



RESEARCH ARTICLE

Effect of foliar application of nano CaO, ZnO and boron on fruit quality and nutrient uptake in tomato (*Solanum lycopersicum* L.)

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Abstract

A field experiment was conducted during the rabi 2020–21 and 2021–22 at Professor Jayashankar Telangana Agricultural University, Telangana, India to evaluate the effect of foliar applications of nano calcium oxide (CaO), nano zinc oxide (ZnO) and nano boron (B) individually and in combination on tomato cv. US-440. A total of 19 treatments were tested in a randomised block design (RBD) with 3 replications. Foliar sprays were applied at 30 and 45 days after transplanting (DAT). The combined application of nano CaO (600 ppm) + nano ZnO (1000 ppm) + nano B (400 ppm) (T₇) significantly improved fruit quality by increasing ascorbic acid (26.41 mg 100 g⁻¹) and titratable acidity (0.51 %), while reducing TSS (3.59 °Brix), total sugars (2.70 %), reducing sugars (2.23 %) and lycopene (5.16 mg 100 g⁻¹). T₇ also recorded the highest leaf concentrations of calcium (Ca) (1.89 %), zinc (Zn) (38.20 ppm) and B (42.43 ppm) and the highest fruit Zn content (65.79 ppm), whereas nano CaO (600 ppm) + nano ZnO (750 ppm) + nano B (400 ppm) (T₈) recorded maximum fruit Ca (0.85 %) and B (44.17 ppm). Additionally, T₇ minimised blossom end rot (2.93 %) and fruit cracking (3.03 %). The superior performance of nanonutrients was attributed to their greater surface area, enhanced absorption efficiency and targeted nutrient delivery. The findings demonstrate the potential of combined nano CaO, nano ZnO and nano B application to improve tomato fruit quality and nutrient use efficiency under field conditions.

Keywords: foliar nutrition; fruit quality; nano boron; nano CaO; nano ZnO; nutrient uptake; tomato

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most economically important vegetable crops grown worldwide, valued for its high nutritional composition, including vitamin C, lycopene, β-carotene, potassium (K) and calcium (Ca). It supplies approximately 13.7 mg vitamin C, 0.27 mg iron (Fe), 10 mg Ca, 24 mg phosphorus (P), along with 2570 µg lycopene per 100 g of fresh fruit (1).

Calcium, a secondary macronutrient, plays a pivotal role in the growth and development of tomato plants, from vegetative to flowering, fruiting, harvesting and post-harvest stages; its deficiency in tomato results in blossom end rot, a physiological disorder that significantly reduces marketable yield and fruit quality. Among the micronutrients, boron (B) and zinc (Zn) play important roles in improving the yield and quality of tomatoes in addition to preventing various diseases and physiological disorders. Micronutrient deficiencies in crop plants have become a major constraint to both productivity and product quality. Approximately 39 % of Indian agricultural soils are deficient in available Zn, making Zn the most widespread micronutrient deficiency affecting crop production in India (2). Boron is the second most widespread micronutrient constraint in crops globally, with approximately 23.2 % of Indian

agricultural soils reported to be deficient in available B (2). These widespread deficiencies highlight the need for efficient nutrient management strategies to ensure sustainable tomato production.

Conventional fertilisation practices often suffer from low nutrient-use efficiency because of fixation, leaching and uneven nutrient availability. These limitations necessitate the development of alternative nutrient delivery systems capable of improving nutrient uptake while reducing fertiliser inputs and environmental losses (3).

Nanotechnology offers a promising approach to nutrient management in crop production. Nano fertilisers, with particle sizes ranging from 1–100 nm, possess unique physicochemical properties including high surface-area-to-volume ratios, high reactivity and superior ability to penetrate biological membranes compared to their bulk counterparts (4). These characteristics confer greater nutrient use efficiency, targeted delivery, reduced environmental contamination and prolonged efficacy. Nano CaO, nano ZnO and nano B were selected for this study because these nanoformulations have been reported to improve nutrient-use efficiency through enhanced foliar absorption, greater surface area and controlled nutrient release compared with conventional fertilisers.

Previous studies have demonstrated the beneficial effects of nano-nutrients on tomato production (5). The foliar application of nano ZnO improved Zn uptake, marketable yield, total soluble solids and vitamin C content in tomato. Similarly, significant improvements in plant growth, fruit yield and nutrient uptake following foliar application of ZnO nanoparticles (6). The nano B enhanced important fruit quality attributes, including total soluble solids, lycopene and sugar content in tomato (7). Furthermore, the calcium phosphate-based nanoparticles enriched with Zn increased tomato yield and enhanced Ca and Zn accumulation in fruits (8). These findings collectively indicate the considerable potential of nanonutrient based fertilisation to enhance tomato productivity and fruit quality. Most previous studies have focused on the individual effects of specific nanonutrients; comprehensive field-level studies evaluating the combined effect of these three nanonutrients on fruit quality parameters and nutrient uptake in tomato under diverse seasonal conditions are limited. Therefore, the present study was undertaken to evaluate the individual and combined effects of foliar-applied nano CaO, nano ZnO and nano B on fruit quality attributes, nutrient uptake and physiological disorder incidence in tomato under field conditions.

Materials and Methods

Experimental site and design

The field experiment was conducted during the rabi seasons of 2020–21 (transplanting on 02-11-2020) and 2021–22 (transplanting on 23-10-2021) at Agricultural College, Palem, Professor Jayashankar Telangana Agricultural University, located at 17°06' N latitude, 78°41' E longitude and at an altitude of 300 m above mean sea level, in Telangana, India. The experiment was laid out in a randomised block design (RBD) with 19 treatments and 3 replications. Each plot measured 4.8 × 4.9 m and accommodated 66 plants, which were planted at a spacing of 120 × 45 cm.

Prior to the preparatory cultivation of the experimental site, soil samples from 0–15 cm depth were collected at random and a composite soil sample was analysed for different physical, physico-chemical, chemical and biological properties by following standard methods. The soil of the experimental site was red soil in texture with a soil pH of 7.21 and electrical conductivity (EC) of 0.23 dSm⁻¹. The organic carbon content is 0.42 %. The availability of nitrogen (N), P and K is 165.67, 63.32 and 320.24 kg ha⁻¹ respectively. The availability of Ca is 0.7 meq/100 g⁻¹, Zn is 0.4 mg kg⁻¹ and B is 0.43 mg kg⁻¹ soil.

During the period from 22-10-2021 to 25-02-2022 of experimentation the mean minimum and maximum temperature is ranged from 18.68–0.69 °C. The range of relative humidity at 0714 hr was 80–95 % and 1414 hr was 30–70 %. There was total rainfall of 174.9 mm.

Nanonutrient preparation and characterisation

All the nanonutrients used in this study were obtained from the Nanotechnology laboratory of the Institute of Frontier Technology (IFT), Regional Agricultural Research Station, Tirupati, Acharya N G Ranga Agricultural University, Andhra Pradesh. Their physicochemical characterisation was carried out by high-resolution transmission electron microscopy (HR-TEM) at a 0.2 µm scale at the Indian Institute of Technology (IIT), Roorkee.

Synthesis and characterisation of nano CaO

Nano CaO was synthesised by the sol-gel method using 1 % calcium nitrate tetrahydrate and 0.05 % sodium citrate tribasic dihydrate. The reaction mixture was stirred at 60 °C for 3 hr, filtered through Whatman No. 1 filter paper and dried at 100 °C for 6 hr (9). High-resolution transmission electron microscopy (HR-TEM) analysis (JEOL 2010F, 200 kV) revealed predominantly spherical, slightly agglomerated nanoparticles with an average particle size of 30 nm. The zeta potential of nano CaO was -28.2 mV.

Synthesis and characterisation of nano ZnO

Nano ZnO was synthesised by the oxalate decomposition (sol-gel) method using 0.2 M zinc acetate and 0.2 M oxalic acid. The zinc oxalate precipitate was washed, dried and calcined at 500 °C for 45 min (9). The HR-TEM (JEOL 3010) showed slightly aggregated ZnO nanoparticles with an average particle size of 25 nm.

Synthesis and characterisation of nano boron

Nano B was prepared by the encapsulation method using 15.2 g borax, 0.1 g nano Zn and gum acacia as a binding agent. The precipitate was washed, air-dried and calcined at 500 °C for 45 min (9). The HR-TEM analysis revealed spherical, crystalline nanoparticles with slight agglomeration due to the absence of surface-protecting ligands.

Treatments

The optimum concentrations of nano CaO, nano ZnO and nano B were determined through prior phytotoxicity studies conducted in polybag experiments during kharif 2020. Concentrations were selected based on preliminary phytotoxicity experiments in which no visible injury symptoms were observed. Based on those results, 19 treatments were selected for evaluation under field conditions (Table 1). These treatments comprised foliar application of both nano and conventional sources of Ca, Zn and B. Nano CaO was applied at 500 and 600 ppm, nano ZnO at 750 and 1000 ppm and nano B at 300 and 400 ppm, either individually or in different combinations. Conventional nutrient sources, namely calcium nitrate at 2 g L⁻¹, zinc sulphate at 5 g L⁻¹ and B (disodium octaborate tetrahydrate) at 1 g L⁻¹, were also included as individual treatments as well as in combination. An untreated control without Ca, Zn and B application was maintained for comparison.

