PLANT SCIENCE TODAY
Vol 12(sp4): 01–12
https://doi.org/10.14719/pst.12009

eISSN 2348-1900

RESEARCH ARTICLE

Formulation of calcium-based nutrition for mitigating bacterial wilt (*Ralstonia solanacearum*) in tomato

S Gowtham[1*], D V Naveen[1], M Mahesh[2], V Venkatatachalapathi[3] & P Veeranagappa[4]

[1]Department of Soil Science and Agricultural Chemistry, University of Agricultural Sciences, Bangalore 560 065, Karnataka, India
[2]Department of Plant Pathology, College of Sericulture, Chintamani 563 125, Karnataka, India
[3]College of Sericulture, Chintamani 563 125, Karnataka, India
[4]ICAR - Krishi Vigyan Kendra, Doddaaballapura, University of Agricultural Sciences, Bangalore 560 065, Karnataka, India

*Correspondence email - gowthamsppb@gmail.com

Received: 26 September 2025; Accepted: 25 November 2025; Available online: Version 1.0: 12 December 2025

Cite this article: Gowtham S, Naveen DV, Mahesh M, Venkatatachalapathi V, Veeranagappa P. Formulation of calcium-based nutrition for mitigating bacterial wilt (*Ralstonia solanacearum*) in tomato. Plant Science Today. 2025;12(sp4):01–12. https://doi.org/10.14719/pst.12009

Abstract

Bacterial wilt, caused by *Ralstonia solanacearum,* is a major constraint in tomato (*Solanum lycopersicum* L.) production, especially in tropical and subtropical regions where favourable soil and climatic conditions support pathogen survival and spread. Conventional management practices have shown limited effectiveness, emphasizing the need for sustainable alternatives. Calcium is an essential nutrient that strengthens cell walls, stabilizes membranes and enhances plant defenses against soil-borne pathogens. This study evaluated calcium-based nutrient formulations for their effectiveness in suppressing bacterial wilt and improving tomato growth and fruit quality as part of a sustainable disease management strategy. *In vitro* assays using a virulent *R. solanacearum* isolate from the Eastern Dry Zone of Karnataka showed strong antagonistic activity, producing inhibition zones of 26.00–29.30 mm after 48 hr. The most effective formulation was further tested in a pot experiment arranged in a completely randomized design with six treatments and four replications, using two tomato varieties: Baaho (wilt-susceptible) and Abhinava (wilt-resistant). The calcium-enriched formulation containing calcium, magnesium, sulfur and potassium significantly improved plant growth, yield and fruit quality in wilt-susceptible Baaho while delaying wilt onset up to 60 days after transplanting. At harvest, calcium-based nutrition to plants recorded a height of 84.61 cm, chlorophyll content of 34.52 (SPAD), 42 fruits plant^{-1}, fruit weight of 71.49 g, diameter of 4.14 cm, firmness of 1.44 kg cm^{-2} and a shelf life of 10.75 days. Abhinava remained resistant and performed better across all treatments. These results demonstrate that calcium-enriched nutrient formulations can effectively suppress bacterial wilt while enhancing yield and fruit quality in tomato.

Keywords: bacterial wilt; calcium-based nutrition; disease mitigation; *Ralstonia solanacearum*; tomato

Introduction

Tomato (*Solanum lycopersicum* L.), a member of the family Solanaceae, is one of the most widely cultivated and consumed vegetable crops worldwide, valued for its nutritional, economic and industrial importance. It is a rich source of lycopene, β-carotene, vitamins A and C and essential minerals, contributing significantly to human health and nutrition. In 2021-22, India produced approximately 20300 tons of tomatoes from 840 thousand hectares, contributing 9.63 % to the nation's total vegetable production. Globally, India ranks second in both area and production after China. However, continuous tomato cultivation with intensive cultivation practices has led to the depletion of soil microbial diversity and the proliferation of soil-borne pathogens, which severely limit productivity (1). Among these, bacterial wilt caused by *Ralstonia solanacearum* is regarded as one of the most destructive diseases of solanaceous crops, ranking as the second most devastating bacterial plant disease globally (2). The pathogen survives in soil, irrigation water, crop residues and alternate weed hosts, making its management particularly challenging (3). Despite the use of resistant cultivars, crop rotation, organic amendments and chemical control, management of *R. solanacearum* remains inconsistent due to its wide host range, high genetic variability and persistence in diverse environments (4, 5). Hence, sustainable and integrated management strategies that enhance host resistance and soil health are essential for long-term disease suppression.

Nutrient management plays a vital role in regulating plant growth, physiology and defence responses (6, 7). Among essential nutrients, calcium (Ca) is fundamental to structural integrity and biochemical defence. It stabilizes cell walls and membranes, activates defence-related enzymes and functions as a secondary messenger in signalling pathways (8, 9). Calcium also regulates reactive oxygen species (ROS) during stress responses and strengthens pectin cross-linking in the middle lamella, restricting pathogen invasion (10). Enhanced Ca uptake has been associated with reduced *R. solanacearum* colonization and improved vascular resistance in tomato (11). In addition, it contributes to fruit firmness, nutrient uptake and postharvest quality (12, 13).

In addition to calcium (Ca), magnesium (Mg), sulphur (S) and potassium (K) play complementary roles in plant growth, physiology and defence. Magnesium, being the central atom of the chlorophyll

molecule, is indispensable for photosynthesis, enzyme activation and carbohydrate metabolism; adequate Mg improves chlorophyll content and photosynthetic efficiency which increases plant resilience to stress (14, 15). Sulphur is crucial for the synthesis of amino acids, vitamins and defence-related compounds such as glucosinolates and phytoalexins, thereby enhancing resistance to soil-borne pathogens (16). Potassium regulates osmotic balance, enzyme activity and photosynthate translocation, leading to improved cell turgor, fruit quality and disease resistance (17, 18).

Therefore, a balanced supply of Ca, Mg, S and K creates a synergistic nutrient environment that strengthens plant physiology, promotes growth and suppresses pathogen development. Despite these established functions, the integrated influence of calcium-based multi-nutrient formulations on *R. solanacearum* suppression, soil properties and tomato performance remains poorly understood under tropical red soil conditions. Therefore, the present study was undertaken to evaluate the antagonistic activity of calcium nutrition against *R. solanacearum* under in vitro conditions and to determine the appropriate calcium dosage and its interaction with Mg, S and K on soil fertility, plant growth, yield and disease suppression under pot culture conditions.

Materials and Methods

Collection of samples

Soil samples and wilted tomato plants exhibiting typical bacterial wilt symptoms were collected from five naturally infected farmers' fields located in Madanahalli village of Kolar district, situated in the Eastern Dry Zone of Karnataka, India (13°17′30″ N, 78°04′25.35″ E). Ten composite soil samples and 10 symptomatic plant samples were collected and coded as P_1-P_{10}, representing different sampling sites within the fields. Samples were transported to the laboratory in sterile polythene bags under aseptic conditions for further isolation and identification of *R. solanacearum*.

Isolation of *Ralstonia solanacearum*

Isolation from infected plant tissue was carried out following the ooze test. Infected vascular tissues were macerated and streaked onto nutrient agar plates. After incubation at 28 ± 1 °C for 48 hr, typical colonies of *R. solanacearum* appeared as irregular, fluidal and milky white (Fig. 1). Wilted tomato stems were then cut longitudinally and bacterial streaming was observed as milky-white ooze from the vascular tissues when suspended in sterile water (Fig. 2A). The procedure followed was as described by (19).

Gram staining

Gram staining was performed according to the standard protocol. A loopful of bacterial suspension was heat-fixed on a clean glass slide, stained with 0.5 % crystal violet for 30 sec, treated with Gram's iodine for 1 min, decolorized with 95 % ethanol, counterstained with 0.5 % safranin for 30 sec, rinsed with sterile distilled water and air-dried. The slides were observed under a compound microscope at 1000 × magnification. *R. solanacearum* was confirmed as a Gram-negative bacterium showing red-coloured cells (20) (Fig. 2B).

Confirmation using TZC medium

Pathogen identity was further confirmed on triphenyl tetrazolium chloride (TZC) medium. The medium contained peptone (10 g), dextrose (5 g), casein hydrolysate (1 g), agar (20 g) and distilled water (1 L), with 1 mL of 1 % TZC solution added per 200 mL of medium

Fig. 1. Isolation of *Ralstonia solanacearum.*

before pouring into Petri plates. After inoculation with 50 µL of a 24 hr old culture, the plates were incubated at 28 ± 1 °C for 48 hr. Typical colonies with irregular fluidal margins and pink centres confirmed *R. solanacearum* (19) (Fig. 2C).

In vitro antibacterial assay of calcium

The antibacterial activity of calcium was evaluated using the disc diffusion method. Sterile Waksman filter paper discs (6 mm) were placed on TZC agar plates pre-inoculated with 50 µL of 24 hr old bacterial suspension. Each disc was treated with 20 µL of calcium solution at concentrations of 0, 500, 1000, 2500, 5000 and 7500 ppm. The plates were incubated at 28 ± 1 °C for 48 hr. The inhibition zones around each disc were measured in millimetres, indicating antibacterial activity (21).

Preparation of bacterial inoculum

A virulent strain of *R. solanacearum* was cultured in nutrient broth. After autoclaving, a single colony was inoculated into sterile broth and incubated at 28 ± 1 °C on a rotary shaker (120 rpm) for 24-48 hr. The actively growing suspension (10^7 cfu mL^{-1}) was used for pot inoculations (22).

