometer (ATAGO N-IE Brix ~32%) on immature fruits, providing an early indication of potential taste quality.

2.6.6. Vitamin C Content

Vitamin C content was measured using redox titration, following the method of Ranganna (1986). In this method, 2,6-dichlorophenol-indophenol was used as an oxidizing agent in an acid medium to convert ascorbic acid to dehydroascorbic acid.

2.6.7. Lycopene Content

Lycopene, a key antioxidant, was quantified using a spectrophotometer (GENESYS 10S UV-Vis, USA), allowing for an objective assessment of this important nutritional component.

2.6.8. Blossom End Rot Incidence

To evaluate the impact of calcium on reducing physiological disorders, the incidence of blossom end rot was assessed by counting affected fruits at seven-day intervals following fruit set.

2.7. Experimental Design

A Completely Randomized Design (CRD) with six treatment combinations and a control was used. Each treatment had four replicates, with two pots per replicate, allowing for precise comparisons across treatments.

2.8. Data Analysis

Data were analyzed using Analysis of Variance (ANOVA) through the Statistical Analysis System (SAS) software package. This analysis allowed for the determination of significant differences among treatments, with mean comparisons made using Duncan's Multiple Range Test (DMRT) at a significance level of $p \leq 0.05$.

3. Results and discussion

The results of experiments conducted to evaluate the effects of applying different levels of calcium at various stages of tomato plant growth, specifically during the vegetative and reproductive phases, are presented in Table 2 and Table 3. Table 2 illustrates how calcium application impacts the physical properties of tomato fruits.

Table 2 Effects of calcium application on physical properties of tomato fruits

Treatment	Weight of the fruit (g)		Fruit circumference (cm)		Fruit firmness (N/mm^2)		Total Soluble Solids (TSS) (%)		Number of fruits with Blossom End Rot (BER)	
Control[1]	17.53 ± 1.50	d[5]	9.95 ± 1.96	b	0.89 ± 0.40	e	4.07 ± 0.30	c	11.75 ± 2.50	a
Calinet[2] in L1	20.85 ± 0.78	cd	11.08 ± 0.95	b	1.66 ± 0.50	cd	4.13 ± 0.16	c	9.00 ± 3.37	ab
Calinet in L2	21.80 ± 1.09	bc	10.81 ± 2.39	b	1.89 ± 0.30	bcd	4.69 ± 0.09	b	9.00 ± 0.82	ab
Calmax[3] in L1	22.80 ± 0.97	bc	14.92 ± 1.16	a	2.61 ± 0.35	b	4.19 ± 0.24	c	8.75 ± 1.71	ab
Calmax in L2	20.95 ± 2.30	cd	10.59 ± 1.41	b	1.32 ± 0.32	de	4.68 ± 0.09	b	7.25 ± 5.12	ab
Winner[4] in L1	26.88 ± 4.17	a	16.68 ± 1.26	a	3.94 ± 0.86	a	4.39 ± 0.49	bc	4.75 ± 3.40	b
Winner in L2	25.35 ± 3.20	ab	10.53 ± 0.63	b	2.29 ± 0.46	bc	5.18 ± 0.33	a	0.25 ± 0.50	c

[1]. No calcium was used. [2]. Calnit contains 19% calcium and 15.5% nitrogen. [3]. Calmax contains 22.5% calcium. [4]. Winner contains 25% calcium and trace amounts of magnesium and boron. [5]. Means followed by the same small letters in the same column are not significantly different at 5% level in Duncan's Multiple Range Test. L1: Early application initiated one week after transplanting, with additional applications every 15 days. L2: Later application starting at the flowering stage, with subsequent applications every 15 days.