Foliar sprays were applied at 30 and 45 days after transplanting (DAT) in all treatments except the control. The volume of spray fluid was 500 mL ha⁻¹. The recommended dose of fertilisers (RDF: 150 : 60 : 60 kg NPK ha⁻¹) was applied uniformly to all plots as the basal nutrient schedule. Nitrogen was applied as urea (46 % N) in three equal splits at 30, 45 and 60 DAT; P was supplied as diammonium phosphate (18 % N and 46 % P₂O₅) and K was applied as muriate of potash (60 % K₂O); both were applied basally at the time of planting.

Crop husbandry

Seeds of tomato cv. US-440 were sown in protrays at a seed rate of 175–200 g ha⁻¹. Healthy and uniform seedlings (measuring 10–15 cm in height and bearing 3–4 leaves) were transplanted into the main field at 23 days after sowing. Weed management consisted of a pre-emergence application of pendimethalin at 1 kg active ingredient ha⁻¹, followed by hand weeding at 25–30 and 55–60 DAT. Irrigation was scheduled based on crop need using the plant indicator approach. Fruits were harvested at the red-ripe stage, while two border rows on either side of each plot were excluded as guard plants to avoid border effects.

Table 1. Treatment details for field experiment

Treatment	Description
T ₁	Foliar spraying with nano CaO 600 ppm
T ₂	Foliar spraying with nano CaO 500 ppm
T ₃	Foliar spraying with nano ZnO 1000 ppm
T ₄	Foliar spraying with nano ZnO 750 ppm
T ₅	Foliar spraying with nano B 400 ppm
T ₆	Foliar spraying with nano B 300 ppm
T ₇	Foliar spraying with nano CaO 600 ppm + nano ZnO 1000 ppm + nano B 400 ppm
T ₈	Foliar spraying with nano CaO 600 ppm + nano ZnO 750 ppm + nano B 400 ppm
T ₉	Foliar spraying with nano CaO 600 ppm + nano ZnO 1000 ppm + nano B 300 ppm
T ₁₀	Foliar spraying with nano CaO 600 ppm + nano ZnO 750 ppm + nano B 300 ppm
T ₁₁	Foliar spraying with nano CaO 500 ppm + nano ZnO 1000 ppm + nano B 400 ppm
T ₁₂	Foliar spraying with nano CaO 500 ppm + nano ZnO 1000 ppm + nano B 300 ppm
T ₁₃	Foliar spraying with nano CaO 500 ppm + nano ZnO 750 ppm + nano B 400 ppm
T ₁₄	Foliar spraying with nano CaO 500 ppm + nano ZnO 750 ppm + nano B 300 ppm
T ₁₅	Foliar spraying with ZnSO ₄ at 5 g L ⁻¹
T ₁₆	Foliar spraying with CaNO ₃ at 2 g L ⁻¹
T ₁₇	Foliar spraying with B at 1 g L ⁻¹
T ₁₈	Foliar spraying with ZnSO ₄ at 5 g L ⁻¹ + CaNO ₃ at 2 g L ⁻¹ + B at 1 g L ⁻¹
T ₁₉	Control (without Zn, Ca and B application)

Zn: zinc; Ca: calcium; B: boron; CaO: calcium oxide; ZnO: zinc oxide; ZnSO₄: zinc sulphate; CaNO₃: calcium nitrate.

Observations recorded

Fruit quality parameters

For fruit quality assessment, three healthy, uniform-sized fruits at the red-ripe stage fruits were collected from each of five randomly tagged plants in each of the 3 replications during the third harvest, resulting in a total of 45 fruits (3 fruits × 5 plants × 3 replications). Fruit quality parameters were assessed using standard analytical procedures. Total soluble solids (TSS) content was measured with a hand refractometer and expressed in °Brix. Fruit pH was measured using a digital pH meter (Elico LI 610). Ascorbic acid content was estimated by the standard 2,6-dichlorophenolindophenol (DCPIP) titrimetric method (10) and expressed as mg 100 g⁻¹ fresh weight. Titratable acidity was determined by titration against sodium hydroxide (NaOH) using phenolphthalein as an indicator and expressed as percentage (10).

Total and reducing sugars were estimated using the Fehling's solution titration method and expressed as percentage, while non-reducing sugars were calculated as the difference between total sugars and reducing sugars. Lycopene content was estimated by using spectrophotometric method and expressed as milligram per 100 gram (mg 100 g⁻¹) (11).

Physiological disorders

The incidence of blossom end rot and fruit cracking was recorded at each harvest and expressed as the percentage of affected fruits per plot.

Blossom end rot incidence (%) =

$$\frac{\text{Number of fruits affected by blossom end rot}}{\text{Total number of fruits harvested}} \times 100$$

Fruit cracking incidence (%) =

$$\frac{\text{Number of cracked fruits}}{\text{Total number of fruits harvested}} \times 100$$

Nutrient content in leaves and fruits

Leaf samples were collected at 30, 60, 90 and 120 DAT for nutrient analysis. At the final harvest, the most recently fully expanded leaves (4th–6th leaf from the shoot apex) were collected from five randomly selected plants per plot, with two leaves collected from each plant to obtain a composite sample for each replication.

Estimation of calcium (Ca) and zinc (Zn): Representative tomato leaf and fruit samples were collected from each treatment, washed with tap water followed by 0.1 N HCl and deionised water, oven-dried at 65–70 °C until constant weight and ground into a fine powder. A 0.5 g sample was digested using the nitric acid-perchloric acid wet digestion method with concentrated HNO₃-HClO₄ (10 : 4 mL). The digest was diluted to 50 mL with deionised water. Calcium and Zn concentrations were determined by atomic absorption spectrophotometric (AAS) method according to AOAC International, 2019, with Zn measured at a wavelength of 213.9 nm (12). Calcium content was expressed as percentage (%) dry weight, while Zn content was expressed as milligram per kilogram (mg kg⁻¹) dry weight.

Estimation of boron: Representative tomato leaf and fruit samples were collected, washed, oven-dried at 65–70 °C and ground into a fine powder. A 0.5 g sample was dry-ashed at 500–550 °C and the ash was dissolved in 0.36 N H₂SO₄ and diluted to 50 mL. Boron concentration was determined by the Azomethine-H colorimetric method using a UV-Visible spectrophotometer at 420 nm as described by a Handbook of Reference Methods for Plant Analysis and expressed as milligram per kilogram (mg kg⁻¹) dry weight (13).

Statistical analysis

The data were statistically analysed using the analysis of variance (ANOVA) technique appropriate for a RBD. The significance of treatment effects was tested using the *F*-test at the 5 % level of probability and wherever treatment effects were found to be significant, the critical difference (CD) was calculated at the 5 % level for comparison of means, while non-significant differences are indicated as NS. To enable comparison of parameters measured on different scales, selected variables were normalised using a min-max scaling approach, whereby values were rescaled between 0 and 1 based on the observed minimum and maximum values across all treatments. For parameters where lower values indicate better performance, such as TSS, blossom end rot (BER) and fruit cracking, the normalised values were inverted to ensure uniform interpretation. The normalised dataset was subsequently used to generate comparative visualisations, including combined performance plots and radar charts, wherein higher normalised values consistently represent superior treatment performance (14). All graphical visualisations were generated using Python (Jupyter Notebook environment).

Results and Discussion

Fruit quality parameters

The data pertaining to fruit quality parameters, viz., TSS, pH, ascorbic acid, titratable acidity, total sugars, reducing sugars, non-reducing sugars and lycopene content as influenced by individual and combination foliar application of nano CaO, nano ZnO and nano B are presented in Table 2 and graphically illustrated in Fig. 1.

Total soluble solids (TSS)

Total soluble solids of fruit are a major quality parameter related to the fruit texture and composition. The TSS in tomato fruits consist mainly of soluble sugars, predominantly glucose and fructose, along with organic acids, which collectively determine fruit sweetness and overall flavour (15). During ripening, polysaccharides degrade to simple sugars resulting in a rise in TSS.

Total soluble solids is an important quality indicator that reflects the sugar and other soluble solid content of fruit. The lowest pooled TSS (3.59 °Brix) was recorded in T₇ (nano CaO 600 ppm +

nano ZnO 1000 ppm + nano B 400 ppm), which was statistically on par with T₈–T₁₄. In contrast, the significantly highest TSS (4.69 °Brix) was recorded in the untreated control.

The reduction in TSS with combined nanonutrient treatments may be attributed to reduced metabolic activity and respiration, which delayed the ripening process. Lower respiration rate results in less conversion of carbohydrates into sugars, thereby resulting in reduced TSS in fruits (16). Boron deficiency is often associated with impaired Ca utilisation, leading to a combined deficiency of both nutrients. Such deficiencies tend to accelerate fruit ripening. Consequently, untreated fruits, being more prone to these deficiencies, exhibit faster ripening and higher sugar accumulation, resulting in elevated TSS compared to treated fruits. These results agree with the findings in cherry tomato (17).

