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RESEARCH ARTICLE

Nourishing plant health and growth through the application of nutrients and plant growth regulator mixture in tomato

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Abstract

A pot culture experiment was conducted to investigate the influence of foliar application of nutrients and plant growth regulators (PGRs) on the growth and physiological attributes of tomatoes. The trial was carried out at the Department of Crop Physiology, Tamil Nadu Agricultural University, Coimbatore, India. Various nutrient-PGR combinations (T1-T9) were applied at two distinct developmental stages: 25 and 50 days after transplanting (DAT). The growth traits, including plant height, number of branches, leaf area and total dry matter production (TDMP), showed significant variation in response to the foliar application of the nutrient-PGR mixture. In addition, several physiological parameters, such as the chlorophyll index and chlorophyll fluorescence, exhibited notable differences among the treatments. Application of tomato booster II (T8), a foliar nutrient-PGR mixture containing nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), manganese (Mn), copper (Cu), naphthaleneacetic acid (NAA) and salicylic acid (SA), significantly enhanced plant growth. This was evidenced by increased plant height (34.1 cm and 67.2 cm) and leaf area (265.89 cm^2 and 1448.55 cm^2 $plant^{-1}$) at 30 and 60 DAT, respectively. Additionally, plants treated with tomato booster II (T8) showed improved root development, characterized by a substantial increase in total root length (4402.86 cm), root volume (58.9 cm^3) and root surface area (1807.84 cm^2). Moreover, T8-treated plants exhibited a significant increase in spectral reflectance, indicative of enhanced photosynthetic efficiency, reaching a maximum of 81.8% following two foliar applications. These results suggest that tomato booster II (T8) is a promising nutrient-PGR mixture for enhancing tomato growth and development.

Keywords

chlorophyll fluorescence; chlorophyll index; nutrients; PGRs; plant defense; spectral reflectance; tomato

Introduction

Tomato (*Solanum lycopersicum* L.) is a nutritious vegetable and is widely consumed throughout the world. Its phytochemical composition, including vitamin C, vitamin A, folic acid and antioxidants like lycopene (1), makes it a valuable dietary choice. Tomato provides a recommended dietary allowance (RDA) of 7% iron (Fe) for women and 10% for men (2). As a day-neutral plant, tomatoes can thrive in various climatic conditions. However, environmental factors such as salinity, drought, extreme temperatures and pests and diseases present major constraints to enhancing tomato growth and development.

Tomato plants are vulnerable to various diseases, including fusarium wilt, early blight, late blight, tomato leaf curl virus and tomato spotted wilt virus, which can lead to a decrease in yield (3). *Fusarium* wilt, caused by *Fusarium oxysporum*, severely affects the tomato vascular systems, leading to wilting and reduced yield (4). Early blight disease, caused by *Alternaria solani*, manifests as dark lesions on foliage, resulting in premature leaf abscission and diminished fruit quality (5). The tomato leaf curl virus significantly impacts global tomato production, resulting in substantial yield losses across diverse regions due to its detrimental impact on plant health and productivity (6).

Mineral nutrients such as N, P, K, boron (B) and zinc (Zn) are essential for improving plant health by activating enzymes essential for synthesizing defensive metabolites. They also indirectly influence microbial activity and the composition of root exudates (7). Mineral nutrients are crucial for plant protection, acting as essential structural components and regulators of metabolic functions (8). In addition, nutrient application significantly influences processes such as biomass accumulation and partitioning, ultimately contributing to crop yield formation (9).

PGRs such as naphthalene acetic acid (NAA) and gibberellic acid (GA) can enhance fruit yield and quality in modern agriculture. They are important for tomato flower initiation, fruiting, lycopene development, and ripening. Naphthalene acetic acid is frequently used to encourage fruit set in the production of various fruits and vegetables, such as tomato (10). SA induces systemic acquired resistance (SAR) in plants, strengthening their defense against both abiotic and biotic stresses (11). SA significantly improves tomato plant resistance to the tomato leaf curl virus by enhancing various physiological and biochemical mechanisms (12).

Nutrients and PGRs can work synergistically to enhance tomato plant health and growth. While nutrients such as N, P and K provide essential building blocks, PGRs (NAA, SA) regulate plant development (13). Their combined application can improve nutrient uptake, enhance photosynthesis and stimulate growth, resulting in higher yields and better fruit quality (14). This approach optimizes plant performance and enhances resilience to environmental stresses (15).

Farmers have long relied on insecticides and fungicides to protect their crops from pests and diseases. However, excessive use of these pesticides and fungicides may lead to the accumulation of toxic residues in the economic part of the plant (16). Applying suitable nutrients and PGRs can enhance crop growth and reduce the need for fungicide sprays, thereby decreasing their toxicity. The purpose of this study was to evaluate how nutrients and PGRs affect plant health and tomato yield.