Pot culture experiment

A pot culture experiment was conducted under greenhouse conditions at the College of Sericulture, Chintamani, Karnataka, following a completely randomized design (CRD) with six treatments and four replications in two tomato varieties: Baaho (wilt-susceptible) and Abhinava (wilt-resistant). Plastic pots (26 cm diameter) were filled with 10 kg of red sandy loam soil, which was analysed for physico-chemical properties following the standard procedures (23). The initial soil data are presented in Table 1.

Healthy seedlings were transplanted into the pots and calcium formulations (Ca_1, Ca_2, Ca_3 and Ca_4) were applied in split doses according to the treatment schedule outlined in Table 2. The first split dose of the respective calcium formulations was applied one week after transplanting and the second split dose was applied at 35 days after transplanting (DAT). At 30 DAT, plants were inoculated with *R. solanacearum* by wounding the roots and drenching each pot with 15 mL of bacterial suspension (10^7 cfu mL^{-1}) to simulate natural infection. Pots were maintained at field capacity moisture throughout the experimental period.

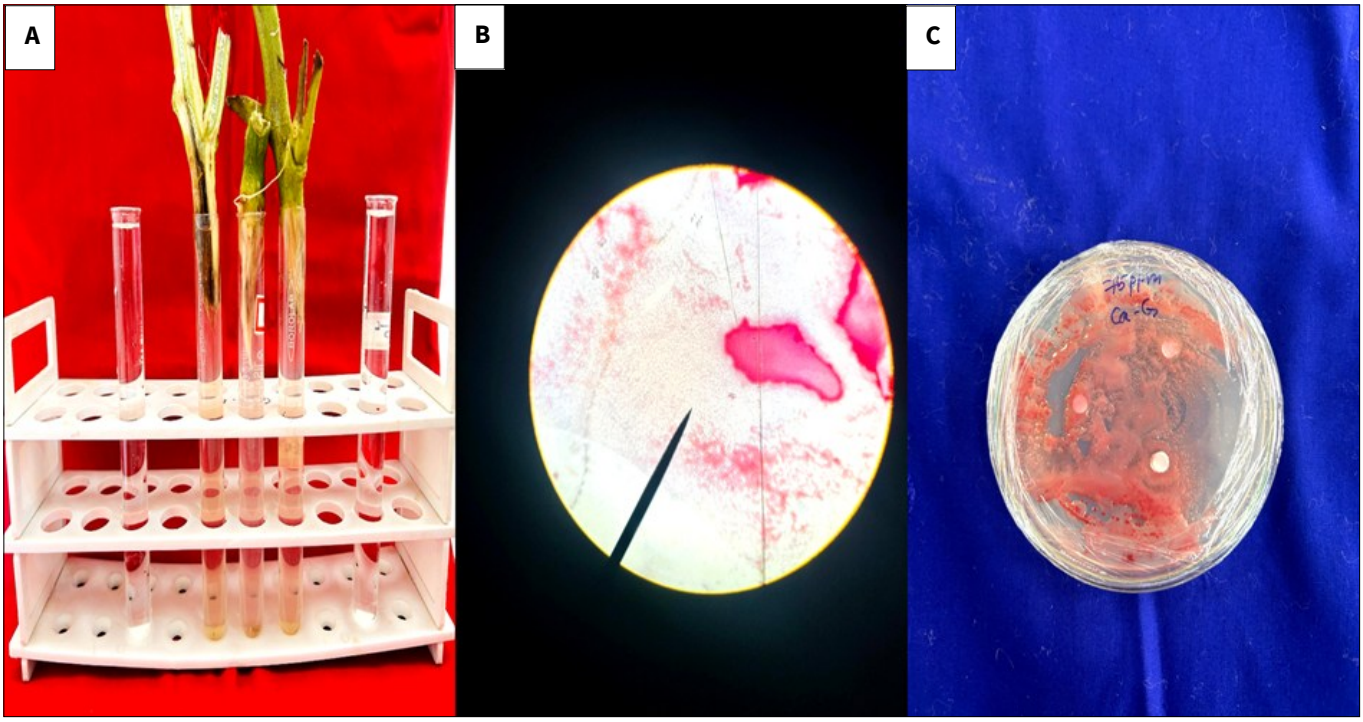

Fig. 2. Confirmation of *Ralstonia solanacearum* through diagnostic tests: (A) Ooze test showing bacterial streaming from cut stem segments, (B) Gram staining revealing Gram-negative rod-shaped cells under microscope and (C) characteristic fluidal, irregular colonies with pink centre's on TZC medium.

Table 1. Physico-chemical properties of the initial soil sample

Soil parameter	Value	Interference
Sand (%)	70.2	-
Silt (%)	11.6	-
Clay (%)	18.2	-
Texture (class)	Sandy loam	-
BD (g/cm^3)	1.48	-
Soil Ph	6.23	Slightly acidic
EC (dS m^{-1})	0.76	Medium
Organic carbon (%)	0.47	Low
Available N (kg ha^{-1})	238.61	Low
Available P (kg ha^{-1})	37.33	Medium
Available K (kg ha^{-1})	175.39	Medium
Exchangeable Ca (cmol (P$^+$) kg^{-1})	2.32	Sufficient
Exchangeable Mg (cmol (P$^+$) kg^{-1})	1.27	Sufficient
Available S (mg kg^{-1})	6.04	Low

Table 2. Treatment details of the greenhouse experiment to evaluate against bacterial wilt

Treatments	Treatment details
T_1	Absolute control
T_2	100 per cent RDF
T_3	T_2 + Ca_1 (only calcium nutrition formulation)
T_4	T_2 + Ca_2 (calcium and magnesium nutrition formulation)
T_5	T_2 + Ca_3 (calcium, magnesium and sulphur nutrition formulation)
T_6	T_2 + Ca_4 (calcium, magnesium, sulphur and potassium nutrition formulation)
Ca_1, Ca_2, Ca_3 and Ca_4 application: Split doses applied at 15 days after transplanting (DAT) and 35 (DAT)	

Note:

250: 250: 250 N, P_2O_5, K_2O/ha and FYM 38 t/ha are added.

- Ca_1 (lime)
- Ca_2 (lime and magnesium sulphate)
- Ca_3 (gypsum and magnesium sulphate)
- Ca_4 (Gypsum, Magnesium Sulphate and Muriate of Potash)

Disease assessment

Wilt incidence and severity were recorded at 60 DAT using the 0-5 wilt rating scale , where 0 = healthy, 1 = chlorosis, 2 = 1/3 wilted, 3 = 2/3 wilted, 4 = whole plant wilted and 5 = plant dead (24).

Statistical analysis

Data were analyzed by ANOVA under a completely randomized design (CRD) using OPSTAT (25). Treatment means were separated using Tukey's HSD test at $p \leq 0.05$.

Results and Discussion

Effect of calcium on *Ralstonia solanacearum* under *in vitro*

Calcium significantly suppressed the growth of *R. solanacearum* under *in vitro* (Table 3). All tested calcium concentrations (500, 1000, 2500, 5000 and 7500 ppm) produced significantly larger inhibition zones (26.0-29.3 mm) compared with the control (no inhibition), with the inhibitory effect increasing slightly with concentration (Fig. 3). These results demonstrate a clear dose-dependent suppression of the pathogen. The suppressive effect of calcium (Ca^{2+}) on *R. solanacearum* can be attributed to its direct action on bacterial physiology, as $CaCl_2$ markedly inhibited growth, biofilm formation and motility even at 5 mM, whereas Cl^- alone exerted only marginal effects. This indicates that the antibacterial activity is specifically associated with Ca^{2+}, most likely through disruption of cell envelope stability, interference with quorum sensing and impairment of motility, thereby highlighting the potential of calcium-based amendments as an eco-friendly strategy for bacterial wilt management (26, 27).

Effect of calcium formulations on bacterial wilt incidence

Significant variation in bacterial wilt incidence was observed among calcium formulation treatments at 60 DAT (Fig. 4, 5). In wilt-susceptible variety Baaho, the highest wilt severity (score 4) was recorded in T_1 (control), while complete suppression of the disease was achieved in T_6 (T_2 + Ca_4: RDF + FYM + calcium, magnesium, sulphur and potassium nutrition formulation). Intermediate levels of wilt reduction were observed in T_3(T_2+ Ca_1: only calcium nutrition formulation), T_4 (T_2 + Ca_2: calcium and magnesium nutrition formulation) and T_5 (T_2 + Ca_3: calcium, Magnesium and sulphur nutrition formulation).

In contrast, Abhinava (wilt-resistant) exhibited complete resistance to bacterial wilt across all treatments. The reduction in bacterial wilt severity under calcium nutrition can be attributed to enhanced uptake of Ca^{2+}, which strengthens cell walls, stabilizes vascular tissues and activates defence-related enzymes. At the molecular level, calcium acts as a secondary messenger in signal transduction pathways that trigger defence gene expression through the activation of calcium-dependent protein kinases. These cascades promote lignin and callose deposition in xylem vessels, physically restricting *R. solanacearum* colonization (28, 29).