The combined nanonutrients treatment also increased the number of fruits per plant, average fruit weight and fruit yield by 15.98, 19.38 and 38.79 % respectively over the control. These improvements indicate that the foliar application of nanonutrients

Table 2. Effect of foliar spraying of nano CaO, ZnO and boron on quality parameters of tomato fruits (pooled data)

Treatment	TSS (°Brix)	pH	Ascorbic acid (mg 100 g ⁻¹)	Titratable acidity (%)	Total sugars (%)	Reducing sugars (%)	Non-reducing sugars (%)	Lycopene (mg 100 g ⁻¹)
T ₁	3.93	4.55	24.67	0.39	3.33	2.91	0.42	6.16
T ₂	3.98	4.50	24.63	0.39	3.46	2.96	0.50	6.18
T ₃	4.09	4.55	23.33	0.36	3.63	3.13	0.48	6.28
T ₄	4.08	4.53	23.41	0.35	3.68	3.16	0.52	6.32
T ₅	4.01	4.55	24.49	0.38	3.50	3.06	0.44	6.22
T ₆	4.06	4.54	24.36	0.38	3.56	3.07	0.49	6.25
T ₇	3.59	4.61	26.41	0.51	2.70	2.23	0.47	5.16
T ₈	3.62	4.50	26.28	0.51	2.75	2.26	0.49	5.18
T ₉	3.65	4.49	26.02	0.49	2.87	2.31	0.56	5.23
T ₁₀	3.75	4.52	25.82	0.50	3.03	2.40	0.63	5.32
T ₁₁	3.68	4.59	25.93	0.48	2.94	2.35	0.59	5.28
T ₁₂	3.78	4.51	25.52	0.46	3.09	2.40	0.69	5.41
T ₁₃	3.80	4.45	25.44	0.46	3.12	2.43	0.69	5.48
T ₁₄	3.79	4.48	25.37	0.46	3.21	2.55	0.67	5.59
T ₁₅	4.48	4.54	20.02	0.31	3.71	3.26	0.45	6.13
T ₁₆	4.29	4.53	21.42	0.33	3.68	3.19	0.49	6.03
T ₁₇	4.32	4.47	21.31	0.32	3.70	3.24	0.46	6.12
T ₁₈	3.89	4.50	25.32	0.42	3.29	2.68	0.60	5.63
T ₁₉	4.69	4.57	18.32	0.27	3.76	3.50	0.25	6.45
CD ($p = 0.05$)	0.25	NS	1.47	0.05	0.42	0.21	0.08	0.38

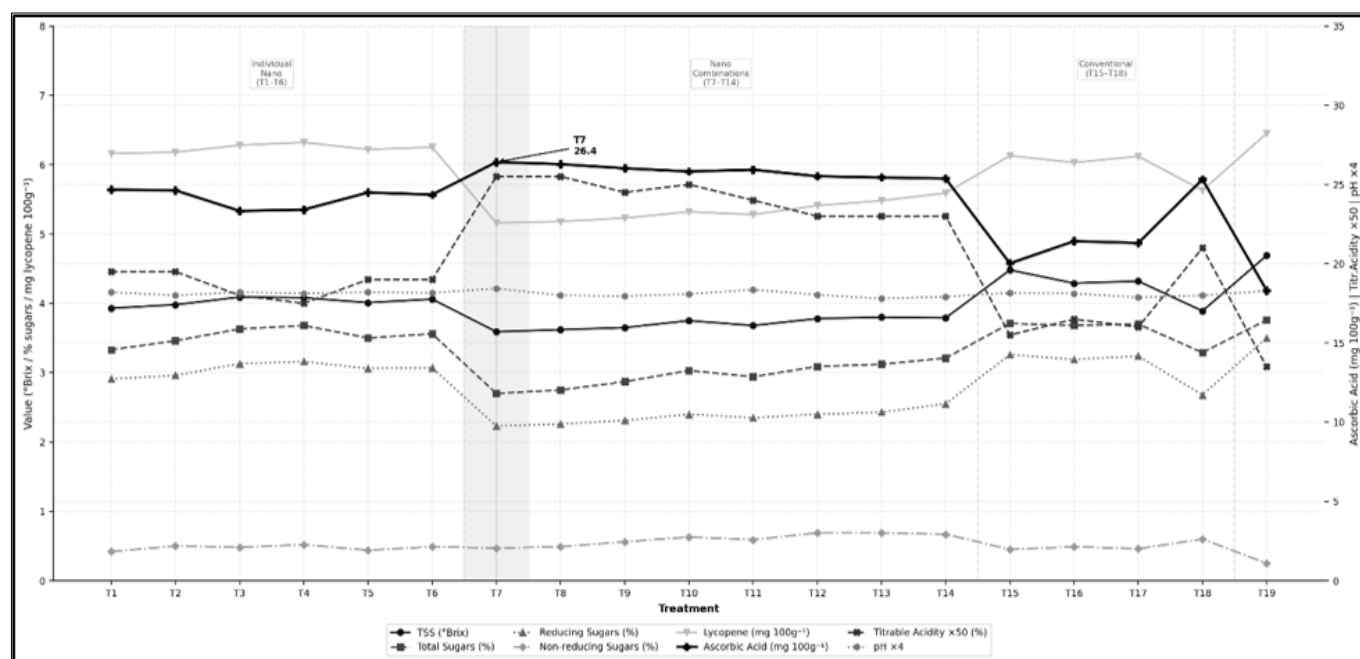


Fig. 1. Effect of foliar application of nano CaO, nano ZnO and nano boron (individually and in combinations) on fruit quality parameters of tomato (*Solanum lycopersicum* L.) cv. US-440-total soluble solids (TSS), pH, ascorbic acid, titratable acidity, total sugars, reducing sugars, non-reducing sugars and lycopene content (pooled data, rabi 2020–21 and 2021–22).

promoted greater assimilate production and fruit development. However, the increased fruit size and higher moisture content likely diluted the concentration of soluble sugars in the fruit juice, resulting in lower TSS values. Although the control recorded higher TSS, the combined nano CaO + nano ZnO + nano B treatment resulted in superior overall fruit quality by improving yield, firmness, shelf life and mineral nutritional quality. The lower TSS in the treated fruits can be considered a consequence of increased fruit biomass production and dilution effect (18).

pH

Foliar application of individual and combined nano CaO, nano ZnO and nano B treatments did not result in significant differences in fruit pH.

Ascorbic acid content

The significantly highest pooled ascorbic acid content (26.41 mg 100 g⁻¹) was recorded in T₇ (nano CaO 600 ppm + nano ZnO 1000 ppm + nano B 400 ppm), followed by T₈, T₉, T₁₀, T₁₁ and T₁₂, which were statistically at par with T₇. The significantly lowest ascorbic acid content (18.32 mg 100 g⁻¹) was recorded in the untreated control.

The increase in ascorbic acid content under combined nanonutrient treatments may be attributed to the beneficial role of each nutrient. Nano CaO delays metabolic activities including respiration rate and ethylene production, thereby helping to preserve ascorbic acid. Nano ZnO application may enhance ascorbic acid accumulation by improving Zn-mediated metabolic processes, photosynthetic activity and antioxidant defence mechanisms, which can promote precursor availability and regulate enzymes involved in ascorbic acid biosynthesis. While nano B promotes Ca absorption, strengthens membrane integrity and slows degradation of ascorbic acid during ripening. The combined application of nanonutrients was more effective than their individual nanonutrient application and the present observations are consistent with the findings in tomato (19) and in chilli (20).

Titrateable acidity

Titrateable acidity is an important maturity index and it represents the sum of all fixed and volatile acids present in the fruit. Significantly highest pooled titrateable acidity (0.51 %) was recorded with T₇ which was statistically at par with T₈. In contrast, the significantly lowest acidity (0.27 %) was observed in untreated control.

The higher titrateable acidity under nanonutrient treatments attributed to the role of nano CaO in delaying fruit ripening and reducing the respiration rate, which in turn minimises the hydrolysis of organic acids during storage and ripening (21). Nano ZnO influences titrateable acidity through its role in carbohydrate metabolism and enzyme synthesis. Nano B increases the titrateable acidity by promoting Ca absorption. These results are in agreement with findings in tomato (19, 22) and in cherry tomato (17).

Sugars (total, reducing and non-reducing)

Sugar accumulation is closely associated with fruit ripening and contributes substantially to tomato flavour and consumer acceptance. Reduced sugar accumulation likely reflects delayed ripening induced by nanonutrient treatments. To prolong shelf life, it is desirable to maintain sugars at a minimum level. An increase in sugars with ripening might be due to the metabolic breakdown of polysaccharides into water-soluble sugars and organic acids into carbon dioxide (23).

Minimum pooled total sugars (2.70 %) and reducing sugars (2.23 %) were recorded with T₇, which was at par with T₈, T₉, T₁₀, T₁₁, T₁₂ and T₁₃. In contrast, significantly higher total sugars (3.76 %) and reducing sugars (3.50 %) were recorded with the control.

The combination of nano CaO, nano ZnO and nano B reduced sugar accumulation by retarding carbohydrate hydrolysis and overall metabolic activity in fruits. Nano CaO reduces the activity of polysaccharide hydrolysing enzymes, thereby lowering respiration and sugar conversion during ripening (17, 10). Nano B influenced total sugars and reducing sugars by affecting carbohydrate metabolism. Non-reducing sugars were significantly highest (0.69 %) in T₁₂ and T₁₃, whereas the lowest (0.25 %) was observed with the control. These results are consistent with findings in strawberry (24) and tomato (25).

Lycopene content

Significantly lowest lycopene content (5.16 mg 100 g⁻¹) was recorded with T₇, which was at par with T₈ to T₁₃, while significantly highest lycopene content (6.45 mg 100 g⁻¹) was recorded with the control.

