PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.9402

eISSN 2348-1900

RESEARCH ARTICLE

Slow-release fertilizers improve micronutrient uptake and boost morphological, physiological and nutritional traits in tomato

Abreeta Kalita[1], M Elayarajan[1*], P Janaki[1], S Suganya[1], A Sankari[2], E Parameswari[3] & S K Behera[4]

[1]Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Department of Horticulture, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[3]Department of Environmental Sciences, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Division of Soil Chemistry and Fertility, Indian Institute of Soil Science, Bhopal 462 038, Madhya Pradesh, India

*Correspondence email - elayarajanm@tnau.ac.in

Received: 10 May 2025; Accepted: 02 July 2025; Available online: Version 1.0: 14 September 2025

Cite this article: Abreeta K, Elayarajan M, Janaki P, Suganya S, Sankari A, Parameswari E, Behera SK. Slow-release fertilizers improve micronutrient uptake and boost morphological, physiological and nutritional traits in tomato. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.9402

Abstract

Slow-Release Fertilizers (SRFs) provide substantial environmental advantages over conventional fertilizers by mitigating nutrient losses via leaching, volatilization and surface runoff. By synchronizing nutrient release with plant uptake, SRFs enhance nutrient use efficiency while minimizing the risk of soil and water contamination. The development of SRFs plays a pivotal role in reducing the environmental footprint and enhancing the yield and quality of crops while minimizing nutrient losses. Keeping all this points in mind an attempt was made to develop a SRF using four essential micronutrients- zinc (Zn), iron (Fe), copper (Cu) and manganese (Mn) based on crop's nutrient requirement which was coated with different polymers comprising a total of 12 treatments. A field trial was conducted to evaluate the results during the *Rabi* season (November to February) in Tamil Nadu. The results demonstrated that treatment T_8 (MNF coated with biochar + humic acid @ 28 kg ha^{-1}) followed by T_7 (MNF coated with biochar + humic acid @14 kg ha^{-1}) significantly enhance the growth, chlorophyll content and quality parameters of tomato compared to uncoated (T_3 & T_4) and absolute control plot (T_1). This study concludes that SRFs can provide a solution to effective nutrient release. Further, it draws attention towards use of biochar and humic acid in attaining marked improvements highlighting their potential to meet crop nutritional demands efficiently over time.

Keywords: biochar; humic acid; micronutrients; nutrient use efficiency

Introduction

By the end of 2050, the world's population is predicted to have grown to 9 billion people at a rate of 1.05 % (1). As the world's population grows, there will be a 60 % rise in food consumption above current levels (2,3). The loss of fertile topsoil due to intensive cropping, inadequate organic matter addition, heavy metal contamination and insufficient micronutrient supplementation is causing serious problems. Additionally, a lack of micronutrients is increasingly making it difficult to get the best yield. Since they regulate most enzymatic reactions, these micronutrients are vital. Their absence in plants led to a notable decrease in yield characteristics (4). Plants use micronutrients for a variety of purposes, including as cofactors of antioxidant enzymes and as structural elements in osmolites under stress, which are essential for plant growth and development (5,6). Furthermore, it is commonly known that a reduction in plant performance and yield due to micronutrient deficiencies negatively impact sustainable agricultural (7). The formation of agricultural plants depends on microelements including manganese, iron, zinc and copper, which are needed in trace levels (8). For plants to meet the world's food needs, fertilisers are a vital supply of nutrients.

Globally, the tomato (*Solanum lycopersicum*) is the third most produced crop. In India, tomato is grown throughout the country. Tomatoes are frequently consumed, either as raw fruit or in processed form, because of their high mineral, vitamin and anti-cancer properties (9). Balanced nutrition through organic manures is advocated; however, they may only support low yield levels. For harnessing the higher yield potential, supplementation of micronutrients is essential. Amongst the vegetables, tomato is very responsive to the application of micronutrients. The micronutrients improve the chemical composition of fruits and general condition of plants and are known to act as catalyst in promoting organic reactions taking place in plants (10). Applications of micro- nutrients i.e., zinc and boron have been reported in increasing growth and seed yield in tomato. When farmers utilise micronutrient fertilisers to increase output, tomatoes (*Solanum lycopersicum*) are the most economical vegetable (11).