Materials and Methods

Plant materials and growing conditions

Tomato seeds of the PKM 1 variety were sown in portrays filled with a growth medium consisting of vermicompost and coir peat in a 1:3 ratio. After seed germination, the seedlings were watered frequently. At 25 days after sowing, the seedlings were transplanted, with one plant placed per pot. For the pot culture study, red soil, sand and vermicompost were mixed in a 3:1:1 ratio.

The pot culture experiment was conducted in the open space of the greenhouse at Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India. The cultivation process followed the guidelines outlined in the "Crop Production Techniques of Horticultural Crops" (2020) by Tamil Nadu Agricultural University. The experiment was designed using a completely randomized block design with four replications. The pots were regularly watered to ensure adequate soil moisture throughout the plant's growth and development.

Treatment preparation and application

The spray solution for the nine different treatments (T1, T2, T3...T9) were prepared as per the composition presented in Table 1. Foliar applications of the various treatments were executed at two distinct developmental stages of the crop. The first spray was applied 25 DAT and the second spray was applied 50 DAT. The plants were thoroughly sprayed using a hand sprayer to prevent the drift of the treatment solution across different rows.

Table 1. Composition of treatments used for foliar application in tomato

Treatments	Composition
T1	Control (Water spray)
T2	KNO_3 (0.5%) + MAP (0.5%) + K_2SO_4 (0.5%) + Boric acid (0.3%)
T3	KNO_3 (0.5%) + K_2SO_4 (0.5%) + Ca $(NO_3)_2$ (0.5%) + Boric acid (0.3%)
T4	KNO_3 (0.5%) + MAP (0.5%) + K_2SiO_3 (0.5%) + Boric acid (0.3%)
T5	KNO_3 (0.5%) + K_2SO_4 (0.5%) + $MnCl_2$ (0.5%) + Boric acid (0.3%)
T6	KNO_3 (0.5%) + MAP (0.5%) + Boric acid (0.3%) + NAA
T7	Tomato booster I (N, P, K, Zn, B, NAA, SA)
T8	Tomato booster II (N, P, K, Mn, Cu, NAA, SA)
T9	Tomato booster III (N, K, Ca, Zn, B, Mn, Cu, NAA, SA)

MAP - Monoammonium phosphate; KNO_3 - Potassium nitrate; K_2SO_4 - Potassium sulfate; $Ca(NO_3)_2$ - Calcium nitrate; K_2SiO_3 - Potassium silicate; $MnCl_2$ - Manganese chloride; NAA - Naphthalene acetic acid; SA - Salicylic acid

Measurement of growth parameters

Plant height was measured from the base of the plant to the apex of the uppermost leaf using a measuring scale and expressed in centimetres (cm). Leaf area was quantified using a leaf area meter (LICOR, Model LI 3000, Lincoln, NE, USA). Leaf samples were collected from each replication of the nine treatments and analysed individually to determine the leaf area per plant, which was expressed in cm^2 $plant^{-1}$.

Root architectural traits were measured using the WinRHIZO Pro image system (Regent Instruments, Inc., Quebee Cit, QC, Canada). The roots were carefully uprooted with minimum damage, washed thoroughly with water to remove the soil particles and then cut into small portions. These portions were spread carefully in a transparent tray filled with water to minimize root overlap. This procedure was repeated for all nine experimental treatments, with four replicates per treatment. The resulting root images were analyzed and the average values for total root length, root volume, root surface area and average root diameter were

calculated and expressed in meters, cm^3, cm^2 and millimetres, respectively. After examining the root system, the plant samples were washed, shade-dried and oven-dried at 80°C for 48 hours. TDMP of the whole plant was recorded and expressed as g $plant^{-1}$.

Measurement of normalized difference vegetation index and physiological parameters

Measurement of the Normalized Difference Vegetation Index (NDVI) and physiological parameters was also conducted. The NDVI was used to assess plant health using a sensor that emits red and infrared light, detecting the amount of light reflected by the plant. Soil plant analytical development (SPAD) readings were taken with a chlorophyll meter (SPAD 502) developed by the SPAD section of Minolta, Japan. The Minolta SPAD-502 measures chlorophyll content based on the ratio of transmittance of light at wavelengths of 650 nm and 940 nm. The maximum quantum yield of photosystem II (chlorophyll fluorescence - Fv/Fm ratio) was measured for the fully expanded leaf using a handheld chlorophyll fluorometer (OS30p+, OptiScience, Hudson, NH). Before measurement, the leaf was dark-adapted for 30 minutes using a leaf clip.