The lower lycopene accumulation observed in nanonutrient-treated fruits is attributed to delayed ripening and altered assimilate partitioning. Calcium and B are known to influence the ethylene-mediated ripening process, thereby slowing lycopene biosynthesis during fruit maturation (26). Although lower lycopene at harvest indicates delayed ripening, the extended shelf life associated with treated fruits provides a clear commercial advantage.

Lycopene accumulation in tomato is a dynamic process influenced by fruit developmental stage, ripening rate, temperature, light intensity and carbohydrate availability. The improved nutritional status due to nanonutrient application promoted rapid cell division, fruit expansion and biomass accumulation, resulting in a greater sink size. Consequently, assimilates preferentially utilised for structural growth and fruit enlargement rather than for the synthesis of secondary metabolites such as lycopene.

Furthermore, Ca maintains cell wall integrity, stabilises cell membranes and reduces ethylene sensitivity, thereby delaying ripening-related metabolic changes and pigment development. The Zn and B also regulate carbohydrate metabolism, nutrient translocation and carbon partitioning, further influencing the balance between primary growth and carotenoids biosynthesis. As a result, lycopene accumulation at harvest was lower in nanonutrient-treated fruits.

In contrast, the higher lycopene content in control fruits recorded due to smaller fruit size, lower yield, early senescence and relatively concentrated pigment accumulation in fruit tissues.

Physiological disorders

The data pertaining to physiological disorders viz., blossom end rot and fruit cracking, as influenced by different treatments are presented in Table 3 and illustrated in Fig. 2.

Blossom end rot

Blossom end rot is a physiological disorder primarily associated with calcium deficiency that significantly reduces marketable yield of tomato fruits. Significantly lowest incidence of blossom end rot (2.93 %) was recorded with T₇ (nano CaO 600 ppm + nano ZnO 1000 ppm + nano B 400 ppm), which was on par with T₈, T₉, T₁₀, T₁₁, T₁₂ and T₁₃. In contrast, the highest incidence (7.02 %) was recorded in the control.

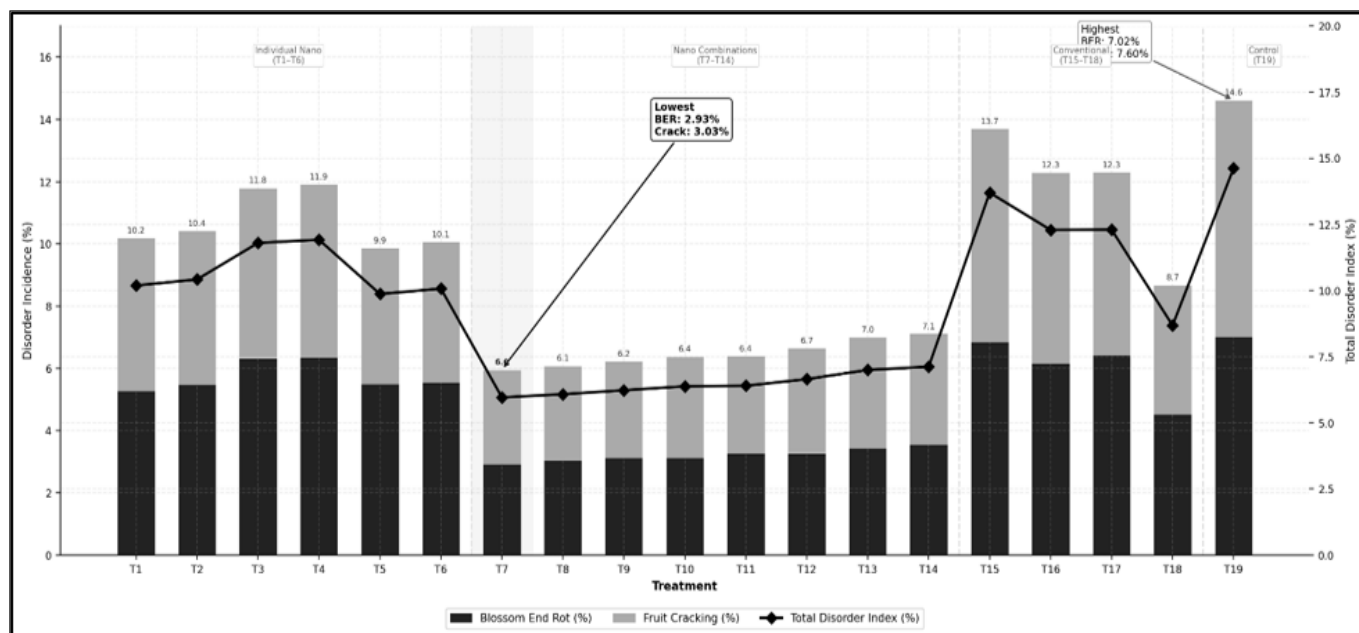


Fig. 2. Incidence of blossom end rot (%), fruit cracking (%) and total disorder index (%) in tomato (*Solanum lycopersicum* L.) cv. US-440 as influenced by foliar application of nano CaO, nano ZnO and nano boron individually and in combinations (pooled data, rabi 2020–21 and 2021–22).

Table 3. Effect of foliar spraying of nano CaO, ZnO and boron on physiological disorders of tomato (pooled data)

Treatment	Blossom end rot (%)	Fruit cracking (%)
T ₁	5.27	4.92
T ₂	5.47	4.95
T ₃	6.33	5.47
T ₄	6.37	5.55
T ₅	5.50	4.37
T ₆	5.55	4.52
T ₇	2.93	3.03
T ₈	3.05	3.03
T ₉	3.13	3.10
T ₁₀	3.13	3.25
T ₁₁	3.27	3.13
T ₁₂	3.28	3.37
T ₁₃	3.43	3.57
T ₁₄	3.55	3.57
T ₁₅	6.85	6.85
T ₁₆	6.17	6.12
T ₁₇	6.42	5.88
T ₁₈	4.53	4.15
T ₁₉	7.02	7.60
CD ($p = 0.05$)	0.52	0.47

Application of Ca and B either alone or in combination reduces the percentage of blossom end rot compared to the Zn treatment and the control. Calcium plays a vital role in stabilising the plasma membrane and pectin constituents of the cell wall, thereby reducing blossom end rot of tomato fruits. Boron further facilitates the uptake of Ca, magnesium (Mg), sodium (Na) and Zn, improves Ca metabolism and strengthens cell wall structure through cross-linking of pectic compounds, which collectively helps to reduce this disorder (27, 28). Combined foliar application of nano CaO, nano ZnO and nano B proved significantly more effective than either individual application of nanonutrients or conventional CaNO_3 treatment, supporting the findings in tomato (29, 30).

Fruit cracking

Boron deficiency is the primary causal factor of fruit cracking in tomato. Boron plays an important roles in cell wall synthesis, lignification and structural integrity.

Significantly lowest fruit cracking incidence (3.03 %) was recorded with both T₇ and T₈, which were at par with T₉, T₁₀, T₁₁ and T₁₂. In contrast, significantly highest incidence (7.60 %) was recorded with the control.

The results revealed that, both B and Ca play an important role in maintaining Ca pectate associations in the cell wall and promote cell wall cross-linking through stabilisation of pectic compounds. This improves the structural integrity of fruit tissues and reduces the probability of cracking (28, 31). The combined application of Ca and B was more effective than either element alone in reducing fruit cracking, consistent with the findings in tomato (28).

Nutrient content in leaves

The data on Ca, Zn and B content in tomato leaves at different growth stages (30, 60, 90 and 120 DAT) as influenced by various treatments are presented in Table 4 and further visualised in Fig. 3 and 4. No significant differences among treatments were observed at 30 DAT, indicating that the initial leaf nutrient status was uniform across all plots prior to the first foliar spray. A declining trend in leaf nutrient content from 60 to 120 DAT was observed across all treatments, corresponding to translocation of nutrients along with photosynthates from leaves to developing fruits in later stages of crop growth (32).

Calcium content in leaves

Significantly highest pooled Ca content in tomato leaves at 60, 90 and 120 DAT (1.89, 1.86 and 1.81 % respectively) was recorded with T₇ (nano CaO 600 ppm + nano ZnO 1000 ppm + nano B 400 ppm), which was at par with T₈, T₉, T₁₀, T₁₁, T₁₂, T₁₃ and T₁₄. In contrast, significantly lowest Ca content (0.93, 0.89 and 0.86 % at 60, 90 and 120 DAT) was recorded with the control. These findings are in agreement with reports in cherry tomato (11), *Moringa oleifera* Lam. (33) and peach leaves (34).