In the experiment, several parameters were considered to assess the physical properties of tomato fruits, including fruit weight, circumference, firmness, total soluble solids (TSS), and the number of fruits affected by Blossom End Rot (BER). Table 2 clearly illustrates the impact of calcium application on these properties. Although increasing calcium levels did not significantly affect fruit weight, the product "Winner," containing 25% calcium along with trace amounts of magnesium and boron, achieved the highest weight (26.88 ± 4.17 g) when applied from the beginning of the growing cycle at 15-day intervals. This was followed by a slightly lower weight (25.35 ± 3.20 g) when applied from the flowering stage. The effect of calcium on fruit circumference was also not significantly impacted by the level of calcium used, but the highest circumference (16.68 ± 1.26 cm) was achieved with early application of Winner. Research shows that calcium promotes fruit weight and size by strengthening cellular integrity, leading to uniform growth and moisture retention. For example, calcium foliar applications increased fruit weight by promoting cell expansion and water retention in tomatoes [9]. Similarly, calcium-treated tomatoes showed increased diameter and weight due to calcium's effect on cellular structure [10].

Fruit firmness was significantly higher at $P \leq 0.05$ (3.94 ± 0.86 N/mm^2) when Winner was applied from early stages. Firmness, a key quality indicator, is heavily influenced by calcium, which strengthens cell walls by stabilizing pectin within the fruit's structure. Adequate calcium prevents cell wall degradation, thereby maintaining firmness during maturation and storage [9]. Studies on calcium-treated apple fruits also showed improved firmness, indicating similar benefits for tomatoes [11]. Additionally, foliar calcium applications in tomatoes have been shown to enhance peel firmness, reducing susceptibility to cracking and other mechanical damage [12].

In contrast, an increase in TSS and a reduction in BER were observed when Winner was applied during the reproductive phase, with TSS reaching 5.18 ± 0.33% and BER incidence significantly decreasing to 0.25 ± 0.50 at $P \leq 0.05$. This indicates that Winner, with its 25% calcium content, enhances fruit weight, circumference, and firmness when applied from the vegetative phase, and improves TSS levels and reduces BER incidence when applied at the reproductive phase. Calcium is crucial in improving tomato fruit quality, including weight, circumference, firmness, TSS, and minimizing BER. TSS, an important factor for flavor and market value, is enhanced by calcium applications, likely due to improved nutrient transport within the fruit and increased sugar accumulation [10]. Similarly, calcium treatment has been shown to increase TSS in bell peppers, suggesting wider applicability across related crops [13].

BER is a common physiological disorder in tomatoes often caused by calcium deficiency. Research confirms that calcium application significantly reduces BER by ensuring sufficient calcium distribution within the fruit, preventing cell breakdown at the blossom end [14]. Furthermore, calcium improves cellular cohesion, reducing tissue collapse in sensitive areas [15]. The findings from our experiment align with these previous studies, highlighting calcium's essential role in maintaining cell wall structure and membrane stability, which contribute to improved fruit firmness and resistance to physiological disorders.

This suggests that calcium is needed from the start of vegetative growth to support fruit development, enhancing fruit growth and the thickness and firmness of the pericarp. Calcium deposits in the plant help increase the weight, circumference, and firmness of tomatoes. Additionally, rapid calcium supplementation is crucial for boosting TSS levels and reducing the incidence of BER.

Table 3 Effects of calcium application on chemical properties of tomato fruits

Treatment	**Fruit pH**		**Vitamin C content (mg/ 100g)**		**Lycopene content (mg/ 100g)**	
Control [1]	4.39 ± 0.38	Bc[5]	11.37 ± 1.10	e	0.28 ± 0.04	f
Calinet[2] in L1	4.57 ± 0.35	ab	27.87 ± 6.84	bc	0.37 ± 0.04	ef
Calinet in L2	4.05 ± 0.13	c	26.91 ± 2.37	c	0.40 ± 0.07	de
Calmax[3] in L1	4.78 ± 0.36	ab	32.90 ± 3.95	b	0.67 ± 0.13	b
Calmax in L2	4.99 ± 0.10	a	39.77 ± 1.78	a	0.94 ± 0.07	a
Winner[4] in L1	4.48 ± 0.42	bc	22.40 ± 4.36	cd	0.49 ± 0.02	cd
Winner in L2	4.09 ± 0.17	c	20.25 ± 0.60	d	0.52 ± 0.03	c