Symptom severity rating

Four weeks after transplantation, tomato plants were visually examined for symptoms of whitefly-induced leaf damage. Symptom severity was assessed using a four-point scale (17): 0 (no symptoms), 1 (slight yellowing), 2 (moderate yellowing and curling), 3 (yellowing, curling and growth retardation) and 4 (severe yellowing, leaf cupping and curling with a size reduction, plants stop growth).

Assessing plant health through spectral reflectance characteristics

Ground-based hyperspectral reflectance assessments were conducted for each treatment during the flowering and fruit development stages using the GER 1500 portable spectroradiometer. Reflectance measurements were taken from a height of one meter above the crop canopy, ensuring the sensor was positioned perpendicular to the plants and facing them directly. For each treatment, spectral reflectance data collected by the GER 1500 spectroradiometer was processed using GER 1500 software and exported as signature files. These files were analyzed to generate spectral signatures, providing critical insights into the health of the tomato crop following the application of the nutrient-PGR mixture.

Spectral reflectance serves as an important indicator of plant health by revealing physiological and biochemical responses to environmental stressors. By analysing specific wavelengths of light reflected from plant surfaces, researchers can evaluate various plant health attributes and stress levels effectively.

Statistical analysis

The experiment was conducted using a completely randomized design, comprising nine treatments with four replications each. Analysis of Variance (ANOVA) was performed using SPSS 16.0 software to evaluate the differences among the treatments. Statistical significance was determined at a p-value of ≤0.05.

Results

Effect of foliar application of nutrient-PGR mixture on the growth traits of tomato

The growth parameters of tomato plants were evaluated at two stages of development: flowering (30 DAT) and fruit development (60 DAT). Two doses of the nutrient-PGR mixture were applied to the plants and their impact on growth traits was assessed (Table 2).

Table 2. Effect of foliar application of nutrient-PGR mixture on growth traits during flowering (30 DAT) and fruit development stage (60 DAT) in tomato

Treatments	Plant height (cm)		Number of branches		Leaf area (cm^2 $plant^{-1}$)		Total dry matter production (g $plant^{-1}$)	
	Flowering stage	Fruit development stage	Flowering stage	Fruit development stage	Flowering stage	Fruit development stage	Flowering stage	Fruit development stage
T1 – Control	25.3^{cd}	57.0^{c}	4.9^{f}	10.8^{e}	207.28^{d}	695.45^{d}	9.84^{e}	22.22^{e}
T2 - KNO_3 (0.5%) + MAP (0.5%) + K_2SO_4 (0.5%) + Boric acid (0.3%)	28.9^{bc}	59.4^{bc}	6.1^{de}	13.0^{cd}	219.32^{cd}	731.27^{d}	10.87^{de}	28.28^{bc}
T3 - KNO_3 (0.5%) + K_2SO_4 (0.5%) + Ca $(NO_3)_2$ (0.5%) + Boric acid (0.3%)	32.4^{ab}	65.2^{ab}	7.7^{bc}	15.8^{ab}	256.15^{ab}	1280.10^{b}	14.23^{ab}	35.93^{a}
T4 - KNO_3 (0.5%) + MAP (0.5%) + K_2SiO_3 (0.5%) + Boric acid (0.3%)	25.8^{cd}	56.6^{c}	6.9^{cd}	11.8^{de}	223.93^{cd}	1082.80^{c}	10.64^{e}	26.68^{cd}
T5 - KNO_3 (0.5%) + K_2SO_4 (0.5%) + $MnCl_2$ (0.5%) + Boric acid (0.3%)	25.1^{d}	56.4^{c}	5.6^{ef}	11.1^{e}	220.42^{cd}	1008.31^{c}	10.06^{e}	23.28^{de}
T6 - KNO_3 (0.5%) + MAP (0.5%) + Boric acid (0.3%) + NAA (10 ppm)	30.9^{ab}	63.9^{ab}	7.0^{c}	14.4^{bc}	230.92^{bcd}	1005.02^{c}	12.12^{cd}	30.75^{b}
T7 - Tomato booster I (N, P, K, Zn, B, NAA, SA)	32.9^{a}	64.1^{a}	8.0^{ab}	15.7^{ab}	228.87^{bcd}	1274.83^{b}	13.44^{abc}	35.58^{a}
T8 - Tomato booster II (N, P, K, Mn, Cu, NAA, SA)	34.1^{a}	67.2^{a}	8.1^{a}	16.0^{a}	265.89^{a}	1448.55^{a}	14.73^{a}	36.50^{a}
T9 - Tomato boster III (N, K, Ca, Zn, B, Mn, Cu, NAA, SA)	32.5^{ab}	63.7^{ab}	7.1^{c}	14.9^{bc}	242.98^{abc}	1114.31^{c}	12.93^{bc}	34.97^{a}
CD (p = 0.05)	**0.07225**	**0.04973**	**0.06864**	**0.06573**	**0.07533**	**0.07965**	**0.07132**	**0.06585**

Mean with different letters in a column were significantly different at p ≤ 0.05. Same letter(s) were not significantly different at p ≤ 0.05. Combinations of letters indicate intermediate values.