Zinc content in leaves

Significantly highest pooled Zn content in tomato leaves at 60, 90 and 120 DAT (38.20, 37.48 and 35.58 ppm respectively) was

Table 4. Effect of foliar spraying of nano CaO, ZnO and boron on Ca (%), Zn (ppm) and boron (ppm) content in tomato leaves (pooled data) at 60, 90 and 120 DAT

Treatment	Ca content in leaves (%)			Zn content in leaves (ppm)			Boron content in leaves (ppm)		
	60 DAT	90 DAT	120 DAT	60 DAT	90 DAT	120 DAT	60 DAT	90 DAT	120 DAT
T ₁	1.66	1.63	1.60	21.63	21.52	20.84	25.77	24.25	21.97
T ₂	1.64	1.63	1.58	20.64	20.68	19.60	25.38	22.54	21.93
T ₃	1.11	1.08	1.04	20.36	20.10	19.32	26.42	24.51	22.44
T ₄	1.09	1.07	1.04	19.66	19.46	19.18	25.41	23.65	20.29
T ₅	1.24	1.21	1.17	27.41	25.86	23.64	32.50	31.37	29.35
T ₆	1.23	1.20	1.16	27.60	25.97	24.81	33.69	31.83	28.12
T ₇	1.89	1.86	1.81	38.20	37.48	35.58	42.43	40.16	37.79
T ₈	1.88	1.84	1.82	37.67	36.56	34.13	42.23	39.83	36.89
T ₉	1.88	1.84	1.81	37.03	35.44	31.50	42.50	40.61	38.34
T ₁₀	1.84	1.80	1.78	36.38	34.33	30.77	41.68	38.74	34.13
T ₁₁	1.86	1.83	1.82	36.89	35.16	30.96	41.66	39.89	36.78
T ₁₂	1.85	1.79	1.76	36.16	33.38	29.84	40.82	37.68	35.47
T ₁₃	1.84	1.82	1.79	35.39	31.50	28.67	40.53	37.31	32.24
T ₁₄	1.80	1.74	1.70	35.35	30.24	27.53	40.35	36.99	32.74
T ₁₅	1.06	1.05	1.03	27.71	24.22	21.55	24.78	22.17	20.49
T ₁₆	1.39	1.39	1.35	19.79	19.47	18.35	23.63	23.24	20.57
T ₁₇	1.14	1.13	1.09	19.54	19.45	19.02	25.77	27.21	25.98
T ₁₈	1.74	1.67	1.64	30.00	27.14	24.27	35.50	32.69	30.87
T ₁₉	0.93	0.89	0.86	18.74	18.43	18.34	22.17	21.32	20.46
CD ($p=0.05$)	0.11	0.13	0.12	2.51	3.27	3.38	2.51	3.33	2.43

Ca: calcium; Zn: zinc; B: boron; DAT: days after transplanting.

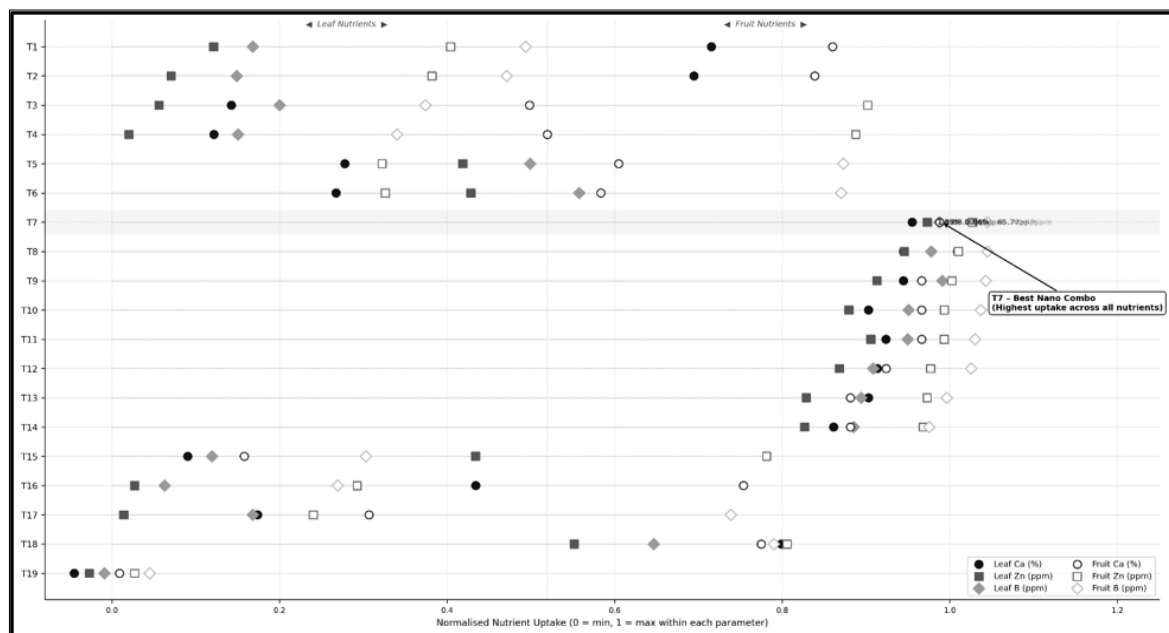


Fig. 3. Normalised uptake of calcium (Ca), zinc (Zn) and boron (B) in leaves (60 DAT) and fruits of tomato (*Solanum lycopersicum* L.) cv. US-440 as influenced by foliar application of nano CaO, nano ZnO and nano boron individually and in combinations - Cleveland dot plot with all six nutrient parameters on a common normalised scale (pooled data, rabi 2020–21 and 2021–22).

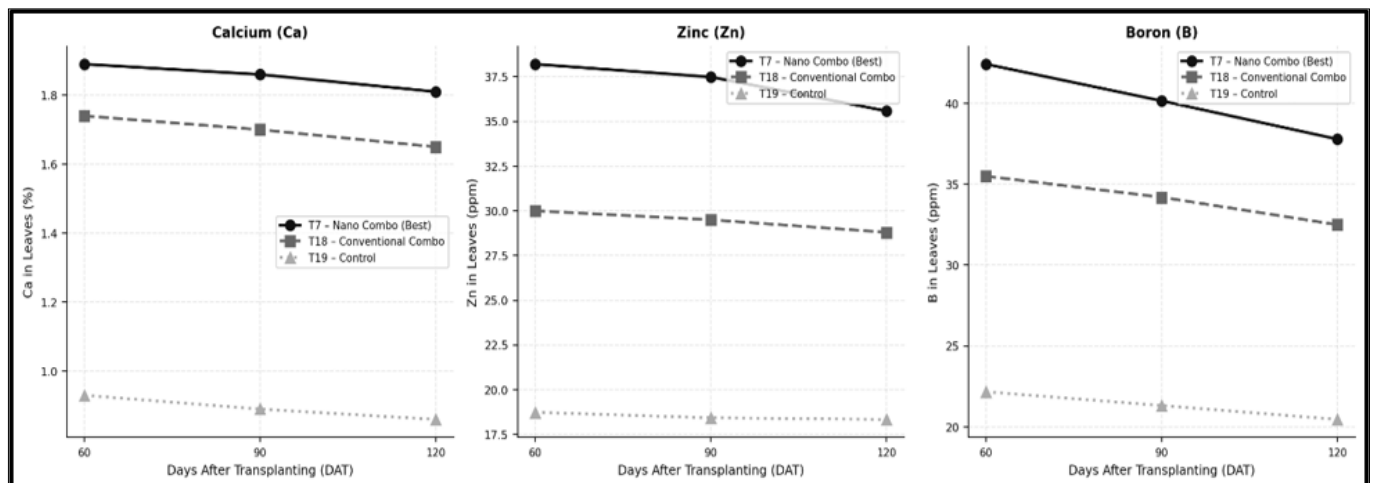


Fig. 4. Temporal dynamics of calcium (Ca, %), zinc (Zn, ppm) and boron (B, ppm) content in tomato (*Solanum lycopersicum* L.) cv. US-440 leaves at 60, 90 and 120 days after transplanting (DAT) for best nanonutrient combination (T₇: nano CaO 600 ppm + nano ZnO 1000 ppm + nano boron 400 ppm), conventional fertiliser combination (T₁₈) and untreated control (T₁₉) (pooled data, rabi 2020–21 and 2021–22).

recorded with T₇, which was at par with T₈, T₉ and T₁₀. In contrast, significantly lowest Zn content (18.74, 18.43 and 18.34 ppm) was recorded with the control. The individual nano ZnO treatments (T₃, T₄) also showed appreciable Zn accumulation in leaves compared to conventional ZnSO₄ treatment (T₁₅), indicating the higher absorption efficiency of nano ZnO. These findings are in agreement with reports in pecan nut trees (35) and pomegranate (36).

Boron content in leaves

Significantly highest pooled B content in leaves at 60, 90 and 120 DAT (42.43, 40.16 and 37.79 ppm respectively) was recorded with T₇, at par with T₈, T₉, T₁₀, T₁₁, T₁₂, T₁₃ and T₁₄. In contrast, significantly lowest B content (22.17, 21.32 and 20.46 ppm at 60, 90, 120 DAT respectively) was recorded with the control. Individual nano B treatments (T₅, T₆) demonstrated markedly higher leaf B content compared to conventional B treatment (T₁₇), indicating the enhanced foliar absorption efficiency of nano-sized B particles. These results are in agreement with the findings of previous studies in cherry tomato (17) and in faba bean (37).

Nutrient content in tomato fruits

The data on Ca, Zn and B content in tomato fruits as influenced by various treatments are presented in Table 5 and summarised in Fig. 3.