Calcium signalling also modulates reactive oxygen species production, maintaining redox homeostasis and inducing oxidative bursts that inhibit pathogen growth (30). Furthermore, calcium

Table 3. Effect of calcium on the diameter of the inhibition zone of *Ralstonia solanacearum*

Characters	Calcium concentration (ppm)							
	0	**500**	**1000**	**2500**	**5000**	**7500**	**Sem**	**0.13**
Inhibition zone	0	26	27	27.7	28	29.3	**CD 1 %**	**0.55**

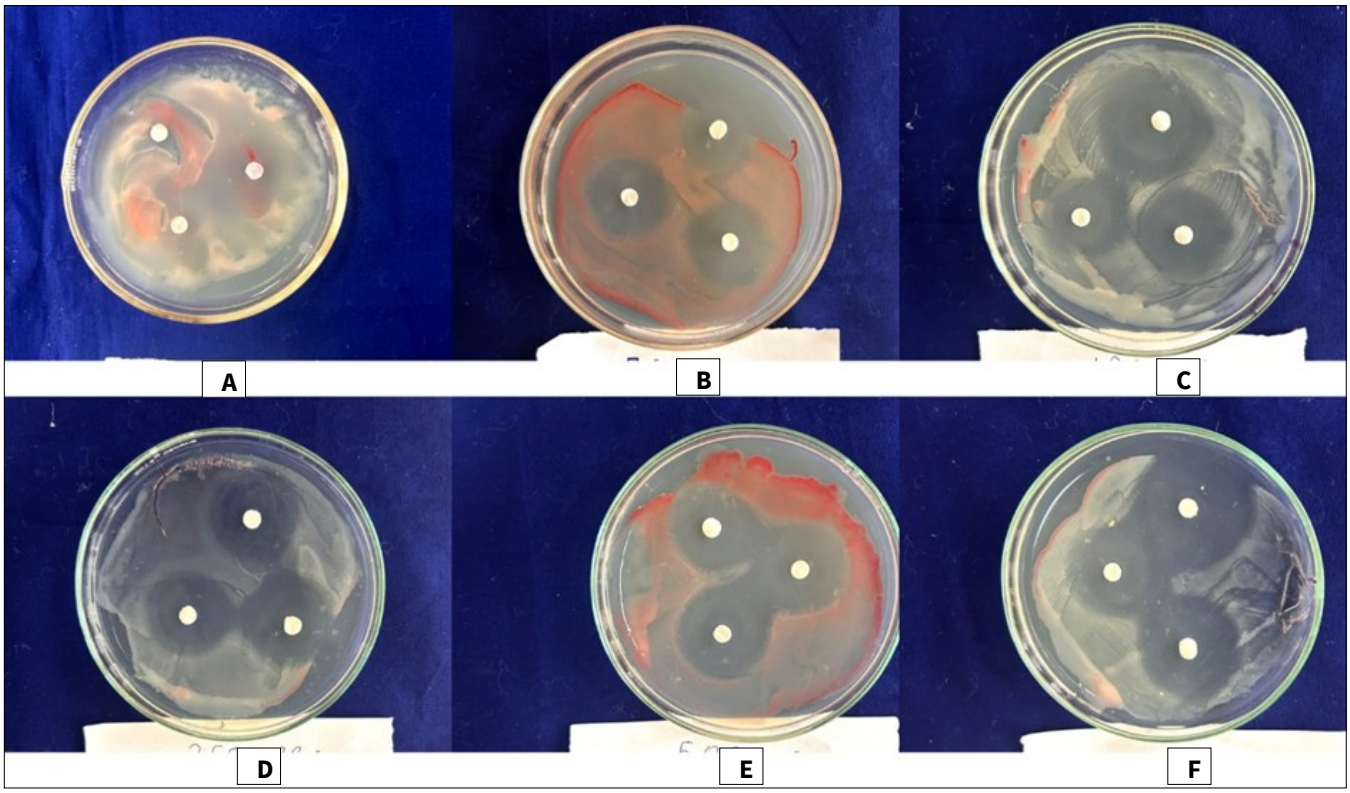

Fig. 3. Effect of calcium on *Ralstonia solanacearum* under *in vitro* conditions. (A) Control (no calcium), (B) 500 ppm, (C) 1000 ppm, (D) 2500 ppm, (E) 5000 ppm and (F) 7500 ppm concentrations. Increasing concentrations of calcium inhibited bacterial growth, as indicated by the larger clear zones around the discs.

Fig. 4. Effect of calcium formulations on bacterial wilt incidence in *Baaho* (wilt-susceptible) and *Abhinava* (wilt-resistant) tomato varieties at 60 days after transplanting (DAT). (A) *Baaho* showing severe wilting symptoms and (B) *Abhinava* exhibiting healthy growth and resistance to *Ralstonia solanacearum* infection.

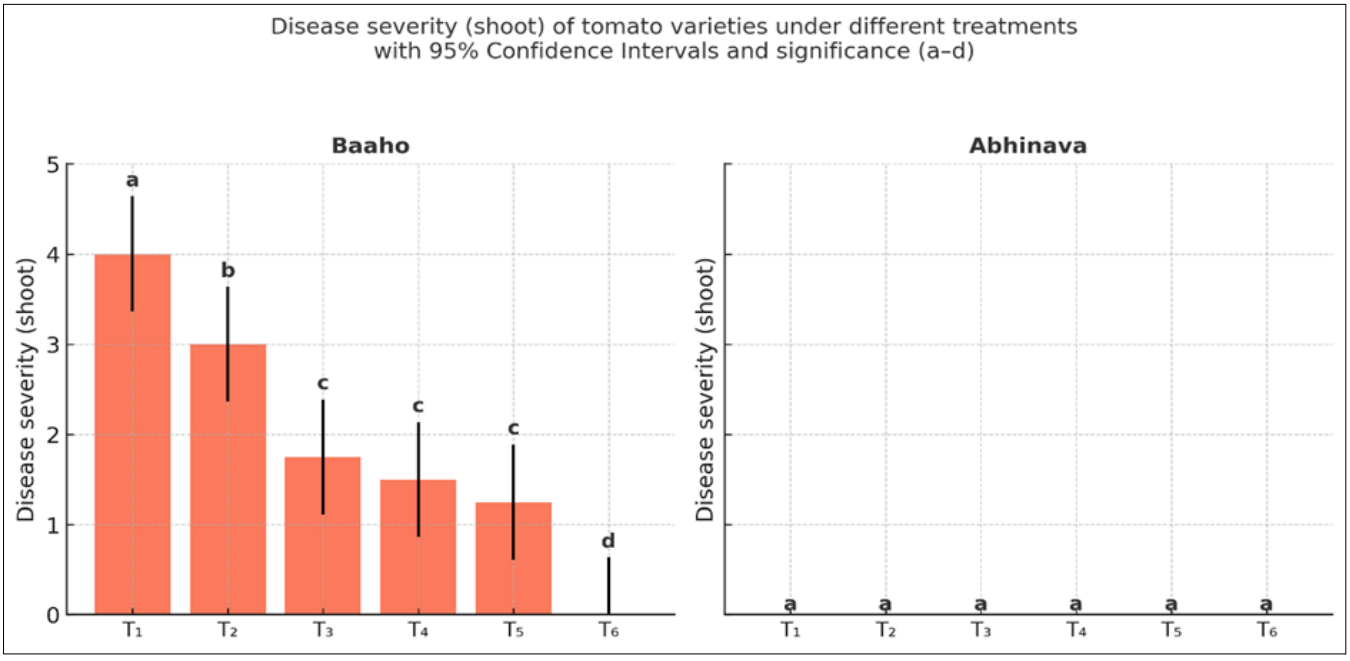

Fig. 5. Effect of calcium formulations on bacterial wilt incidence (60 DAT).

enhances the expression of pathogenesis-related proteins, such as β -1,3-glucanases and chitinases, which degrade bacterial cell walls and strengthen host defences (31, 32). Potassium complements calcium by enhancing enzymatic activity, photosynthetic efficiency and stress tolerance, thereby reducing pathogen colonization. Together, calcium and potassium strengthen physiological and molecular defence mechanisms in tomato, resulting in improved resistance to *R. solanacearum* (33, 34).

Effect of calcium formulation on soil chemical properties after the harvest of tomato

Application of calcium formulations produced non-significant but notable changes in soil pH, EC and organic carbon (OC) (Table 4). The higher pH was recorded in T_3 (6.38 in Baaho, 6.36 in Abhinava), while the lowest occurred in T_6 (6.23 and 6.20). Soil EC was lowest in T_1 (0.83 and 0.76 dS m^{-1}) and highest in T_6 (1.13 and 1.10 dS m^{-1}). Similarly, OC ranged from 0.49 % (Baaho, T_1) to 0.57 % (Baaho, T_6), with corresponding increases in Abhinava. Lime application increased Ca^{2+} in the soil solution and exchange complex, raising soil pH through CO_3^{2-} hydrolysis and reducing exchangeable Al^{3+} precipitation as $Al(OH)_3$ (35). The rise in EC under gypsum, magnesium sulphate and MOP was due to the release of Ca^{2+}, Mg^{2+} through and K^+ along with SO_4^{2-} and Cl^-, which elevated ionic strength by solubilizing salts (36-38). Increases in SOC were associated with greater root biomass, gypsum-induced mineralization, sulphur-mediated stabilization of organic matter, microbial diversification under magnesium and higher carbon return from potassium inputs, consistent with (39-43).

Table 4. Effect of calcium formulation on soil pH, EC and OC content after the harvest of tomato

Treatments	pH		EC (dS m^{-1})		OC (%)	
	Susceptible (Baaho)	Resistant (Abhinava)	Susceptible (Baaho)	Resistant (Abhinava)	Susceptible (Baaho)	Resistant (Abhinava)
T_1	6.26	6.23	0.83	0.76	0.49	0.53
T_2	6.25	6.23	0.95	0.90	0.54	0.62
T_3	6.38	6.36	0.96	0.91	0.54	0.63
T_4	6.37	6.34	0.97	0.92	0.55	0.65
T_5	6.25	6.22	1.07	1.03	0.55	0.66
T_6	6.23	6.20	1.13	1.10	0.57	0.69
SEm (±)	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
CD (5 %)	**-**	**-**	**-**	**-**	**-**	**-**

Note: T_1 = absolute control; T_2 = 100 % RDF; T_3 = T_2 + Ca_1 (calcium nutrition formulation); T_4 = T_2 + Ca_2 (calcium and magnesium nutrition formulation); T_5 = T_2 + Ca_3 (calcium, magnesium and sulphur nutrition formulation); T_6 = T_2 + Ca_4 (calcium, magnesium, sulphur and potassium nutrition formulation).