MAP - Monoammonium phosphate; KNO_3 - Potassium nitrate; K_2SO_4 - Potassium sulfate; $Ca(NO_3)_2$ - Calcium nitrate; K_2SiO_3 - Potassium silicate; $MnCl_2$ - Manganese chloride; NAA - Naphthalene acetic acid; SA - Salicylic acid

The results demonstrated that the application of nutrient-PGR mixtures significantly increased plant height and the number of branches compared to the control. Among the treatments, T8 (tomato booster II) consistently exhibited the highest plant height, reaching 34.1 cm and 67.2 cm at 30 and 60 DAT, respectively. In addition to height, the number of branches was positively influenced by the consortia application (Table 2). Control plants exhibited a significantly lower branch count (4.9 and 10.8) at 30 and 60 DAT, respectively, compared to the significantly higher branch count (8.1 and 16.0) observed in T8-tested plants at the same developmental stages.

Leaf area also showed substantial improvement under T8 treatment, with the highest recorded values of 265.89 cm^2 $plant^{-1}$ at 30 DAT and 1448.55 cm^2 $plant^{-1}$ at 60 DAT. In contrast, the control (T1) exhibited the lowest leaf area values, measuring 207.28 cm^2 $plant^{-1}$ and 695.45 cm^2 $plant^{-1}$ at the respective time points. Additionally, T8-treated plants consistently achieved the highest TDMP, recording 14.73 g per plant at 30 DAT and 36.50 g per plant at 60 DAT. Conversely, control plants showed the lowest TDMP, with values of 9.84 g per plant and 22.22 g per plant at the corresponding growth stages. These findings highlight the superior performance of T8 in enhancing tomato plant growth.

Effect of foliar application of nutrient-PGR mixture on root architectural traits in tomato

The impact of the foliar application of a nutrient-PGR mixture on root architectural traits in tomato plants was investigated. The results demonstrated that the treatment significantly enhanced root growth and development compared to the control .

Among the treatments, T8 (tomato booster II) exhibited the most substantial root growth, with a total root length of 4402.86 cm, indicating a robust root system (Fig. 1). This treatment also recorded a root volume of 58.9 cm^3, a larger root surface area of 1807.84 cm^2 and an average root diameter of 3.017 mm.

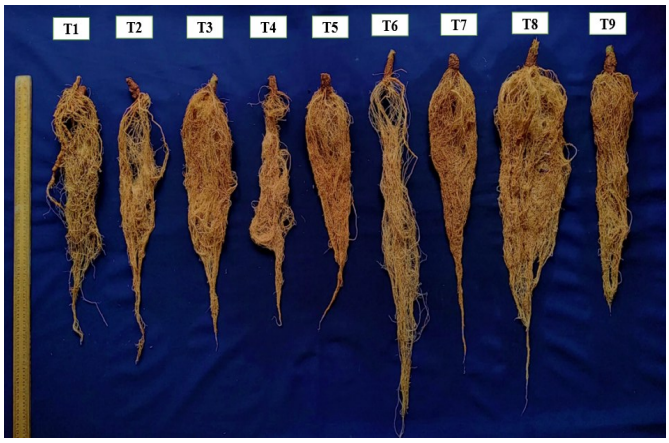


Fig. 1. Effect of the nutrient-PGR mixture on growth and development of the root system in tomato.

In contrast, the control (T1) exhibited significantly lower values across all root architectural traits, including a total root length of 2135.24 cm, a root volume of 20.2 cm^3, a root surface area of 643.82 cm^2 and an average root diameter of 0.919 mm. These results highlight the effectiveness of T8 in enhancing root development and overall plant health.

Effect of foliar application of nutrient-PGR mixture on NDVI in tomato

The NDVI is a crucial metric for assessing plant growth and health. It calculates the ratio of near-infrared (NIR) to red-light reflectance, providing a quantitative measure of vegetation density and photosynthetic activity. The assessment of NDVI values revealed significant differences among the treatments.

Both T7 (tomato booster I) and T8 (tomato booster II) recorded a notably high NDVI value of 0.69 at 30 DAT, exhibiting similar performance during this stage. However, at 60 DAT, T8 (tomato booster II) demonstrated a significantly higher NDVI value of 0.75, compared to the other treatments.