Table 5. Effect of foliar spraying of nano CaO, ZnO and boron on Ca (%), Zn (ppm) and B (ppm) content in tomato fruits (pooled data)

Treatment	Ca content in fruits (%)	Zn content in fruits (ppm)	B content in fruits (ppm)
T ₁	0.78	45.76	31.27
T ₂	0.77	45.04	30.74
T ₃	0.61	61.77	28.47
T ₄	0.62	61.31	27.68
T ₅	0.66	43.13	40.14
T ₆	0.65	43.25	40.08
T ₇	0.84	65.79	44.16
T ₈	0.85	65.25	44.17
T ₉	0.83	65.00	44.12
T ₁₀	0.83	64.71	43.98
T ₁₁	0.83	64.70	43.82
T ₁₂	0.81	64.18	43.71
T ₁₃	0.79	64.05	43.03
T ₁₄	0.79	63.90	42.54
T ₁₅	0.45	57.89	26.81
T ₁₆	0.73	42.17	26.02
T ₁₇	0.52	40.49	37.00
T ₁₈	0.74	58.67	38.20
T ₁₉	0.38	33.63	20.77
CD ($p = 0.05$)	0.05	3.25	2.32

Calcium content in tomato fruits

Significantly highest pooled Ca content in tomato fruits (0.85 %) was recorded with T₈ (nano CaO 600 ppm + nano ZnO 750 ppm + nano B 400 ppm), which was at par with T₇, T₉, T₁₀, T₁₁, T₁₂, T₁₃ and T₁₄. In contrast, significantly lowest Ca in fruits (0.38 %) was recorded with the control. The higher Ca content in fruits treated with nanonutrients was associated with a lower incidence of blossom end rot, as adequate calcium strengthens the plasmalemma and cell wall, particularly in the blossom-end tissues of the fruit. These results are in agreement with pepper (38), in cherry tomato (17).

Zinc content in tomato fruits

Significantly highest Zn content in fruits (65.79 ppm) was recorded with T₇, which was at par with T₈, T₉, T₁₀, T₁₁, T₁₂, T₁₃ and T₁₄. Significantly lowest Zn (33.63 ppm) was recorded with the control.

Notably, individual nano ZnO treatments (T₃: 61.77 ppm; T₄: 61.31 ppm) also recorded higher Zn content in fruits, which were

superior to conventional ZnSO₄ (T₁₅: 57.89 ppm). This indicates the improved translocation efficiency of nano ZnO from leaves to fruits. These results are consistent with the findings in radish (39) and in snap bean (40).

Boron content in tomato fruits

Significantly highest B content in fruits (44.17 ppm) was recorded with T₈ which were at par with T₇, T₉, T₁₀, T₁₁, T₁₂, T₁₃ and T₁₄. In contrast, significantly lowest B content (20.77 ppm) was recorded with the control. Individual nano B treatments (T₅: 40.14 ppm; T₆: 40.08 ppm) recorded a markedly higher B content in fruits, superior to conventional B (T₁₇: 37.00 ppm).

The higher nutrient content in leaves and fruits treated with nanonutrients compared to conventional nutrients may be attributed to the larger surface area of nanoparticles facilitating enhanced enzymatic and biochemical reactions, higher penetration of nanoparticles through the cuticle resulting in rapid absorption by plant cells and slow-release characteristics enabling prolonged nutrient availability (32). These results are similar to the findings in cherry tomato (17).

Superiority of nanonutrients over conventional fertilisers

Across most fruit quality, nutrient uptake and physiological disorder parameters, combined nanonutrient treatments produced superior responses compared with the corresponding conventional fertiliser treatments. The combined nanonutrient treatment [nano CaO (600 ppm) + nano ZnO (1000 ppm) + nano B (400 ppm)] consistently recorded higher leaf and fruit concentrations of Ca, Zn and B than the corresponding conventional fertilisers, indicating greater nutrient absorption and translocation efficiency. It also significantly reduced blossom end rot and fruit cracking. A comparative representation of treatment performance based on both actual and normalised values is presented in Fig. 5. The ability of nanonutrients to produce superior results at substantially lower application rates highlights their potential to reduce fertiliser inputs while maintaining or enhancing crop productivity. A multi-attribute performance comparison using normalised values further demonstrates the overall superiority of T₇ over the conventional treatment and control across key quality and nutrient parameters (Fig. 6).

Relationships among fruit quality, disorders and nutrient uptake

Correlation analysis

Pearson correlation analysis revealed significant ($p < 0.001$) relationships among leaf nutrient status, fruit quality attributes, physiological disorders and fruit nutrient concentrations (Fig. 7 and Table 6). Leaf Ca concentration was positively correlated with ascorbic acid ($r = 0.851$), titratable acidity ($r = 0.924$) and fruit Ca content ($r = 0.932$), whereas significant negative correlations were observed with TSS ($r = -0.893$), total sugars ($r = -0.909$), lycopene ($r = -0.891$), blossom end rot ($r = -0.944$) and fruit cracking ($r = -0.887$). Similarly, leaf Zn showed positive correlations with ascorbic acid ($r = 0.734$), titratable acidity ($r = 0.901$) and fruit Zn concentration ($r = 0.761$), but negative correlations with TSS ($r = -0.796$), lycopene ($r = -0.925$), blossom end rot ($r = -0.926$) and fruit cracking ($r = -0.865$). Leaf B also exhibited strong positive correlations with ascorbic acid ($r = 0.824$), titratable acidity ($r = 0.942$) and fruit B concentration ($r = 0.938$), while showing strong negative correlations with TSS ($r = -0.870$), lycopene ($r = -0.919$), blossom end rot ($r = -0.961$) and fruit cracking ($r = -0.938$).

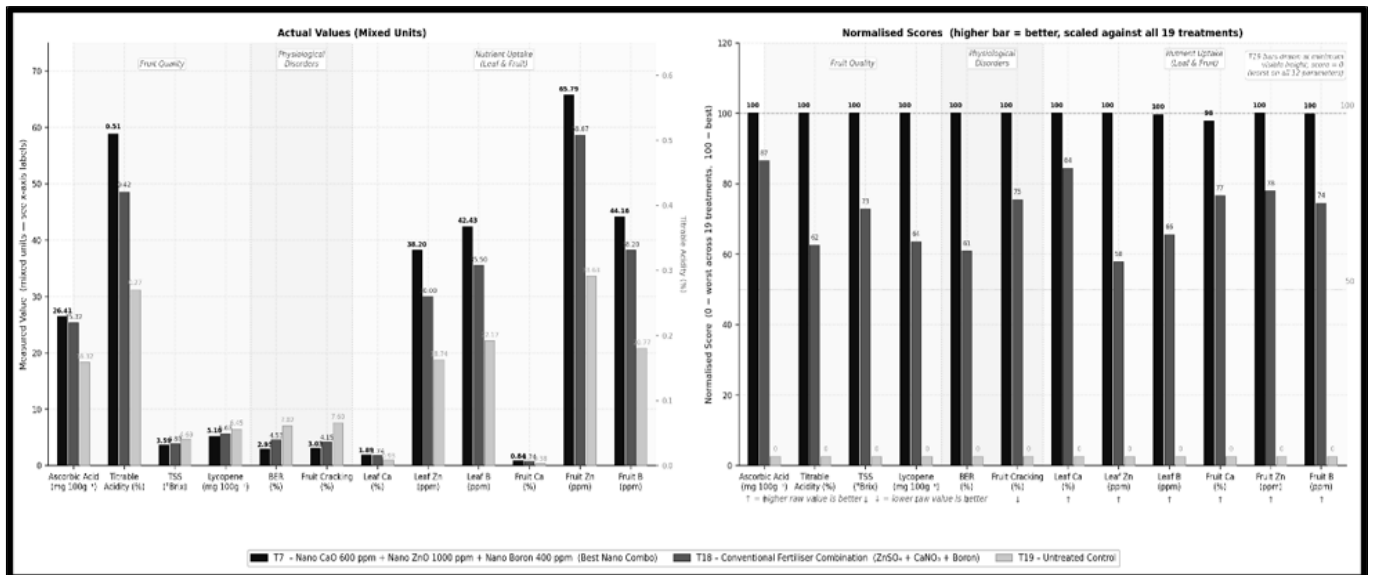


Fig. 5. Comparison of best nanonutrient combination (T₇: nano CaO 600 ppm + nano ZnO 1000 ppm + nano boron 400 ppm), conventional fertiliser combination (T₁₈: ZnSO₄ + CaNO₃ + boron) and untreated control (T₁₉) for key fruit quality and physiological disorder parameters - actual values (left panel) and normalised scores (right panel) for tomato (*Solanum lycopersicum* L.) cv. US-440 (pooled data, rabi 2020–21 and 2021–22).