[1]. No calcium was used. [2]. Calnit contains 19% calcium and 15.5% nitrogen. [3]. Calmax contains 22.5% calcium. [4]. Winner contains 25% calcium and trace amounts of magnesium and boron. [5]. Means followed by the same small letters in the same column are not significantly different at 5% level in Duncan's Multiple Range Test. L1: Early application initiated one week after transplanting, with additional applications every 15 days. L2: Later application starting at the flowering stage, with subsequent applications every 15 days

Table 3 presents the effects of calcium application at different stages of tomato growth, specifically, the vegetative and reproductive phases. It highlights how fruit pH, vitamin C content, and lycopene content vary with increased levels of calcium in foliar applications.

In contrast to the improvements in physical properties achieved with Winner (containing 25% calcium), Calmax, which contains 22.5% calcium, was observed to enhance chemical properties such as fruit pH, vitamin C content, and lycopene content more effectively. Specifically, Calmax applied during the reproductive stage reduced fruit acidity significantly, resulting in a pH of 4.99 ± 0.10, with the second lowest acidity observed when Calmax was applied from the start of the vegetative phase (pH 4.78 ± 0.36). These findings suggest that calcium application influences the pH levels of tomato fruits. By stabilizing cell membranes and reducing cell degradation, calcium helps maintain a balanced pH, positively affecting taste and preservation. Tomatoes treated with calcium exhibited more stable pH levels than untreated fruits, which supports acidity levels that enhance flavor and inhibit microbial growth [16].

Moreover, vitamin C content was significantly higher when Calmax was applied during the reproductive stage (39.77 ± 1.78 mg/100 g) at $P \leq 0.05$, followed by a value of 32.90 ± 3.95 mg/100 g when applied from the vegetative growth phase, though this difference was not significant at $P \leq 0.05$. Vitamin C, a key antioxidant in tomatoes, benefits indirectly from calcium, which helps reduce oxidative stress in plant cells. Research has demonstrated that calcium treatments enhance vitamin C levels in tomatoes by protecting cell structure and promoting efficient nutrient uptake [16]. Similarly, studies on strawberries and bell peppers have shown that calcium increases ascorbic acid synthesis by stabilizing enzyme systems [17].

Lycopene, an essential carotenoid in tomatoes responsible for their antioxidant properties and red color, also increased significantly with a 22.5% calcium foliar application at $P \leq 0.05$. The highest lycopene content was recorded with Calmax application during the reproductive stage (0.94 ± 0.07 mg/100 g), and the second highest when applied from the start of the vegetative phase (0.67 ± 0.13 mg/100 g). Calcium enhances lycopene concentration by stabilizing cellular structures and promoting the activity of enzymes involved in carotenoid synthesis [18]. It has been reported that increased calcium availability in tomatoes supports lycopene levels, which is attributed to improved nutrient allocation towards fruit development and pigmentation pathways [17].

Our experiment also highlights that rapid calcium supplementation during the development stages is crucial for enhancing tomato fruit chemical properties, though continuous calcium application from the vegetative phase also has beneficial effects.

As a whole, calcium plays a vital role in improving key quality parameters in tomatoes, including pH, vitamin C (ascorbic acid) content, and lycopene levels. Previous research underscores the importance of calcium in regulating fruit acidity, boosting antioxidant levels, and stabilizing cell walls, all of which contribute to improved fruit quality and extended shelf life.

4. Conclusion

The experiment underscores the essential role of calcium in enhancing both physical and chemical qualities of tomato fruits, with targeted application yielding optimal results. Calcium applied as the product "Winner" during the vegetative phase improved fruit weight, circumference, and firmness, while applications during the reproductive phase enhanced total soluble solids (TSS) and reduced Blossom End Rot (BER), which are vital for flavor and disease resistance. The product "Calmax" effectively boosted chemical properties like pH, Vitamin C, and lycopene content, particularly when applied during the reproductive phase. These results highlight calcium's importance in maintaining cellular integrity, stabilizing pH, reducing oxidative stress, and promoting nutrient allocation, thereby supporting growth, taste, and nutritional quality in tomato fruits.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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