Table 3. Effect of foliar application of nutrient-PGR mixture on NDVI, chlorophyll index (SPAD value), chlorophyll fluorescence (Fv/Fm ratio) in tomato during flowering (30 DAT) and fruit development stage (60 DAT) in tomato

Treatments	Normalized difference vegetative index (NDVI)		Chlorophyll index (SPAD value)		Chlorophyll fluorescence (Fv/Fm ratio)	
	Flowering stage	Fruit development stage	Flowering stage	Fruit development stage	Flowering stage	Fruit development stage
T1 – Control	0.56^{d}	0.51^{d}	29.60^{d}	27.34^{e}	0.651^{d}	0.625^{c}
T2 - KNO_3 (0.5%) + MAP (0.5%) + K_2SO_4 (0.5%) + Boric acid (0.3%)	0.58^{c}	0.67^{c}	31.03^{cd}	35.13^{d}	0.699^{c}	0.704^{bc}
T3 - KNO_3 (0.5%) + K_2SO_4 (0.5%) + Ca $(NO_3)_2$ (0.5%) + Boric acid (0.3%)	0.68^{a}	0.74^{ab}	37.96^{a}	43.26^{ab}	0.762^{ab}	0.767^{ab}
T4 - KNO_3 (0.5%) + MAP (0.5%) + K_2SiO_3 (0.5%) + Boric acid (0.3%)	0.60^{bc}	0.68^{bc}	31.96^{cd}	39.21^{bcd}	0.716^{bc}	0.756^{ab}
T5 - KNO_3 (0.5%) + K_2SO_4 (0.5%) + $MnCl_2$ (0.5%) + Boric acid (0.3%)	0.62^{b}	0.66^{c}	29.13^{d}	37.73^{cd}	0.702^{abc}	0.736^{b}
T6 - KNO_3 (0.5%) + MAP (0.5%) + Boric acid (0.3%) + NAA (10 ppm)	0.66^{a}	0.68^{abc}	33.82^{bc}	35.13^{d}	0.726^{abc}	0.732^{b}
T7 - Tomato booster I (N, P, K, Zn, B, NAA, SA)	0.69^{a}	0.70^{abc}	38.81^{a}	41.06^{abc}	0.755^{abc}	0.751^{ab}
T8 - Tomato booster II (N, P, K, Mn, Cu, NAA, SA)	0.69^{a}	0.75^{a}	38.43^{a}	43.73^{a}	0.782^{a}	0.816^{a}
T9 - Tomato booster III (N, K, Ca, Zn, B, Mn, Cu, NAA, SA)	0.67^{a}	0.71^{abc}	35.60^{ab}	42.20^{ab}	0.751^{abc}	0.762^{ab}
CD (p = 0.05)	**0.02875**	**0.04937**	**0.05687**	**0.06606**	**0.04868**	**0.05729**

Mean with different letters in a column were significantly different at $p \leq 0.05$. Same letter(s) were not significantly different at $p \leq 0.05$. Combinations of letters indicate intermediate values.

MAP - Monoammonium phosphate; KNO_3 - Potassium nitrate; K_2SO_4 - Potassium sulfate; $Ca(NO_3)_2$ - Calcium nitrate; K_2SiO_3 - Potassium silicate; $MnCl_2$ - Manganese chloride; NAA - Naphthalene acetic acid; SA - Salicylic acid

In contrast, the control plants (T1) showed a slight decline in NDVI values from 30 DAT to 60 DAT. Overall, the control exhibited the lowest NDVI values throughout both growth stages (Table 3).

Effect of foliar application of nutrient-PGR mixture on chlorophyll index in tomato

The chlorophyll index of the treatments was determined using a SPAD meter and the results are presented in Table 3. SPAD values are a reliable indicator of the nutritional status of plants, particularly for assessing N levels, which are vital for optimal growth and yield.

Plants treated with T8 (tomato booster II) showed higher SPAD values of 38.43 and 43.73 at 30 and 60 DAT respectively. In contrast, SPAD values in the control (T1) decreased slightly at 60 DAT (27.34) compared to 30 DAT (29.60). Throughout both growth stages, T1 consistently showed lower SPAD values.

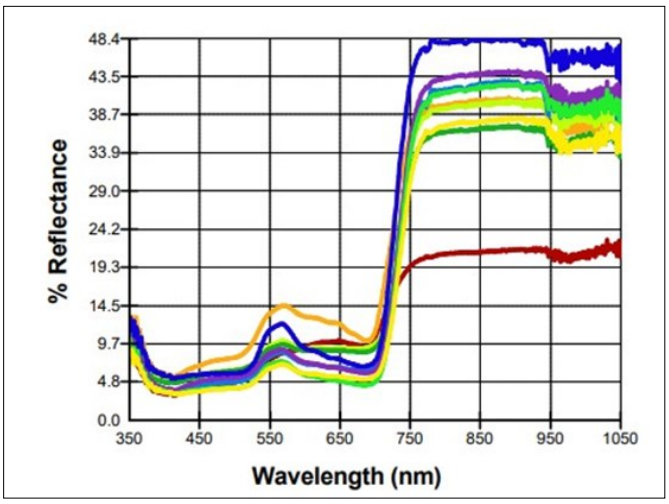
Effect of foliar application of nutrient-PGR mixture on chlorophyll fluorescence in tomato

The Fv/Fm ratio, a vital measure of photosystem II efficiency, reflects the photosynthetic potential of a plant. This parameter is key for determining plant health and resilience to stress, yielding important information about their physiological condition in various environmental conditions.