Effect of calcium formulation on soil available major nutrients after the harvest of tomato

Significant variation in post-harvest soil available N, P and K was observed (Table 5). The lowest values were consistently recorded in T_1 (205.65 and 194.23 kg ha^{-1} N; 31.31 and 30.75 kg ha^{-1} P; 161.36 and 147.12 kg ha^{-1} K in Baaho and Abhinava, respectively). All other treatments recorded significantly higher values. T_2 showed the highest N (268.12 and 263.18 kg ha^{-1}), whereas T_6 recorded the highest K (235.93 and 224.48 kg ha^{-1}). Phosphorus availability was also higher in fertilized treatments, with T_2 recording the maximum (49.44 and 45.37 kg ha^{-1}). Enhanced soil nitrogen availability may be attributed to calcium-induced improvements in organic carbon and cation exchange capacity, magnesium-mediated nutrient uptake and microbial activity balanced K application with other macronutrients, sulphur and nitrogen interactions that promote mineralization and efficiency and the contribution of FYM in enriching organic matter and expanding the soil N pool (44-47). Phosphorus availability was improved through sulphur-induced acidification and FYM-mediated release of organic acids, which solubilize fixed P and complex Al and Fe ions, thereby increasing P solubility (48, 49). Potassium availability and crop response were significantly enhanced with MOP application confirming the previous reports (50).

Effect of calcium formulation on soil available secondary nutrients after the harvest of tomato

Calcium formulations significantly enhanced post-harvest soil Ca, Mg and S availability (Table 6). The lowest values were consistently recorded in treatment T_1, with Ca at 2.21 and 2.09 cmol (P^+) kg^{-1}, Mg at 1.23 and 1.20 cmol (P^+) kg^{-1} and S at 5.30 and 4.43 mg kg^{-1} in Baaho and Abhinava, respectively. In contrast, maximum Ca was observed in treatment T_3 with 5.12 and 5.03 cmol (P^+) kg^{-1}, maximum Mg in treatment T_4 with 2.75 and 2.57 cmol (P^+) kg^{-1} and maximum S in T_5 with 58.47 and 52.20 mg kg^{-1}. Treatment T_6 also maintained significantly higher Ca, Mg and S than the control. Lime application, though less soluble than gypsum improved post-harvest soil calcium under slightly acidic conditions by raising pH, reducing

Table 5. Effect of calcium formulation on available N, P_2O_5 and K_2O at harvest in tomato

Treatment	Available N kg ha^{-1}		Available P_2O_5 kg ha^{-1}		Available K_2O kg ha^{-1}	
	Susceptible (Baaho)	Resistant (Abhinava)	Susceptible (Baaho)	Resistant (Abhinava)	Susceptible (Baaho)	Resistant (Abhinava)
T_1	205.65^b	194.23^b	31.31^b	30.75^b	161.36^c	147.12^c
T_2	268.12^a	263.18^a	49.44^a	45.37^a	214.49^b	201.87^b
T_3	263.02^a	259.59^a	47.91^a	44.84^a	208.26^b	204.19^b
T_4	261.05^a	257.81^a	46.77^a	43.47^a	210.85^b	206.39^b
T_5	261.76^a	253.01^a	44.30^a	42.79^a	204.67^b	197.02^b
T_6	254.49^a	249.02^a	42.31^a	41.12^a	235.93^a	224.48^a
SEm (±)	**10.02**	**9.24**	**2.40**	**1.70**	**4.14**	**3.91**
CD (5 %)	**29.78**	**27.45**	**7.15**	**5.08**	**12.31**	**11.64**
LSD	**45.05**	**41.52**	**10.81**	**7.68**	**18.62**	**17.60**

Note: T_1 = absolute control; T_2 = 100 % RDF; T_3 = T_2 + Ca_1 (calcium nutrition formulation); T_4 = T_2 + Ca_2 (calcium and magnesium nutrition formulation); T_5 = T_2 + Ca_3 (calcium, magnesium and sulphur nutrition formulation); T_6 = T_2 + Ca_4 (calcium, magnesium, sulphur and potassium nutrition formulation).

Table 6. Effect of calcium formulation on available Ca, Mg and S at harvest in tomato

Tr. No.	Ca (cmol (P^+) kg^{-1})		Mg (cmol (P^+) kg^{-1})		Available S (mgkg^{-1})	
	Susceptible (Baaho)	Resistant (Abhinava)	Susceptible (Baaho)	Resistant (Abhinava)	Susceptible (Baaho)	Resistant (Abhinava)
T_1	2.21^d	2.09^d	1.23^c	1.20^c	5.30^d	4.43^d
T_2	2.60^c	2.43^c	1.67^b	1.47^b	11.71^c	9.28^c
T_3	5.11^a	5.01^a	1.54^b	1.49^b	9.47^c	8.88^c
T_4	5.12^a	5.03^a	2.75^a	2.57^a	23.40^b	18.77^b
T_5	4.77^b	4.48^b	2.64^a	2.46^a	58.47^a	52.20^a
T_6	4.74^b	4.53^b	2.51^a	2.47^a	55.01^a	50.50^a
SEm (±)	**0.07**	**0.07**	**0.06**	**0.06**	**0.82**	**0.81**
CD (5 %)	**0.22**	**0.21**	**0.18**	**0.17**	**2.44**	**2.41**
LSD	**0.33**	**0.32**	**0.27**	**0.26**	**3.69**	**3.64**

Note: T_1 = absolute control; T_2 = 100 % RDF; T_3 = T_2 + Ca_1 (calcium nutrition formulation); T_4 = T_2 + Ca_2 (calcium and magnesium nutrition formulation); T_5 = T_2 + Ca_3 (calcium, magnesium and sulphur nutrition formulation); T_6 = T_2 + Ca_4 (calcium, magnesium, sulphur and potassium nutrition formulation).

aluminium saturation and enhancing cation exchange and base saturation, thus ensuring a gradual release of Ca for subsequent crops. Magnesium availability is usually limited by fixation on clay and organic matter, increases with magnesium sulphate, which provides a soluble and readily available source. Gypsum supplied sulphate ions steadily improving S status in deficient soils, while magnesium sulphate further enriched both Mg and S pools, thereby enhancing nutrient uptake, crop yield and quality (51-54).

Effect of calcium formulation on tomato growth

Tomato plant height and chlorophyll content were significantly influenced by calcium formulations (Fig. 6, 7). At 30 DAT, plant height in Baaho ranged from 37.54 cm in T_1 to 49.44 cm in T_6, while Abhinava ranged from 39.41 cm in $T_1$to 53.87 cm in T_6. At 60 DAT, T_6 again recorded the tallest plants (70.03 cm in Baaho; 101.57 cm in Abhinava). At harvest, Plants of Baaho in T_1exhibited complete wilt symptoms by harvest, whereas other treatments attained 59.69 cm (T_2) to 84.61 cm (T_6). In Abhinava, plant height ranged from 86.84 cm in T_2 to 117.80 cm in T_6, with T_2, T_3, T_4 and T_5 statistically comparable to T_6. Chlorophyll content followed a similar trend, with significantly higher values in all fertilized treatments compared with T_1. Application of calcium, magnesium, sulphur and potassium significantly improved tomato plant height and chlorophyll content, with calcium enhancing nutrient absorption and chlorophyll stability. Magnesium serving as the central chlorophyll component, sulphur supporting protein and enzyme synthesis and potassium improving nutrient transport and stress tolerance, thereby enhancing growth and photosynthesis (55-60).

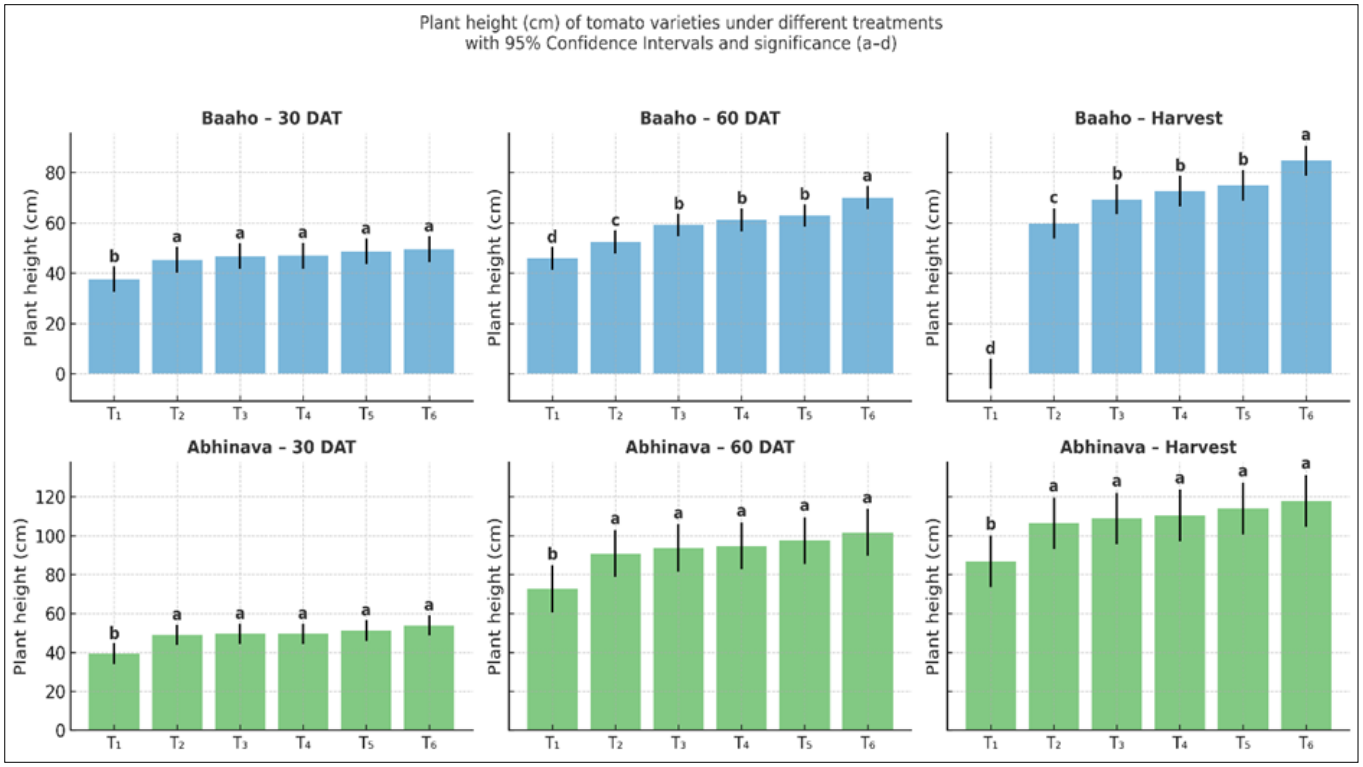

Fig. 6. Effect of calcium formulation on plant height (cm).