SRFs application is advised to get around problems with conventional fertiliser such as fertility loss from indiscriminate use, groundwater pollution and environmental stress (12). SRFs demonstrated a more secure, cost-effective and effective method of supplying fertilisers to satisfy crop needs. SRFs are defined as a fertilizer coated with an organic/inorganic compound aimed at sustaining the nutrient release and increase the duration for nutrient availability to the crops significantly due to presence of polymeric coating material (13). SRFs are made to satisfy crops' nutrient needs according to their growth cycle (10). Fertiliser is used as the core material in SRF manufacturing and coating materials such as resin or polymers are used to shield the core and release the core nutrients in a regulated way (14,15). Considering the urgent need for food security and sustainable development, the importance of introducing effectively formulated fertilizers is nowadays very noticeable and severe. Therefore, many efforts have been focused on offering environmentally benign coatings to produce the SRFs (16-18).

The present work aims to evaluate different SRF formulations developed using combination of different organo-monomers (19) used for coating the MNF granules at two different levels (14 and 28 kg ha^{-1}) and validate the best treatment under field conditions. Therefore, keeping the above points, this study was conducted with an aim to improve the morphological, physiological and nutritional parameters of tomato (*S. lycopersicum* L.) crop using the different organo-monomeric coated SRFs at two different levels under field condition.

Materials and Methods

Study area and experimental design

The experiment was conducted in Ettimadai town of Coimbatore district. The experimental sites were located at an elevation of 313 m above mean sea level, with the main site having geographical coordinates of latitude 10.8900° N and longitude 76.9088° E. The study aimed to assess and develop SRF products under various treatments to manage and increase the micronutrient uptake, content along with growth, yield and quality parameters of tomato crop. The experimental layout followed a Randomized Block Design (RBD), with three replications assigned per treatment to account for environmental variability. Each treatment was applied to plots of equal dimensions, measuring 3 m by 5 m, with buffer zones of 25 cm between plots to minimize cross-contamination.

Soil characteristics and fertilizer application

The initial surface soil analysis of the experimental field revealed the following characteristics: a clayey loam texture with 22.08 % coarse sand, 24.41 % fine sand, 20.6 % silt and 32.5 % clay estimated using international pipette method. The bulk density of 1.25 Mg m^{-3}, particle density of 2.65 Mg m^{-3} and porosity of 50 % was recorded using cylinder method. The pH of the soil was recorded as 7.62 using 1:2.5 soil: water suspension potentiometry, with an Electrical Conductivity (EC) of 0.16 dS m^{-1} using 1:2.5 soil: water suspension conductimetry and a Cation Exchange Capacity (CEC) of 32.5 C mol (p^+) kg^{-1}. The soil had a free $CaCO_3$ content of 2.75 % which was estimated using rapid titration method, organic carbon content of 0.75 % estimated through wet digestion method, available $KMnO_4$-N at 210 kg ha^{-1} estimated by alkaline permanganate method Olsen-P at 16 kg ha^{-1} estimated using spectrophotometer and NH_4OAc-K at 392 kg ha^{-1} estimated through flame photometer. The DTPA-extractable micronutrients were measured as follows: zinc (3.93 mg kg^{-1}), copper (2.18 mg kg^{-1}), iron (3.44 mg kg^{-1}) and manganese (1.08 mg kg^{-1}) which were estimated using 0.005 M DTPA extractant as outlined by Lindsay and Norvell method.