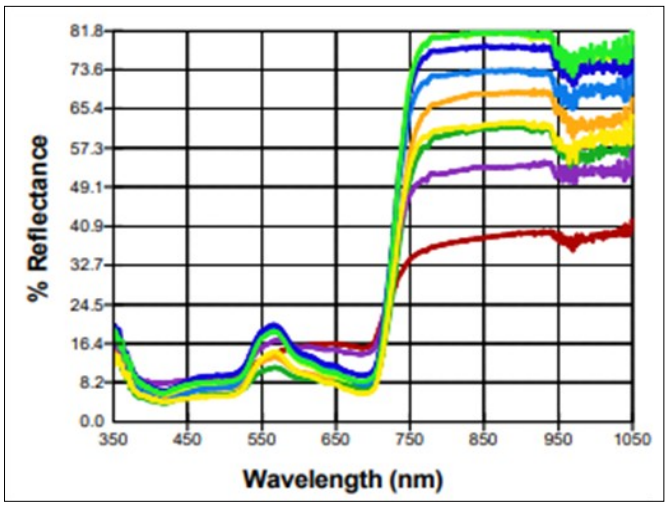
Foliar application of the nutrient-PGR mixture significantly influenced the maximum quantum yield of the PS II ratio in tomato plants (Table 3). Plants treated with T8 (tomato booster II) recorded higher Fv/Fm ratios of 0.782 at 30 DAT and 0.816 at 60 DAT. In contrast, the control (T1) showed the lowest Fv/Fm ratios of 0.651 and 0.625 at 30 and 60 DAT, respectively, with a further decline observed over time.

Effect of foliar application of nutrient-PGR mixture on spectral reflectance characteristics and symptom severity rating in tomato

Spectral reflectance characteristics were analyzed to assess crop health, with the spectral signatures for each treatment obtained during the flowering and fruit development stages (Fig. 2). The results revealed variations in reflectance characteristics, with evident peaks in the red edge region (700 -730 nm) and the near infrared (NIR) region (730-1000 nm) across treatments.



Reflectance in Tomato leaves during flowering stage (30 DAT)



Reflectance in Tomato leaves during the fruit development stage (60 DAT)

Fig. 2. Spectral signatures of the plant across various treatments using GER 1500 portable field spectroradiometer.

Table 4. Effect of foliar application of nutrient-PGR mixture on root architectural traits in tomato

Treatments	Total root length (cm)	Root volume (cm^3)	Root surface area (cm^2)	Average root diameter (mm)
T1 – Control	2135.24^{d}	20.2^{e}	643.82^{f}	0.919^{f}
T2 - KNO_3 (0.5%) + MAP (0.5%) + K_2SO_4 (0.5%) + Boric	2269.29^{c}	26.6^{d}	1154.06^{d}	1.844^{d}
T3 - KNO_3 (0.5%) + K_2SO_4 (0.5%) + Ca $(NO_3)_2$ (0.5%) +	4159.97^{a}	50.6^{b}	1761.19^{ab}	2.787^{a}
T4 - KNO_3 (0.5%) + MAP (0.5%) + K_2SiO_3 (0.5%) + Boric	2402.87^{c}	22.3^{de}	656.28^{f}	1.122^{f}
T5 - KNO_3 (0.5%) + K_2SO_4 (0.5%) + $MnCl_2$ (0.5%) + Boric	2152.76^{c}	32.3^{c}	951.19^{e}	1.501^{e}
T6 - KNO_3 (0.5%) + MAP (0.5%) + Boric acid (0.3%) +	4189.29^{a}	48.4^{b}	1237.67^{d}	2.140^{c}
T7 - Tomato booster I (N, P, K, Zn, B, NAA, SA)	3198.49^{b}	31.8^{c}	1632.93^{bc}	2.301^{bc}
T8 - Tomato booster II (N, P, K, Mn, Cu, NAA, SA)	4402.86^{a}	58.9^{a}	1807.84^{a}	3.017^{a}
T9 - Tomato booster III (N, K, Ca, Zn, B, Mn, Cu, NAA,	4060.12^{a}	48.9^{b}	1549.66^{c}	2.388^{b}
CD (p = 0.05)	**0.06873**	**0.07546**	**0.06058**	**0.07165**

Mean with different letters in a column were significantly different at $p \leq 0.05$. Same letter(s) were not significantly different at $p \leq 0.05$. Combinations of letters indicate intermediate values.