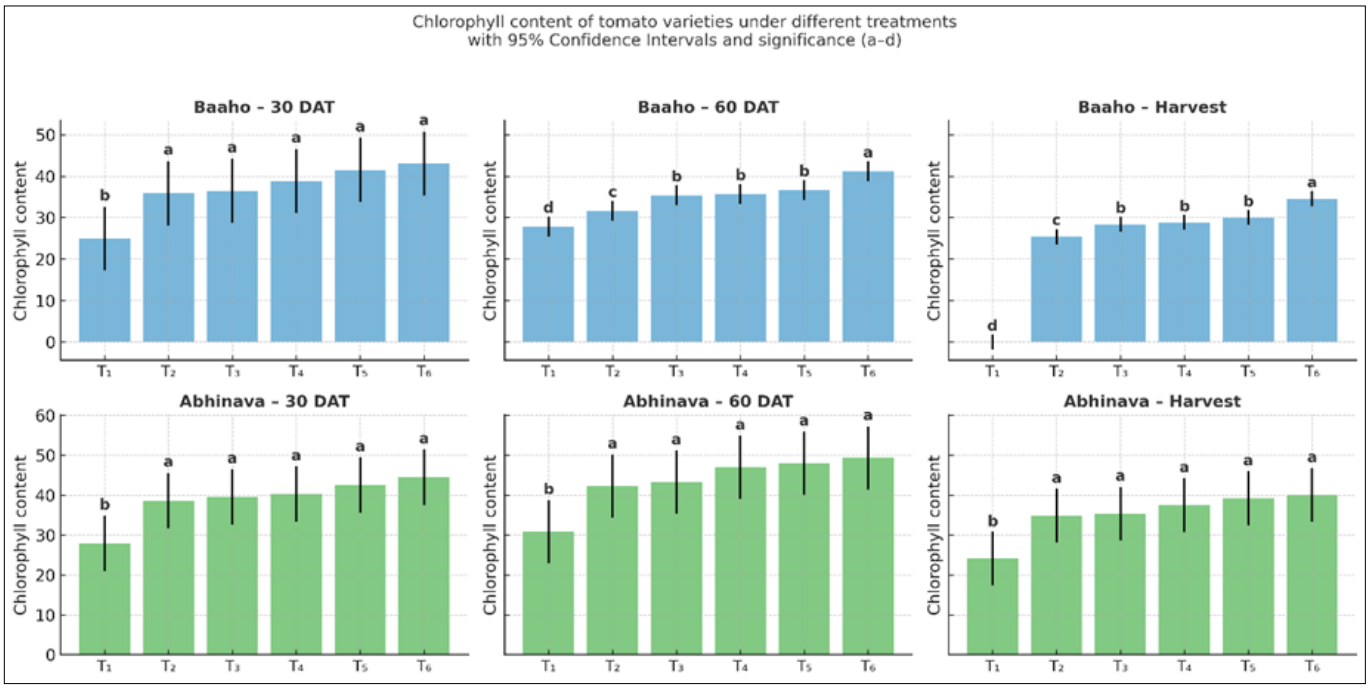

Fig. 7. Effect of calcium formulation on chlorophyll content.

Effect of calcium formulation on yield attributes

Tomato yield attributes showed significant differences (Fig. 8-10). In T_1, Baaho plants succumbed to wilt and produced no yield, while Abhinava produced only 35 fruits per plant (32.36 g fruit weight; 9.75 days keeping quality). T_6 recorded the higher yield performance, producing 42 fruits plant^{-1} in Baaho and 66.50 in Abhinava, with fruit weights of 71.49 g and 91.03 g and keeping quality extended to 10.75 and 17.25 days, respectively. T_2-T_5 were statistically on par with T_6 in Abhinava. Application of calcium, magnesium, sulphur and potassium significantly enhanced tomato fruit yield and quality, with calcium improving fruit number, weight and shelf life, magnesium increasing yield and firmness through chlorophyll synthesis, sulphur enhancing nutrient balance and biochemical quality and potassium promoting fruit weight and firmness (61-65).

Effect of calcium formulation on fruit quality

Fruit firmness and diameter were significantly improved by calcium formulations (Fig. 11, 12). In T_1, Baaho plants failed to produce fruits and Abhinava fruits were small (2.37 cm diameter) and soft (1.48 kg cm^{-2} firmness). In contrast, T_6 recorded the best performance (4.14 cm and 1.44 kg cm^{-2} in Baaho; 5.93 cm and 1.94 kg cm^{-2} in Abhinava). Treatments T_2-T_5 were statistically comparable to T_6 in Abhinava. These results confirm that calcium strengthens fruit cell walls and stabilizes pectin, magnesium contributes to fruit expansion and storage firmness and potassium regulates sugar metabolism and osmotic balance, thereby improving fruit size and firmness (66-68).

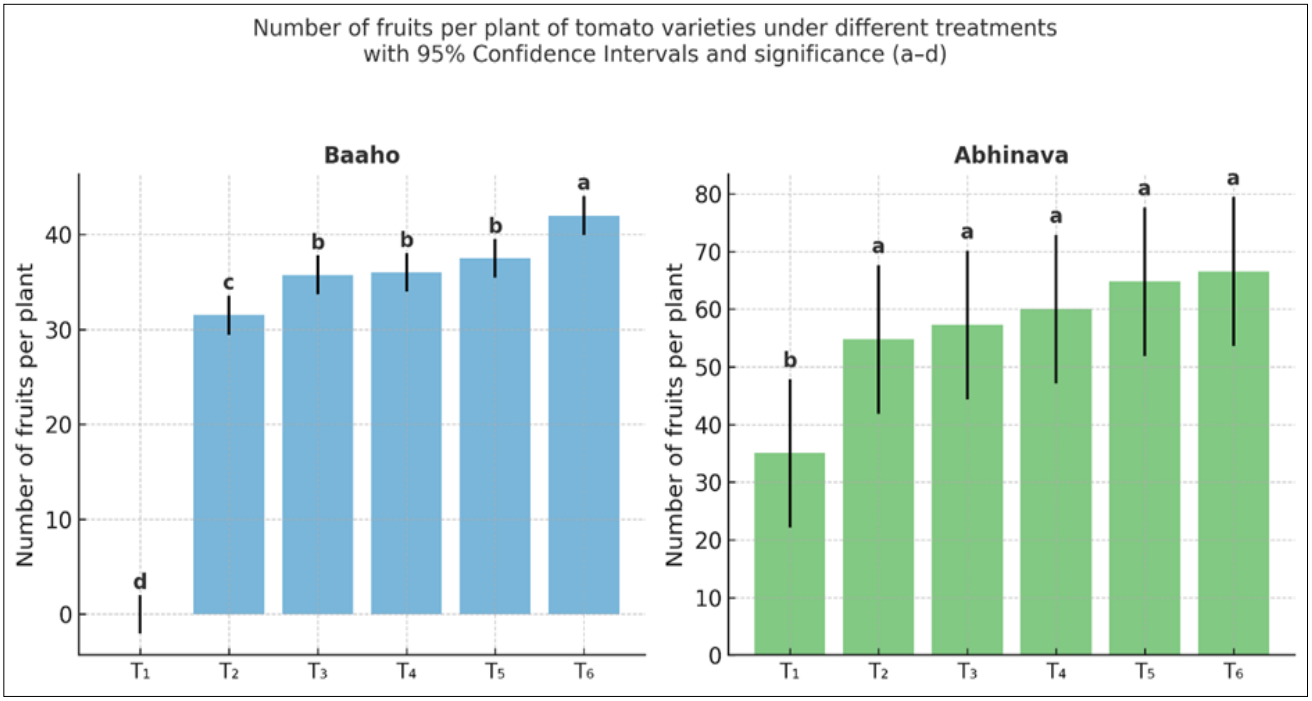

Fig. 8. Effect of calcium formulation on number of fruits per plant.