Preparation of SRF by rotary drum method

The micronutrient formulation was made with respect to the Tamil Nadu Agricultural University (TNAU) micronutrient recommendation given in Crop Production Guide (CPG) and according to that the respective fertilizers such as zinc sulphate, iron sulphate, copper sulphate and manganese sulphate were mixed in a specific ratio. Then with addition of potato dextrose as a binder the mixture was further rotated at 360 rpm for 30 min which gave it a spherical granular shape. Those granules were further coated with biochar (coconut husk pyrolyzed under a temperature of 600 °C) in 2:1 ratio and after drying it was further double coated with Humic Acid (HA) (6 % w/v), Cassava Starch (CS) (6 % w/v).

Likewise, the micronutrient granules were also coated with bentonite using 2:1 ratio and further double coated with HA and with CS at 6 % w/v. All the SRFs were tested at two levels (14 and 28 kg ha^{-1}) of fertilizer application along with uncoated and absolute control treatments. The tomato variety used was PKM-1 with a row spacing of 45 cm by 30 cm to ensure optimal plant stand. Standard agronomic practices, including irrigation, weed management and pest control, were uniformly implemented across all plots. Irrigation was applied as required and all cultural operations were performed to promote ideal crop growth.

The treatments comprised a total of 12 numbers of details of which are as follows in Table 1.

Plant height measurement

Plant height (cm) was monitored regularly throughout the crop growth period to evaluate the effect of each treatment. Five tomato plants were randomly selected from each plot, excluding border rows. The height of each plant was measured from the soil surface to the tip of the tallest leaf. These measurements were recorded at different growth stages and the average plant height for each plot was calculated.

Table 1. Treatment details

Treatment	Details
T_1	Absolute control (No MN)
T_2	MN applied as per TNAU recommendation
T_3	Uncoated MNCF granules @ 14 kg ha^{-1}
T_4	Uncoated MNCF granules @ 28 kg ha^{-1}
T_5	Biochar+CS @ 14 kg ha^{-1}
T_6	Biochar+CS @ 28 kg ha^{-1}
T_7	Biochar+HA @ 14 kg ha^{-1}
T_8	Biochar+HA @ 28 kg ha^{-1}
T_9	Bentonite+CS @14 kg ha^{-1}
T_{10}	Bentonite+CS @ 28 kg ha^{-1}
T_{11}	Bentonite+ HA @14 kg ha^{-1}
T_{12}	Bentonite+ HA @14 kg ha^{-1}

Root length

Root length (cm) was monitored regularly throughout the crop growth period to evaluate the effect of each treatment. Five tomato plants were randomly selected from each plot, excluding border rows. The length of the primary root from each plant was measured from the point of attachment of the crop to the tip. These measurements were recorded at different growth stages and the average root length for each plot was calculated.

SPAD

The SPAD chlorophyll meter was used to evaluate chlorophyll concentration, indicating the photosynthetic potential and overall plant health. Chlorophyll content was measured in the physiologically active leaves of the five labelled plants at various growth stages in each plot. The SPAD readings were averaged for each plot and these values provided insights into how nutrient availability from different fertilizer treatments influenced plant health (20).

Enzymatic activity

Reaction mixture of pyrogallol and hydrogen peroxide without the leaf extract constituted the blank. 500 mg of fresh leaves was homogenized with 0.1 M phosphate buffer and centrifuged at 5000 rpm for 15 min in cool condition. 1 mL of supernatant, 3 mL of 0.05 M pyrogallol and 0.5 mL of 30 % H_2O_2 were taken in a test tube. The change in absorbance was measured at 430 nm for every 30 sec up-to 150 sec and the enzyme activity was calculated and expressed as unit g FW^{-1} of sample.

Data analysis

The collected data on plant growth parameters, yield and quality attributes were subjected to analysis of variance (ANOVA) to evaluate the statistical significance of the differences between treatments. Mean values were compared using the Least Significant Difference (LSD) test at a 5 % significance level. All statistical analyses were conducted using GRAPES (General Rshiny Based Analysis Platform Empowered by Statistics) software version 1.0.0 and graphical representations were generated to illustrate the effects of the various treatments.