MAP - Monoammonium phosphate; KNO_3 - Potassium nitrate; K_2SO_4 - Potassium sulfate; $Ca(NO_3)_2$ - Calcium nitrate; K_2SiO_3 - Potassium silicate; $MnCl_2$ - Manganese chloride; NAA - Naphthalene acetic acid; SA - Salicylic acid

Among the treatments, T7 (tomato booster I) initially exhibited higher reflectance in both the red edge and NIR regions, reaching 48.4% during the flowering phase (30 DAT). However, following two applications of the nutrient-PGR mixture, plants treated with T8 (tomato booster II) displayed the highest reflectance in these regions, achieving 81.8% during the fruit development stage (60 DAT). This increased reflectance in T8-treated plants may be attributed to improved growth conditions. Conversely, the control (T1) recorded the lowest spectral reflectance.

Disease symptom development on tomato leaves was evaluated using a 0-4 severity scale in conjunction with spectral signature analysis. Plants treated with T8 (tomato booster II) exhibited no visible symptoms and recorded the highest spectral reflectance, corresponding to a severity rating of 0. In contrast, control plants sprayed with water showed pronounced disease symptoms and the lowest spectral reflectance, resulting in a severity rating of 4 (Fig. 3).

Discussion

The various treatments used in this experiment demonstrated a notable influence on the morphological and physiological characteristics of tomato plants. The application of nutrients such as N, P, K, Ca and B along with NAA and SA, considerably improved the growth characteristics of the crop. Potassium is indispensable for plant growth, yield and stress tolerance (18). Boron and Ca play crucial roles in the structural integrity and formation of cell walls (19). NAA promotes protein synthesis and improves photosynthesis, thereby enhancing cell elongation and division, which in turn substantially improves various growth parameters (20).

Fig. 3. Symptom severity rating on a 0 - 4 scale during flowering stage in tomato.

Plant height and branch number are critical determinants of TDMP and crop yield. TDMP is a measure of a plant's photosynthetic efficiency and biomass accumulation, directly impacting fruit number and weight, which are key factors in determining tomato yield (21). Tomato plants treated with T8 (tomato booster II) exhibited enhanced growth, characterized by increased plant height and a greater number of branches. This positive effect is likely due to the presence of growth-promoting nutrients, including N, P, K, Ca and PGRs (NAA), which facilitate growth processes in plants, such as cell division and elongation, stimulating vegetative growth in tomatoes.

Leaf area is a key factor influencing net photosynthetic rate, TDMP and ultimately, crop yield. Treatment with T8 (tomato booster II) resulted in an increase in leaf area, likely attributed to its nutrient and PGR composition, including N, P, K, Ca, NAA and SA. NAA, a plant hormone, plays a pivotal role in stimulating both cell division and elongation, contributing to the observed expansion of leaf area.

Plants treated with specific treatments exhibited a gradual improvement in both root length and root volume when compared to the control (T1) (Table 4). Expanding root volume and root length plays a crucial role in efficiently transporting photo-synthetically assimilated compounds to the economically valuable parts of the plant (22). Foliar application of K, magnesium (Mg), Fe and Mn led to enhanced vegetative growth, increased root length, and greater root volume in tomato (23). Moreover, treatments enriched with P boosted root growth and development. The application of P enhanced root development, enabling the plant to take in greater nutrients from the soil. Additionally, P application also helps in minimizing seedling and fungal infections by promoting root development, this makes plants escape from the disease infestation (24). Enhanced nutrient and PGR availability boosts shoot and root growth in plants (Fig 1). Improved root growth promotes better nutrient absorption and water uptake, resulting in better fruit yield and dry matter production (25). Tomato plants can access more moisture by spreading their root system into deeper soil layers, which increases their resistance to water stress and optimizes resource use in changing environmental conditions (26).

The most used method for assessing vegetation conditions in agricultural and environmental monitoring situations is the NDVI (27). NDVI measurements are sensitive indicators of plant health, demonstrating a decline in values when plants are affected by various diseases. In the present study, the application of nutrients and PGRs assisted the plants in sustaining their health throughout the various growth stages of the crop. The application of tomato booster II (T8) resulted in higher NDVI values in leaves (Table 3), potentially due to the presence of nutrients such as Cu, Mn and PGRs (NAA, SA). Copper-based compounds are highly toxic to plant pathogens, making them effective in controlling crop diseases and providing a cost-effective and affordable option for farmers to protect their crops (28). SA can induce SAR in plants, which helps in the defense against biotic and abiotic stresses (11). However, a decrease in NDVI values is observed for T1 (control) due to the incidence of disease, which has shown yellowing symptoms in the plants.