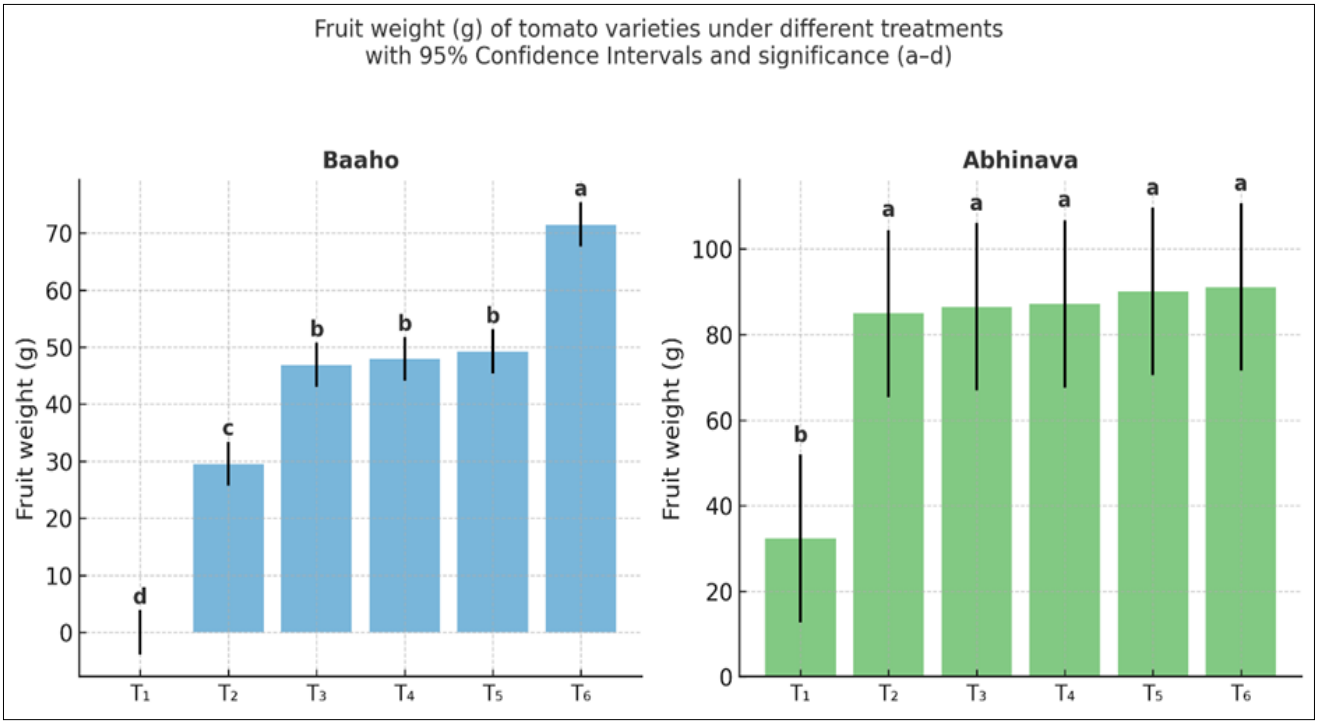

Fig. 9. Effect of calcium formulation on fruit weight (g).

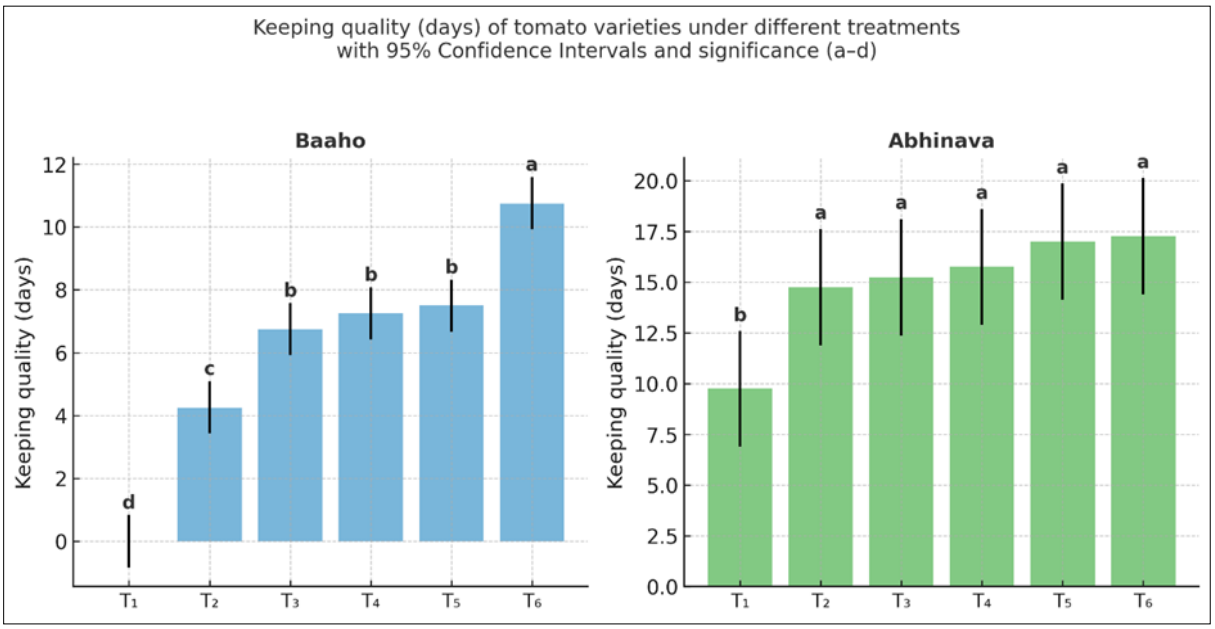

Fig. 10. Effect of calcium formulation on keeping quality (days).

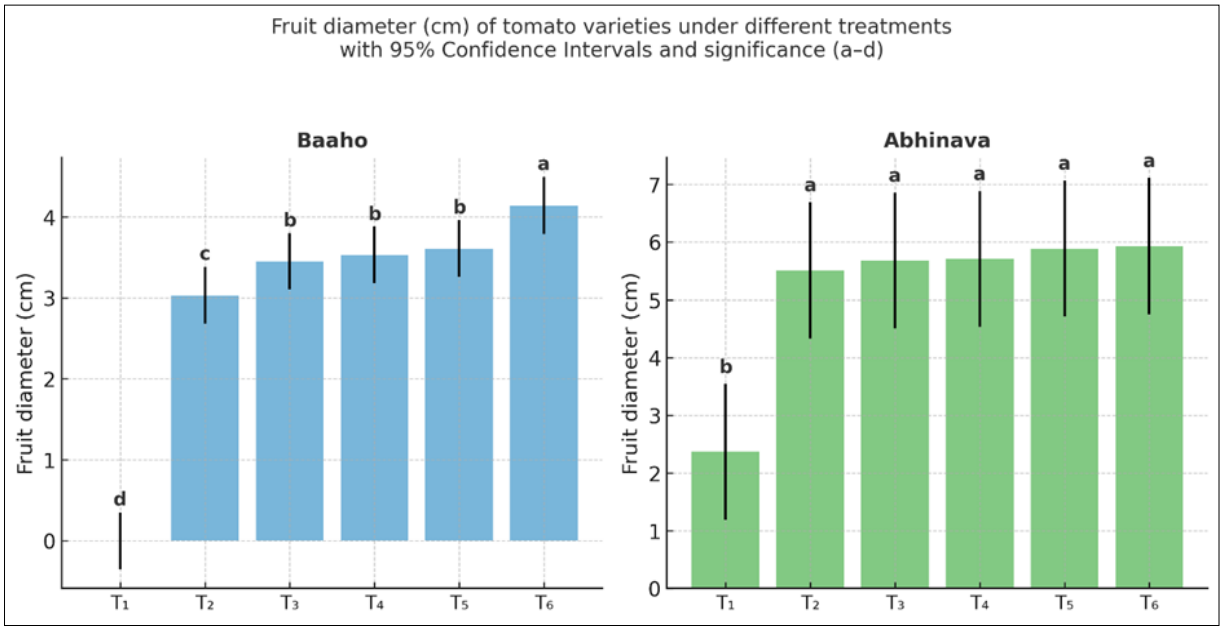

Fig. 11. Effect of calcium formulation on fruit diameter (cm).

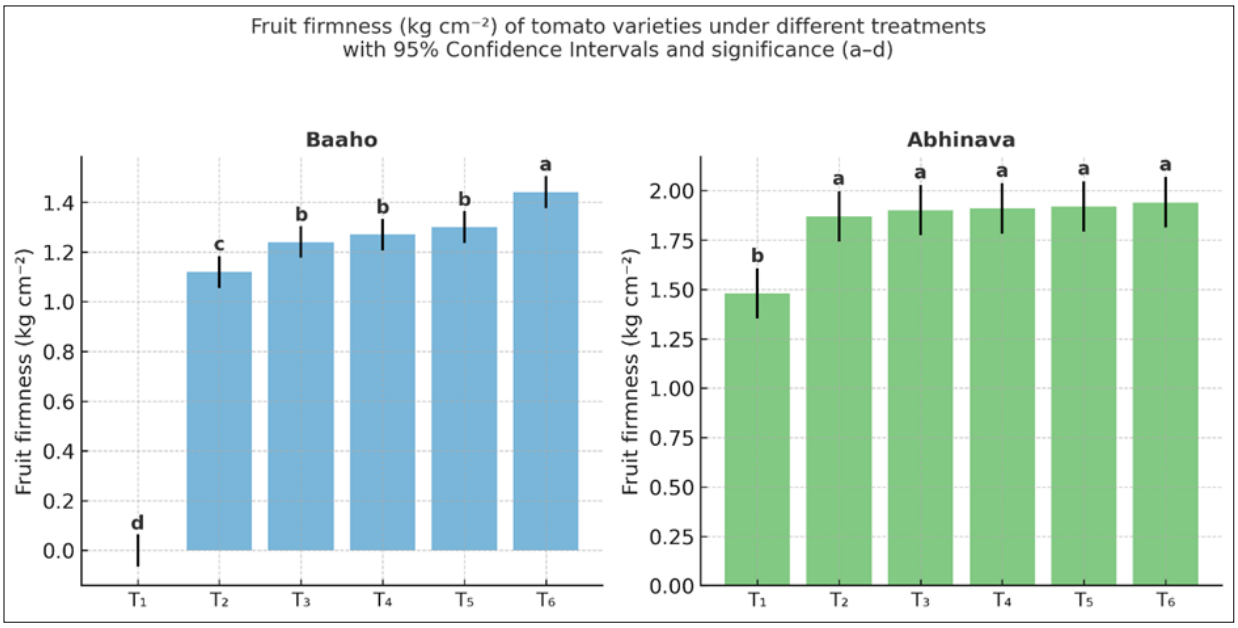

Fig. 12. Effect of calcium formulation on fruit firmness (kg cm^{-2}).