Table 6. Pearson correlation coefficients (*r*) between leaf nutrient concentrations and selected fruit quality, physiological disorder and fruit nutrient parameters in tomato (*n* = 19 treatment means)

Variable 1	Variable 2	<i>r</i>	<i>R</i> ²	<i>p</i> -value	Direction
Leaf Ca (%)	Ascorbic acid (mg 100 g ⁻¹)	+0.851	0.724	< 0.001	Positive
Leaf Ca (%)	Titrateable acidity (%)	+0.924	0.853	< 0.001	Positive
Leaf Ca (%)	TSS (°Brix)	-0.893	0.797	< 0.001	Negative
Leaf Ca (%)	Lycopene (mg 100 g ⁻¹)	-0.891	0.794	< 0.001	Negative
Leaf Ca (%)	Total sugars (%)	-0.909	0.826	< 0.001	Negative
Leaf Ca (%)	Blossom end rot (%)	-0.944	0.890	< 0.001	Negative
Leaf Ca (%)	Fruit cracking (%)	-0.887	0.787	< 0.001	Negative
Leaf Ca (%)	Fruit Ca (%)	+0.932	0.869	< 0.001	Positive
Leaf Zn (ppm)	Ascorbic acid (mg 100 g ⁻¹)	+0.734	0.539	< 0.001	Positive
Leaf Zn (ppm)	Titrateable acidity (%)	+0.901	0.811	< 0.001	Positive
Leaf Zn (ppm)	TSS (°Brix)	-0.796	0.633	< 0.001	Negative
Leaf Zn (ppm)	Lycopene (mg 100 g ⁻¹)	-0.925	0.855	< 0.001	Negative
Leaf Zn (ppm)	Blossom end rot (%)	-0.926	0.858	< 0.001	Negative
Leaf Zn (ppm)	Fruit cracking (%)	-0.865	0.748	< 0.001	Negative
Leaf Zn (ppm)	Fruit Zn (ppm)	+0.761	0.579	< 0.001	Positive
Leaf B (ppm)	Ascorbic acid (mg 100 g ⁻¹)	+0.824	0.679	< 0.001	Positive
Leaf B (ppm)	Titrateable acidity (%)	+0.942	0.888	< 0.001	Positive
Leaf B (ppm)	TSS (°Brix)	-0.870	0.756	< 0.001	Negative
Leaf B (ppm)	Lycopene (mg 100 g ⁻¹)	-0.919	0.845	< 0.001	Negative
Leaf B (ppm)	Blossom end rot (%)	-0.961	0.923	< 0.001	Negative
Leaf B (ppm)	Fruit cracking (%)	-0.938	0.880	< 0.001	Negative
Leaf B (ppm)	Fruit B (ppm)	+0.938	0.879	< 0.001	Positive
Ascorbic acid	Titrateable acidity	+0.921	0.848	< 0.001	Positive
Ascorbic acid	TSS	-0.982	0.964	< 0.001	Negative
Ascorbic acid	Total sugars	-0.830	0.689	< 0.001	Negative
Ascorbic acid	Blossom end rot	-0.868	0.753	< 0.001	Negative
Ascorbic acid	Fruit cracking	-0.963	0.927	< 0.001	Negative
TSS	Total sugars	+0.905	0.820	< 0.001	Positive
TSS	Reducing sugars	+0.938	0.879	< 0.001	Positive
Total sugars	Reducing sugars	+0.975	0.950	< 0.001	Positive
Blossom end rot	Fruit cracking	+0.953	0.908	< 0.001	Positive
Blossom end rot	Fruit Ca	-0.875	0.766	< 0.001	Negative

Pearson correlation coefficients were calculated using pooled treatment means (*n* = 19). All correlations were significant at *p* < 0.001 (two-tailed); TSS: total soluble solids; Ca: calcium; B: boron; Zn: zinc.

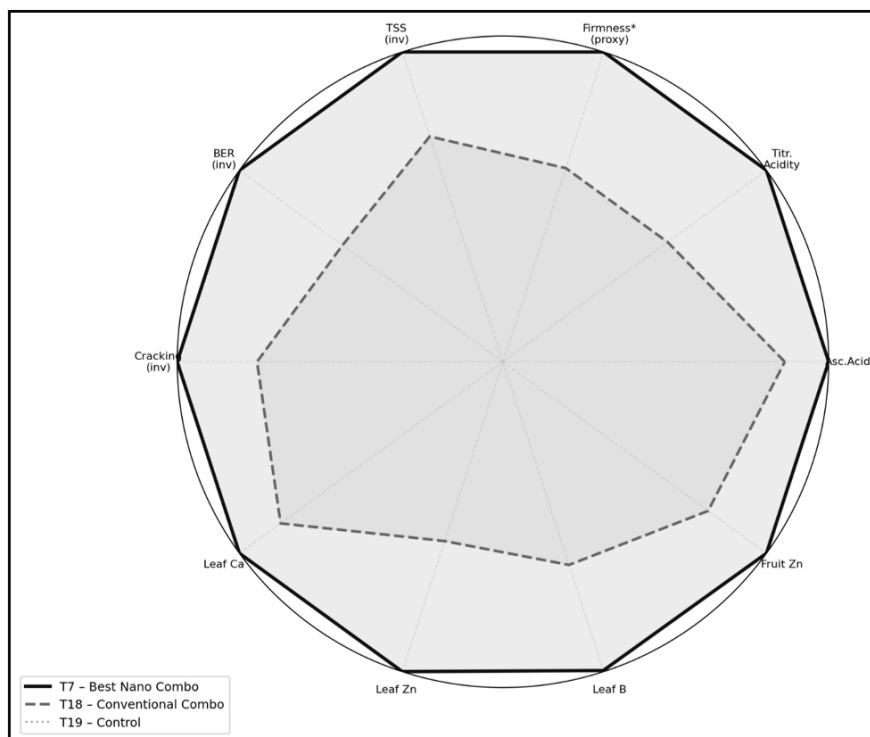


Fig. 6. Radar chart showing multi-attribute performance comparison of best nanonutrient combination (T₇: nano CaO 600 ppm + nano ZnO 1000 ppm + nano boron 400 ppm), conventional fertiliser combination (T₁₈) and untreated control (T₁₉) across nine normalised quality and nutrient attributes in tomato (*Solanum lycopersicum* L.) cv. US-440 (pooled data, rabi 2020–21 and 2021–22). Inverted metrics (total soluble solids (TSS), blossom-end rot (BER), fruit cracking) are inverted prior to normalisation so that outward = better performance on all axes.

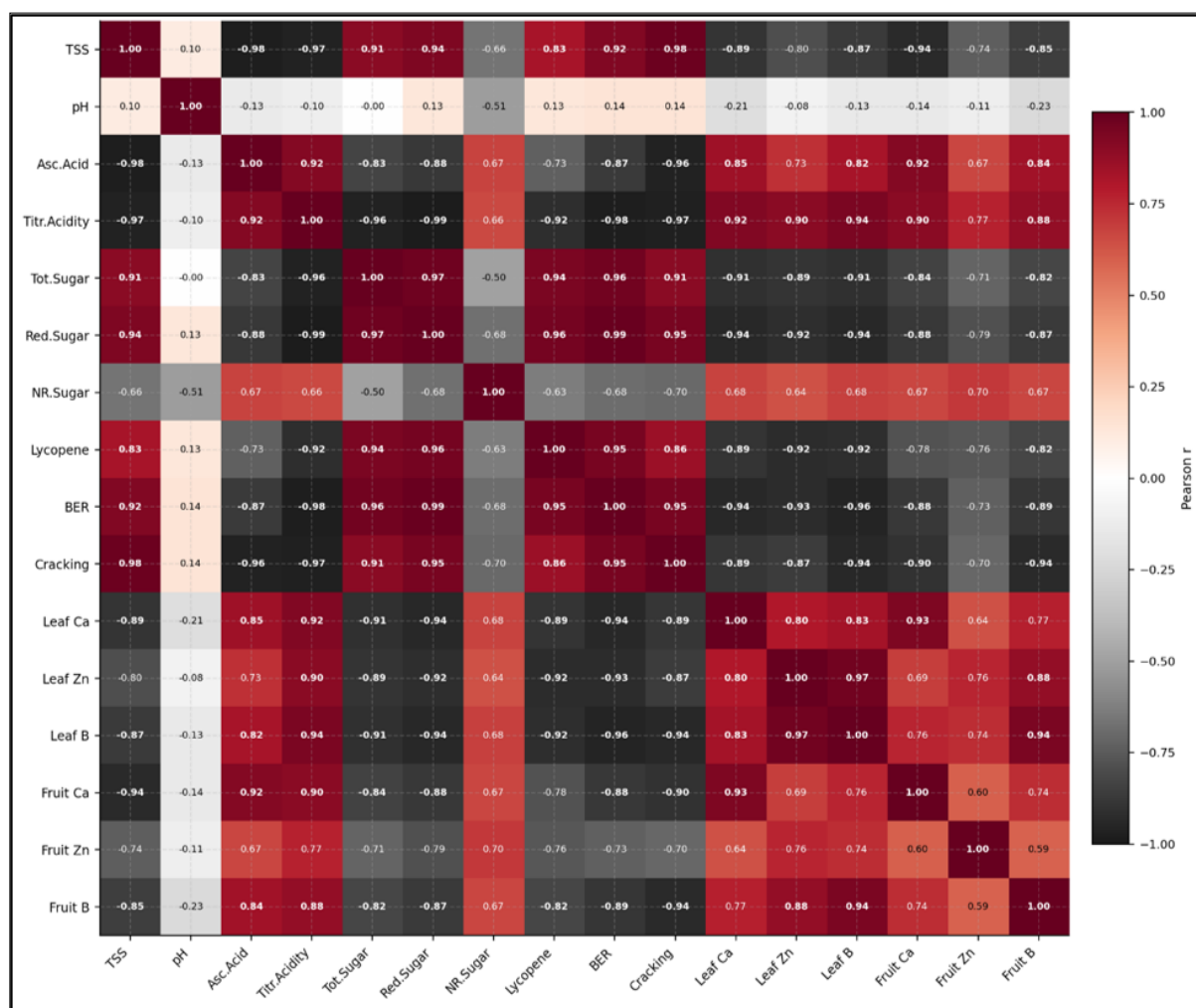


Fig. 7. Pearson correlation matrix among fruit quality parameters (total soluble solids (TSS), pH, ascorbic acid, titratable acidity, total sugars, reducing sugars, non-reducing sugars, lycopene), physiological disorder parameters (blossom end rot, fruit cracking) and nutrient uptake variables (leaf Ca, Zn, B; fruit Ca, Zn, B) across 19 treatments in tomato (*Solanum lycopersicum* L.) cv. US-440 (n = 19; pooled data, rabi 2020–21 and 2021–22).