Results

The findings show that tomato plant height rose gradually across all the growth stages, starting from vegetative, flowering, reproductive and harvest stages. Table 2 shows the noteworthy differences between various treatments with T_8 (biochar + HA coated @ 28 kg ha^{-1}) emerging as the best treatment followed by T_7 (biochar + HA coated @ 14 kg ha^{-1}) while T_1 (control without any micronutrients) consistently recorded the lowest values among all treatments. T_8 recorded a plant height of 54.5 cm during the vegetative stage followed by T_7 49.46 cm and T_1 24.93 cm. T_8 continued with this increasing trend and measured 71.00 cm, 89.00 cm and 108.33 cm during the flowering, reproductive and harvest stages respectively. This was followed by T_7 with showed the measurements as 67.33 cm, 84.66 cm and 95.66 cm while T_1 showed 37.13 cm, 51.66 cm and 65.90 cm respectively for flowering, reproductive and harvest stages of the crop. The SE(D) and C.D. values (5 %) showed that the difference between the treatments were significant statistically which has been indicated by different letters along a column.

Consequently, root length also showed a similar trend and T_8 emerged as the best treatment. At vegetative stage it was observed that maximum root length of 10.20 cm belonged to T_8 followed by T_7 (9.60 cm) and least was for T_1 (6.42 cm). Similarly, for flowering, reproductive and harvest stages it was found to follow the same trend with T_8 having values 17.32 cm, 20.20 cm and 25.49 cm corresponding for flowering, reproductive and harvest stages respectively. T_7 had values as 16.78 cm, 19.30 cm and 24.40 cm belonging to flowering, reproductive and harvest stages whereas for T_1 observed values were 8.10 cm, 9.80 cm and 15.20 cm belonging to flowering, reproductive and harvest stages. It was observed that T_8 emerged as the most effective treatment followed by T_7 and least with T_1 treatments T_9, T_{10}, T_2 and T_3 were found to be statistically insignificant (Table 2).

Comparably the chlorophyll content also gave us similar result with T_8 as the best treatment for all the stages of growth namely vegetative (65.5), flowering (68.8), reproductive (70.60) and harvest (71.40) as shown in Table 3. This was followed by T_7 with values starting from 63.19 (vegetative), 66.72 (flowering), 68.5 (reproductive) and 69.8 (harvest) stages. T_1 was found to have SPAD values with vegetative stage at 38.40, flowering stage (40.39), reproductive stage (44.59) and harvest stage at 46.39. These findings demonstrate well that the application of micronutrients is critical to plant's optimal functioning and contributing to photosynthetic activity as well. Use of coated fertilizers can give superior results as compared to uncoated fertilizers.

Consequently, enzymatic activity was also evaluated at successive stages for the crop and it was found that T_8 emerged superior for all the growth stages of the crop starting with vegetative (64.4), flowering (70.8), reproductive (77.2) and harvest (72.6) corresponding for peroxidase activity as indicated in Table 4. It was found that there is a gradual increase in the values starting from vegetative up to reproductive and further it declines at harvest stage. Treatment T_7 emerged as second best with values being recorded as 60.6,

Table 2. Effect of different treatments on plant height and root length as observed during various growth stages