Conclusion

The present study demonstrates that calcium-based nutrient formulations, particularly those integrating calcium with magnesium, sulphur and potassium, can effectively delay wilt incidence, reduce disease severity and enhance tomato growth, yield and fruit quality. Calcium played a crucial role in suppressing *R. solanacearum*, improving nutrient uptake and promoting overall plant performance. The resistant variety Abhinava consistently performed better than Baaho, emphasizing the importance of combining varietal resistance with balanced nutrient management. These findings highlight calcium-enriched formulations as a sustainable and eco-friendly approach for managing bacterial wilt and improving tomato productivity under field conditions. However, as the study was conducted under controlled pot conditions, field variability and molecular mechanisms underlying calcium-induced defence signalling warrant further investigation. Future field trials and mechanistic studies on calcium signalling pathways are recommended to validate and strengthen these nutrient-based disease management strategies.

Acknowledgements

The authors gratefully acknowledge the University of Agricultural Sciences, Bangalore and the Government of India Fellowship for financial support. The facilities provided by the Soil and Water Laboratory and the Biocontrol Laboratory, College of Sericulture, Chintamani, Karnataka, are duly acknowledged.

Authors' contributions

SG undertook conceptualization, investigation, validation, methodology, nutrient analysis, visualization and the preparation of the original draft, followed by revision and editing, while DVN, MM, VV and PV provided supervision and essential facilities supporting the completion of the work. All authors read and approve the final manuscript.

Compliance with ethical standards

Conflict of interest: The authors declare no conflict of interest.

Ethical issues: None

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author used AI tools (ChatGPT) to rephrase the sentences and standardize the paragraphs. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

References

1. Jiang G, Zhang Y, Gan G, Li W, Wan W, Jiang Y, et al. Exploring rhizo-microbiome transplants as a tool for protective plant-microbiome manipulation. ISME J. 2022;2:10. https://doi.org/10.1038/s43705-022-00094-8
2. Tessema GL, Seid HE. Potato bacterial wilt in Ethiopia: History, current status and future perspectives. PeerJ. 2023;11:e14661. https://doi.org/10.7717/peerj.14661
3. Genin S, Denny TP. Pathogenomics of the *Ralstonia solanacearum* species complex. Annu Rev Phytopathol. 2012;50:67-89. https://doi.org/10.1146/annurev-phyto-081211-173000
4. Vanitha SC, Niranjana SR, Mortensen CN, Umesha S. Bacterial wilt of tomato in Karnataka and its management by *Pseudomonas fluorescens.* Biocontrol. 2009;54(5):685-95. https://doi.org/10.1007/s10526-009-9217-x
5. Nion YA, Toyota K. Recent trends in control methods for bacterial wilt diseases caused by *Ralstonia solanacearum*. Microbes Environ. 2015;ME14144.
6. Huber DM, Graham RD. The role of nutrition in crop resistance and tolerance to disease. In: Rengel Z, editor. Mineral Nutrition of Crops: Fundamental Mechanisms and Implications. New York (NY): CRC Press; 1999. p.205-26.
7. Agrios GN. Plant Pathology. 5th ed. Amsterdam: Elsevier; 2005.
8. Bush DS. Calcium regulation in plant cells and its role in signaling. Annu Rev Plant Physiol Plant Mol Biol. 1995;46:95-122. https://doi.org/10.1146/annurev.pp.46.060195.000523
9. Yang T, Poovaiah BW. Hydrogen peroxide homeostasis: Activation of plant catalase by calcium/calmodulin. Proc Natl Acad Sci USA. 2002;99:4097-102. https://doi.org/10.1073/pnas.052564899
10. Taylor MD, Locascio SJ. Blossom-end rot: A calcium deficiency. J Plant Nutr. 2004;27:123-39. https://doi.org/10.1081/PLN-120027551
11. Yamazaki H, Kikuchi S, Hoshina T, Kimura T. Effect of calcium concentration in nutrient solution on development of bacterial wilt and population of its pathogen *Ralstonia solanacearum* in grafted tomato seedlings. J Soil Sci Plant Nutr. 2000;46:535-39.
12. Ustun N, Altunlu H, Yokaş I, Saygili H. Influence of potassium and calcium levels on severity of tomato pith necrosis and yield of greenhouse tomatoes. Acta Hortic. 2009;808:347-50. https://doi.org/10.17660/ActaHortic.2009.808.56
13. Akhtar ME, Khan MZ, Rashis MT, Ahsan Z, Ahmad S. Effect of potash application on yield and quality of tomato (*Lycopersicon esculentum* Mill.). Pak J Bot. 2010;42(3):1695-702.
14. Ahmed N, Zhang B, Bozdar B, Chachar S, Rai M, Li J, et al. The power of magnesium: Unlocking the potential for increased yield, quality and stress tolerance of horticultural crops. Front Plant Sci. 2023;14:1285512. https://doi.org/10.3389/fpls.2023.1285512
15. Tian G, Qin H, Liu C, Xing Y, Feng Z, Xu X, et al. Magnesium improved fruit quality by regulating photosynthetic nitrogen use efficiency, carbon-nitrogen metabolism and anthocyanin biosynthesis in 'Red Fuji' apple. Front Plant Sci. 2023;14:1136179. https://doi.org/10.3389/fpls.2023.1136179
16. Kunstler A, Gullner G, Ádám AL, Kolozsváriné Nagy J, Király L. The versatile roles of sulfur-containing biomolecules in plant defense. Plants. 2020;9(12):1705. https://doi.org/10.3390/plants9121705
17. Tripathi R, Tewari R, Singh KP, Keswani C, Minkina T, Srivastava AK, et al. Plant mineral nutrition and disease resistance: A significant linkage for sustainable crop protection. Front Plant Sci. 2022;13:883970. https://doi.org/10.3389/fpls.2022.883970
18. Bayındır Ü, Küçükyumuk Z. The effects of potassium on plant nutrient concentration, plant development and *Rhizoctonia* rot in pepper. Horticulturae. 2025;11(5):516. https://doi.org/10.3390/horticulturae11050516
19. Kelman A. The relationship of pathogenicity of *Pseudomonas solanacearum* to colony appearance on a tetrazolium medium. Phytopathology. 1954;44:693-5. https://doi.org/10.1094/Phyto-44-693
20. Vincent JM, Humphrey B. Gram staining. In: Norris JR, editor. Methods in Microbiology. Vol.3B. London: Academic Press; 1970. p.143-5.
21. Bauer AW, Kirby WMM, Sherris JC, Turck M. Antibiotic susceptibility testing by a standardized single disk method. Am J Clin Pathol. 1966;45(4):493-96. https://doi.org/10.1093/ajcp/45.4_ts.493
22. Cappuccino JG, Sherman N. Microbiology: A Laboratory Manual. 7th

ed. San Francisco (CA): Pearson Education; 2005.

23. Jackson ML. Soil Chemical Analysis. New Delhi: Prentice Hall of India; 1973.

24. Ziedan EHE. Studies on *Fusarium* wilt diseases of sesame (*Sesamum indicum*) in A.R.E. [MSc thesis]. Cairo: Ain Shams Univ; 1993.

25. Sheoran OP, Tonk DS, Kaushik LS, Hasija RC, Pannu RS. Statistical software package for agricultural research workers. Hisar (India): CCS HAU; 1998.

26. He K, Yang SY, Li H, Wang H, Li ZL. Effects of calcium carbonate on the survival of *Ralstonia solanacearum* in soil and control of tobacco bacterial wilt. Eur J Plant Pathol. 2014;140(4):665-75. https://doi.org/10.1007/s10658-014-0496-4

27. Ferreira MV, Naranjo E, Denis N, Cobine P, De La Fuente L, Siri MI. Calcium modulation of bacterial wilt disease on potato. Appl Environ Microbiol. 2024;90(6):e00242-24. https://doi.org/10.1128/aem.00242-24

28. Xu W, Huang W. Calcium-dependent protein kinases in phytohormone signaling pathways. Int J Mol Sci. 2017;18(11):2436. https://doi.org/10.3390/ijms18112436

29. Yuan P, Tanaka K, Poovaiah BW. Calcium/calmodulin-mediated defense signaling: AtSR1/CAMTA3-mediated signaling in plant immunity. Front Plant Sci. 2022;12:795353. https://doi.org/10.3389/fpls.2021.795353

30. Bleau JR, Spoel SH. Selective redox signaling shapes plant-pathogen interactions. Plant Physiol. 2021;186(1):53-65. https://doi.org/10.1093/plphys/kiaa088

31. Aldon D, Mbengue M, Mazars C, Galaud JP. Calcium signalling in plant biotic interactions. Int J Mol Sci. 2018;19(3):665. https://doi.org/10.3390/ijms19030665

32. Negi NP, Prakash G, Narwal P, Panwar R, Kumar D, Chaudhry B, et al. The calcium connection: Exploring calcium signaling in plant-microbe interactions. Front Plant Sci. 2023;14:1248648. https://doi.org/10.3389/fpls.2023.1248648

33. Wang Y, Dai X, Xu G, Dai Z, Chen P, Zhang T, et al. The Ca2+-CaM signaling pathway mediates potassium uptake under low-K+ stress in tobacco roots. Front Plant Sci. 2021;12:658609. https://doi.org/10.3389/fpls.2021.658609

34. Rosyidah A, Murwani I, Siswadi B. Effect of potassium fertilizer on resistance and growth of tomato to bacterial wilt caused by *Ralstonia solanacearum*. Int J Environ Agric Biotechnol. 2017;2:2265-69. https://doi.org/10.22161/ijeab/2.4.89

35. Koesrini W. Effect of ameliorant application on plant growth and yield of three snap bean varieties on acid sulphate soil. J Agron Indones. 2009;37:34-39.