The chlorophyll index (SPAD) in leaves is an excellent indicator of plant injury caused by various biotic, and abiotic factors (29). In the present study, the treatments applied with tomato booster I and II have demonstrated higher SPAD values during both stages of the crop (Table 3). All the treatments recorded higher SPAD values compared to T1 (control). This increase in the chlorophyll index may be due to the application of N, which helped preserve the level of N in tomato leaves that was necessary to retain the chlorophyll in plants. Moreover, a study indicated that foliar application of Ca is associated with elevated chlorophyll levels, especially under stress conditions, thereby enhancing plant resilience (30). Furthermore, the application of K has been shown to boost chlorophyll content and leaf area index in maize, ultimately resulting in increased yield (31). The application of NAA with other growth regulators boosts chlorophyll content and also enhances other physiological parameters, such as root development and antioxidant enzyme activity, supporting plant health and productivity (32).

Regarding chlorophyll fluorescence parameters, the proportion of active photosystem II (PSII) reaction centres is a potential early identification of both biotic and abiotic stresses (33). The application of Ca salts like calcium chloride ($CaCl_2$) and calcium nitrate ($CaNO_3$) has been linked to increased Fv/Fm ratios, reflecting enhanced photosystem II efficiency in tomato seedlings under heat stress (34). Naphthalene acetic acid is known to promote root development and increase nutrient uptake, which can contribute to better leaf health and chlorophyll content. This, in turn, supports higher photosynthetic activity, reflected in the improved Fv/Fm ratio (32). In our research, the application of nutrients and NAA slightly enhanced the Fv/Fm ratio across all treatments compared to the control. A high Fv/Fm ratio indicates healthy plants with efficient photosynthesis, while a low ratio suggests stress or damage to the photosynthetic apparatus (35). The treatments (T3 and T8) that resulted in the highest Fv/Fm ratios probably achieved the best balance of these factors, supporting effective photosynthetic machinery and overall plant health.

Plant spectral reflectance at each wavelength is affected by many variables, including biochemicals such as chlorophyll, carotenoids and xanthophylls, as well as leaf water content, intra-and inter-cellular structure and photosynthesis performance (36). Spectral reflectance characteristics are valuable for assessing plant health. The spectral signatures of tomato leaves affected by diseases exhibited low reflectance, likely resulting from reduced chlorophyll levels in the leaves, indicating plant stress and allowing clear differentiation from healthy plants (Fig 2). Furthermore, a strong correlation was observed between the severity of disease symptoms and the recorded spectral signatures of tomato leaves. These findings strongly suggest a relationship between the presence of disease symptoms and spectral reflectance.

The highest percentage of reflectance was observed in T8 (tomato booster II), which contains Cu, Mn and SA, contributing to the maintenance of plant health under stressful conditions. Manganese plays a crucial role in the synthesis of lignin, suberin, tannin and phenolic compounds,

thereby protecting plants from oxidative damage, pests and diseases (37). Salicylic acid treatment induces the expression of pathogenesis-related (PR) proteins and stress-responsive genes, which are vital for SAR in plants. Additionally, SA enhances the activity of antioxidant enzymes, such as ascorbate peroxidase (APX) and peroxidase (POD), helping mitigate oxidative stress caused by pathogenic infections (12).

Conclusion

The present study investigated the effects of various combinations of nutrients and PGRs during the flowering and fruit development stages of tomato plants. The findings revealed that the combined application of nutrients and PGRs significantly enhanced crop growth and development, with T8 (tomato booster II) delivering the most substantial improvements in plant vitality and overall development. Furthermore, the integrated use of nutrients and PGRs demonstrated the potential to reduce dependence on pesticides and fungicides, thereby minimizing the accumulation of harmful chemical residues.

Improving food crop yield is essential to addressing the issues of food security brought on by a world population that is expanding at an accelerated rate. Future research should focus on exploring the interactions between mineral nutrients and plant defense mechanisms. Employing molecular approaches to study nutrient-PGR mixtures could provide critical insights into their synergistic effects. Identifying optimal nutrient combinations and their precise application methods is essential for efficient pest and disease management. Additionally, field trials are required to validate nutrient strategies under real-world conditions, further reducing reliance on chemical pesticides and fungicides. Ultimately, integrating nutrient and PGR applications with sustainable agricultural practices will support the development of environmentally friendly farming systems.

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Authors' contributions

RJ conducted the investigation and authored the initial draft. RS conceived the study and provided critical revisions to the manuscript. PB coordinated the overall study design and execution. PSK and VS contributed significantly to the experiment and supervised the execution of the procedures. All authors contributed to the final manuscript and approved its content.

Compliance with ethical standards

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Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

In the process of preparing this manuscript, the authors used Grammarly (an AI writing tool) to improve grammar, punctuation and spelling for better readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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