	VS	FS	RS	HS	VS	FS	RS	HS
T_1	24.93 ^{j}	37.13 ^{j}	51.66 ^{j}	65.90 ^{l}	6.42 ^{j}	8.10 ^{j}	9.80 ^{j}	15.20 ^{j}
T_2	27.10 ^{i}	40.53 ^{i}	56.23 ^{i}	72.70 ^{i}	7.08 ^{i}	9.39 ^{i}	11.20 ^{i}	16.40 ^{i}
T_3	28.03 ^{i}	41.96 ^{i}	57.20 ^{i}	73.83 ^{i}	7.25 ^{i}	9.64 ^{i}	11.66 ^{i}	16.39 ^{i}
T_4	30.66 ^{h}	45.46 ^{h}	62.00 ^{h}	76.26 ^{h}	7.65 ^{h}	11.87 ^{h}	12.80 ^{h}	17.50 ^{h}
T_5	33.23 ^{g}	49.16 ^{g}	64.80 ^{g}	78.53 ^{g}	7.91 ^{g}	12.49 ^{g}	14.20 ^{g}	18.60 ^{g}
T_6	36.03 ^{f}	52.90 ^{f}	67.96 ^{f}	80.93 ^{f}	8.28 ^{f}	13.12 ^{f}	15.00 ^{f}	19.20 ^{f}
T_7	49.46 ^{b}	67.33 ^{b}	84.66 ^{b}	95.66 ^{b}	9.60 ^{b}	16.78 ^{b}	19.30 ^{b}	24.40 ^{b}
T_8	54.50 ^{a}	71.00 ^{a}	89.00 ^{a}	108.33 ^{a}	10.20 ^{a}	17.32 ^{a}	20.20 ^{a}	25.49 ^{a}
T_9	38.56 ^{e}	55.50 ^{e}	70.43 ^{e}	84.53 ^{e}	8.56 ^{e}	11.32 ^{e}	15.80 ^{e}	20.40 ^{e}
T_{10}	39.83 ^{e}	56.00 ^{e}	71.60 ^{e}	85.73 ^{e}	8.62 ^{e}	11.45 ^{e}	16.30 ^{e}	20.00 ^{e}
T_{11}	43.16 ^{d}	59.93 ^{d}	75.56 ^{d}	89.06 ^{d}	8.90 ^{d}	16.00 ^{d}	17.20 ^{d}	21.80 ^{d}
T_{12}	45.76 ^{c}	62.66 ^{c}	79.00 ^{c}	91.66 ^{c}	9.20 ^{c}	15.43 ^{c}	18.40 ^{c}	23.20 ^{c}
SE(d)	0.715	0.721	1.269	0.753	0.124	0.266	0.316	0.417
C.D.	1.483	1.495	2.632	1.562	0.257	0.551	0.655	0.866

VS - Vegetative stage; FS - Flowering stage; RS - Reproductive stage; HS Harvest stage.

Treatment means within column with different letters are significantly different

Table 3. Effect of different treatments on chlorophyll content as observed during various growth stages and fruit nutrient uptake at harvest stage

Treatments	SPAD			
	VS	FS	RS	HS
T_1	38.40 ^{l}	40.39 ^{l}	44.59 ^{l}	46.39 ^{i}
T_2	40.20 ^{k}	42.40 ^{k}	46.60 ^{k}	48.39 ^{h}
T_3	42.80 ^{j}	44.60 ^{j}	49.60 ^{j}	50.59 ^{g}
T_4	45.20 ^{i}	48.40 ^{i}	52.59 ^{i}	54.10 ^{f}
T_5	47.79 ^{h}	50.40 ^{h}	54.30 ^{h}	55.60 ^{f}
T_6	49.59 ^{g}	53.60 ^{g}	58.49 ^{g}	60.60 ^{e}
T_7	63.19 ^{b}	66.72 ^{b}	68.50 ^{b}	69.80 ^{a}
T_8	65.5 ^{a}	68.80 ^{a}	70.60 ^{a}	71.40 ^{a}
T_9	52.60 ^{f}	55.40 ^{f}	60.80 ^{f}	62.40 ^{d}
T_{10}	55.80 ^{e}	58.40 ^{e}	62.80 ^{e}	63.60 ^{d}
T_{11}	57.40 ^{d}	60.40 ^{d}	64.29 ^{d}	65.59 ^{c}
T_{12}	60.19 ^{c}	63.79 ^{c}	66.39 ^{c}	67.67 ^{b}
SE(D)	0.423	0.585	0.453	0.78
C.D.	0.876	1.213	0.94	1.618