36. Oliveira IPD, Asher CJ, Edwards DG, Santos RSM. Magnesium sulphate and development of common bean cultivated in an Ultisol. Sci Agric. 2000;57:153-57. https://doi.org/10.1590/S0103-90162000000100025

37. Turan MA, Taban S, Katkat AV, Kucukyumuk Z. Evaluation of elemental sulfur and gypsum effect on soil pH and EC. J Food Agric Environ. 2013;11:572-75.

38. Theresa K, Shanmugasundaram R, Kennedy JS. Effect of varied NPK levels on soil reaction and electrical conductivity. Int J Chem Stud. 2020;8:2632-36. https://doi.org/10.22271/chemi.2020.v8.i1an.8669

39. Sharma SP, Subehia SK, Sharma PK. Research bulletin on long-term effects of chemical fertilizers on soil quality, crop productivity and sustainability. Palampur: Dept Soil Sci, CSK HPKV; 2002.

40. Adekiya AO, Alori ET, Aboyeji CM, Dunsin O, Adegbite KA, Aremu CO, et al. MgO fertilizer effects on soil properties and turmeric quality in a tropical Alfisol. Sci World J. 2019;2019:8140276. https://doi.org/10.1155/2019/8140276

41. Liu Y, Zhang Z, Wang X, Wu R, Ding S, Wang S, et al. Gypsum application increases microbial activity and organic carbon mineralization in saline paddy soils. Appl Soil Ecol. 2025;208:106004. https://doi.org/10.1016/j.apsoil.2025.106004

42. Gokila B, Manimaran G, Jayanthi D, Sivakumar K, Sridevi G, Thenmozhi S, et al. Long-term fertilization effects on sulphur distribution and SOC in an Inceptisol. Sci Rep. 2024;14:9758. https://doi.org/10.1038/s41598-024-60357-3

43. Kaewu N. Effects of agricultural potassium fertilizer application on soil carbon cycle. Acad J Sci Technol. 2024;11(2):122-25. https://doi.org/10.54097/fy0zmz82

44. Mir L, Sheikh YA, Kumar R, Shahnaz E, Ahmed S, Butt IA, et al. Effects of calcium nitrate application on soil properties in apple plantations. J Sci Res Rep. 2025;31:265-73. https://doi.org/10.9734/jsrr/2025/v31i22845

45. Syamsiyah J, Hartati S, Rahmanisa L, Maro'ah S, Herdiansyah G. Effect of balanced N, P, K, Ca, Mg fertilizer on soil and leaf nutrients and corn yield (*Zea mays* L.). J Aridland Agric. 2024;10:58-64. https://doi.org/10.25081/jaa.2024.v10.8646

46. Talukdar L, Dutta S, Dutta P, Hussain J. Nitrogen and sulphur interaction on nutrient use efficiency in field crops. J Pharm Innov. 2022;11:1372-76.

47. Tadesse T, Dechassa N, Bayu W, Gebeyehu S. Effects of farmyard manure and inorganic fertilizer on soil properties and nutrient balance in rain-fed rice. Am J Plant Sci. 2013;4:309-16. https://doi.org/10.4236/ajps.2013.42041

48. Hemmaty S, Dilmaghani MR, Naseri L. Effects of sulfur application on soil pH and uptake of P, Fe and Zn in apple trees. J Plant Physiol Breed. 2012;2(1):1-10.

49. Rakotoson T, Tsujimoto Y. Effect of farmyard manure on P availability to rice in low C and low pH paddy soils. Plant Prod Sci. 2020;23:314-21. https://doi.org/10.1080/1343943X.2020.1740601

50. Sindhu GP, Reddy KS, Gunasekar J, Vamshi M. Effect of MOP and SOP on growth of green gram (*Vigna radiata* L.). Int J Curr Microbiol Appl Sci. 2019;8:2577-92. https://doi.org/10.20546/ijcmas.2019.802.300

51. Bossolani JW, Crusciol CAC, Garcia A, Moretti LG, Portugal JR, Rodrigues VA, et al. Long-term lime and phosphogypsum amended soils alleviate drought by improving soil fertility and root growth. Front Plant Sci. 2021;12:650296. https://doi.org/10.3389/fpls.2021.650296

52. Zhang Q, Tang D, Yang X, Geng S, He Y, Chen Y, et al. Plant availability of magnesium in tea plantation soils. Front Plant Sci. 2021;12:641501. https://doi.org/10.3389/fpls.2021.641501

53. Radwan S, Abouhussien EHE, Tantawy M, Hassan S. Effect of elemental sulfur and gypsum on growth and nutrient content of barley in saline soils. Menoufia J Soil Sci. 2024;9:17-29. https://doi.org/10.21608/mjss.2024.272076.1024

54. Mondal S, Ghosh GK, Mandal J. Effect of graded sulphur as magnesium sulphate on yield and quality of onion in red soils. Int J Curr Microbiol Appl Sci. 2020;9(1):1-9. https://doi.org/10.20546/ijcmas.2020.904.335

55. Birgin O, Akhoundnejad Y, Dasgan HY. Effect of foliar calcium application in tomato under drought stress. Appl Ecol Environ Res. 2021;19(4):2971-82. https://doi.org/10.15666/aeer/1904_29712982

56. Chauhan S, Deependra Y, Kumar S, Kumar R, Kumar A. Effect of calcium on growth and yield of tomato (*Solanum lycopersicum* L.). Biol Forum Int J. 2023;15(2):1162-6.

57. Alrashidi AA, Alhaithloul HAS, Soliman MH, Attia MS, Elsayed SM, Sadek AM, et al. Role of calcium and magnesium on physiological and anatomical responses in tomato plants. Not Bot Horti Agrobo. 2022;50(1):12614. https://doi.org/10.15835/nbha50112614

58. Narayan OP, Kumar P, Yadav B, Dua M, Johri AK. Sulfur nutrition and its role in plant growth and development. Plant Signal Behav. 2023;18:2030082. https://doi.org/10.1080/15592324.2022.2030082

59. Ddamulira G, Idd R, Namazzi S, Kalali F, Mundingotto J, Maphosa M.

Nitrogen and potassium fertilizers increase cherry tomato height and yield. J Agric Sci. 2019;11(10):207. https://doi.org/10.5539/jas.v11n13p48

60. Naciri R, Lahrir M, Benadis C, Chtouki M, Oukarroum A. Interactive effect of potassium and cadmium on growth and chlorophyll fluorescence in tomato. Sci Rep. 2021;11:5384. https://doi.org/10.1038/s41598-021-84990-4
61. Tongali NC, Ashoka KR, Ananthakumar MA, Kumar NK. Effect of calcium sources and levels on growth and yield of tomato in Alfisols. Plant Arch. 2024;24. https://doi.org/10.51470/PLANTARCHIVES.2024.v24.no.2.066
62. Santhosh SS, Chitdeshwari T, Jegadeeswari D, Kavitha C. Effect of calcium levels and sources on post-harvest physiology of hybrid tomatoes. J Appl Nat Sci. 2021;13(4):1357-64. https://doi.org/10.31018/jans.v13i4.3058
63. Kasinath BL, Ganeshamurthy AN, Nagegowda NS. Effect of magnesium on growth, dry matter and yield in tomato (*Lycopersicon esculentum* L.). J Hortic Sci. 2015;10:190-3. https://doi.org/10.24154/jhs.v10i2.128
64. Rashid M. Effect of sulphur and boron fertilizer on growth and yield of Bari tomato-2 (*Lycopersicon esculentum*). [Thesis]. Sher-e-Bangla Agricultural University, Dhaka. 2021.
65. Ahmad N, Sarfraz M, Farooq U, Arfan-ul-Haq M, Mushtaq MZ, Ali MA. Effect of potassium and its time of application on yield and quality of tomato. Int J Sci Res Publ. 2015;5(3):1-4.
66. Polwaththa KDM, Amarasinghe AY. Optimizing calcium application strategies to enhance fruit quality in tomato (*Lycopersicon esculentum* L.). Int J Sci Res Arch. 2024;13(02):596–602. https://doi.org/10.30574/ijsra.2024.13.2.2188
67. Tian G, Qin H, Liu C, Xing Y, Feng Z, Xu X, et al. Magnesium improved fruit quality by regulating nitrogen use efficiency in apple. Front Plant Sci. 2023;14:1136179. https://doi.org/10.3389/fpls.2023.1136179
68. Timileyin OA, Olajide BT, Temitayo IA, Faith OO, Arem WT, Nwafor IP. Effect of potassium fertilizer rate on growth, fruit yield and nutritional quality of tomato varieties. Int J Res Publ Rev. 2025;6(4):14752-772. https://doi.org/10.55248/gengpi.6.0425.16148

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Copyright: © The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited (https://creativecommons.org/licenses/by/4.0/)

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.