Among fruit quality attributes, ascorbic acid was positively correlated with titratable acidity ($r = 0.921$) and negatively correlated with TSS ($r = -0.982$), total sugars ($r = -0.830$), blossom end rot ($r = -0.868$) and fruit cracking ($r = -0.963$). Total soluble solids were positively correlated with total sugars ($r = 0.905$) and reducing sugars ($r = 0.938$), while blossom end rot was strongly associated with fruit cracking ($r = 0.953$). Overall, these relationships indicate that improved Ca, Zn and B nutrition was associated with greater nutrient accumulation, higher ascorbic acid and titratable acidity and reduced incidence of physiological disorders. The observed negative associations with TSS and lycopene are consistent with delayed ripening under improved nutrient status and should not be interpreted as an enhancement of these quality attributes.

Regression analysis

Linear regression analysis further confirmed the relationships observed in the correlation analysis (Fig. 8). Leaf Ca showed a positive relationship with ascorbic acid ($R^2 = 0.724$) and a strong negative relationship with blossom end rot ($R^2 = 0.890$), indicating that improved Ca nutrition was associated with increased ascorbic acid content and reduced physiological disorder incidence. Likewise, leaf B exhibited a strong positive relationship with titratable acidity ($R^2 = 0.888$) and a negative relationship with fruit cracking ($R^2 = 0.880$), highlighting its role in maintaining fruit structural integrity. Leaf Zn was positively associated with ascorbic acid ($R^2 = 0.539$) and negatively associated with lycopene content ($R^2 = 0.855$), suggesting delayed pigment accumulation under improved nutrient status. All regression models were significant ($p < 0.001$), indicating that leaf Ca, Zn and B concentrations at 60 DAT were reliable predictors of fruit quality attributes, nutrient enrichment and physiological disorder incidence in tomato under field conditions.

The interrelationships among fruit quality attributes, physiological disorders and nutrient uptake variables were assessed using Pearson correlation analysis, which revealed distinct patterns of association among these parameters (Fig. 5). Strong positive and negative correlations were observed among key variables, indicating that nutrient status plays a crucial role in determining fruit quality and the incidence of physiological disorders. In addition, scatter plot analysis provided further insight into the nature and strength of relationships between leaf nutrient concentrations and important fruit quality and disorder traits (Fig. 6). The results suggest strong associations between nutrient status and fruit quality traits, indicating that Ca, Zn and B may play important roles in determining fruit quality and physiological disorder incidence.

Conclusion

The results of this two-season field experiment demonstrate that foliar application of nano CaO (600 ppm) + nano ZnO (1000 ppm) + nano boron (B) (400 ppm) (T₇) significantly improved fruit quality, nutrient uptake and physiological disorder management in tomato (*Solanum lycopersicum*) cv. US-440 under field conditions. This treatment recorded the highest ascorbic acid content (26.41 mg 100 g⁻¹), titratable acidity (0.51 %) along with the lowest total soluble solids (TSS) (3.59 °Brix), total sugars (2.70 %) and lycopene content (5.16 mg 100 g⁻¹), reflecting delayed, well-regulated fruit ripening.

Nutrient uptake was substantially enhanced under this treatment, with higher leaf calcium (Ca) (1.89 %), zinc (Zn) (38.20 ppm) and B (42.43 ppm) at 60 days after transplanting (DAT), as well as increased fruit Ca (0.84 %), Zn (65.79 ppm) and B (44.16 ppm). Physiological disorder incidence was markedly reduced, with blossom end rot limited to 2.93 % and fruit cracking to 3.03 %.

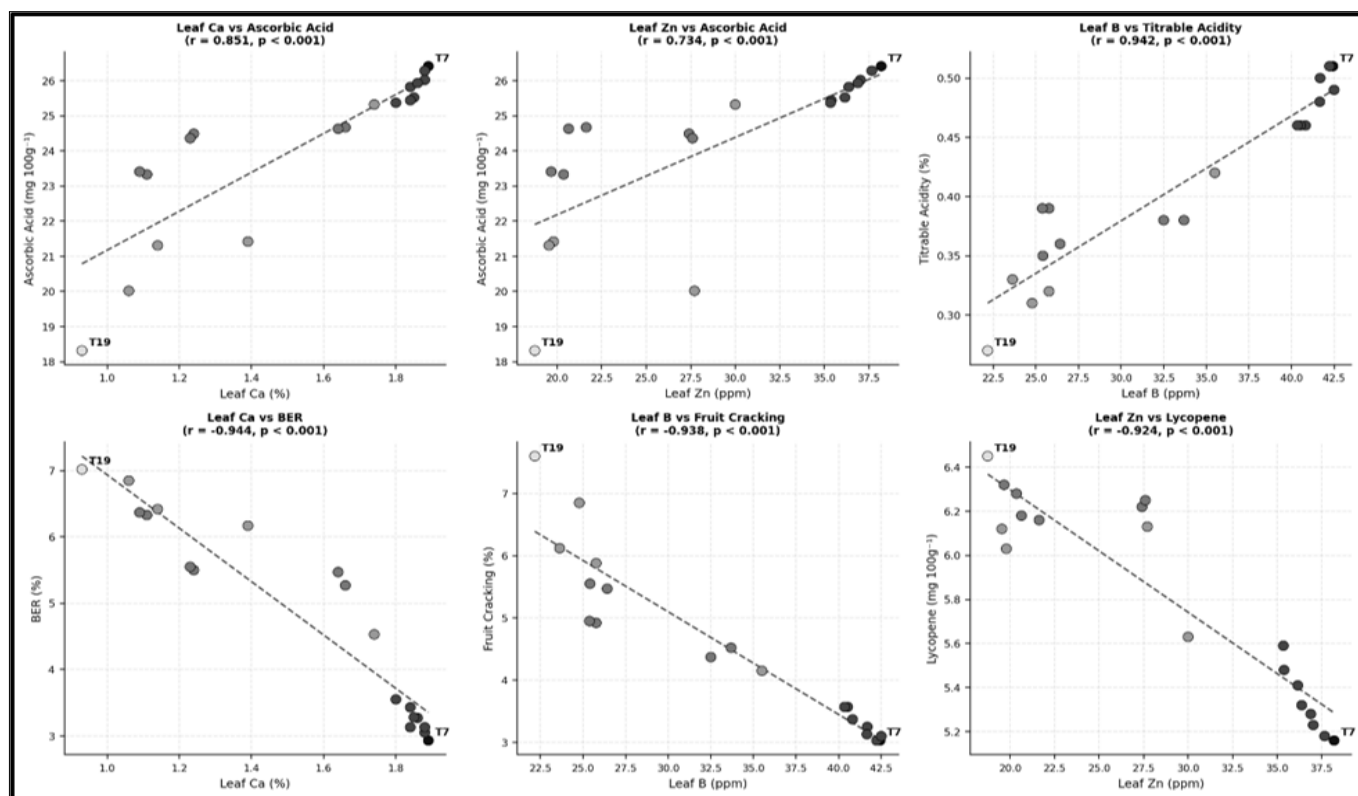


Fig. 8. Scatter plots showing relationships between leaf nutrient concentrations and key fruit quality/disorder parameters in tomato (*Solanum lycopersicum* L.) cv. US-440 across 19 treatments: (a) leaf Ca vs. ascorbic acid, (b) leaf Zn vs. ascorbic acid, (c) leaf B vs. titratable acidity, (d) leaf Ca vs. blossom end rot (BER), (e) leaf B vs. fruit cracking and (f) leaf Zn vs. lycopene. Dashed regression lines and Pearson r with p -values shown ($n = 19$; pooled data, rabi 2020–21 and 2021–22).

The nanonutrient combination was found to be superior to both individual nanonutrient applications and to the conventional nutrient combination ($\text{ZnSO}_4 + \text{CaNO}_3 + \text{B}$), producing higher yields using substantially lower quantities of nanonutrients per hectare. Based on the results of the present study, foliar application of nano CaO (600 ppm) + nano ZnO (1000 ppm) + nano B (400 ppm) at 30 and 45 DAT appears to be a promising strategy for improving fruit quality, nutrient enrichment and yield in tomato under the agro-climatic conditions of Telangana. Further research should focus on reducing the production cost of nanonutrients and validating these results under diverse agro-climatic conditions through multi-location trials.

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Authors' contributions

DR conceptualised and conducted the research work and prepared the manuscript. MP and MRK provided technical guidance and supervision. KA assisted in data analysis and manuscript preparation. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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

During the preparation of this work the authors used Claude (Anthropic) and ChatGPT (OpenAI) to assist with manuscript organisation, language editing, grammar improvement and refinement of the text. After using this tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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