VS - Vegetative stage; FS - Flowering stage; RS - Reproductive stage; HS Harvest stage.
Treatment means within column with different letters are significantly different

Table 4. Effect of different treatments on peroxidase activity and polyphenol activity as observed during various growth stages

Treatments	Peroxidase activity			
	VS	FS	RS	HS
T_1	23.60 ^{l}	28.22 ^{k}	44.20 ^{l}	39.80 ^{k}
T_2	28.59 ^{k}	32.79 ^{j}	47.30 ^{k}	42.10 ^{j}
T_3	32.80 ^{j}	36.61 ^{i}	52.80 ^{j}	44.69 ^{i}
T_4	37.76 ^{i}	42.70 ^{h}	56.40 ^{i}	48.70 ^{h}
T_5	40.00 ^{h}	46.30 ^{g}	60.19 ^{h}	52.20 ^{g}
T_6	43.79 ^{g}	50.11 ^{f}	63.70 ^{g}	55.80 ^{f}
T_7	60.60 ^{b}	68.60 ^{b}	75.00 ^{b}	70.70 ^{b}
T_8	64.40 ^{a}	70.80 ^{a}	77.20 ^{a}	72.60 ^{a}
T_9	47.80 ^{f}	53.20 ^{e}	66.30 ^{f}	58.40 ^{e}
T_{10}	50.60 ^{e}	57.40 ^{d}	68.90 ^{e}	61.30 ^{d}
T_{11}	53.40 ^{d}	65.50 ^{c}	71.20 ^{d}	67.50 ^{c}
T_{12}	57.80 ^{c}	66.57 ^{c}	73.20 ^{c}	69.40 ^{b}
SE(D)	0.438	0.87	0.732	0.675
C.D.	0.909	1.804	1.519	1.4

VS - Vegetative stage; FS - Flowering stage; RS - Reproductive stage; HS Harvest stage.
Treatment means within column with different letters are significantly different

68.6, 75.0 and 70.7 correlating to vegetative, flowering, reproductive and harvest stages respectively. It was likely that T_1 was having the minimum values for all the stages namely vegetative (23.60), flowering (28.22), reproductive (44.20) and harvest (39.8).

Discussion

The results showed that biochar and HA can load nutrients and releasing them gradually over time, significantly influencing the morphological, physiological and quality parameters of tomato. In terms of plant height, root length, chlorophyll content and enzymatic activity treatment T_8 performed better than control and other fertilizers as indicated in Fig. 1a & 1b. These findings align with results and trials conducted with slow -release fertilizer on tomato crop which emphasizes how SRFs boosts the microbial diversity, improve nutrient holding capacity and soil structure and concurrently increase the nutrient availability which contribute to better crop performance (21). The gradual and continuous release of nutrients from the porous structure of the coated fertilizers is responsible for the noteworthy distinctions in terms of plant height, root length and chlorophyll content.

T_8 had the maximum plant height, root length, SPAD and enzyme activity for all stages as compared to control (T_1). These results are comparable to previous studies that combined application of micronutrients like zinc, boron and iron results in a synergistic effect, leading to a more pronounced increase in plant height compared to individual applications. This combination enhances various metabolic activities, promoting vigorous vegetative growth (22-24). On the other hand, lowest values were observed in T_1 (control) highlighting the essence of micronutrients for the enhanced growth and development. In terms of root growth and development it was found that T_8 consisting of biochar and HA coated fertilizer showed the highest value which can be attributed to the fact that HA can stimulate H^+-ATPase activity in roots, promoting ion uptake and growing. Both biochar and HA are known to improve porosity, soil aeration and structure which promotes healthier nutrient uptake reducing the stress on roots and better organ development (23,24).

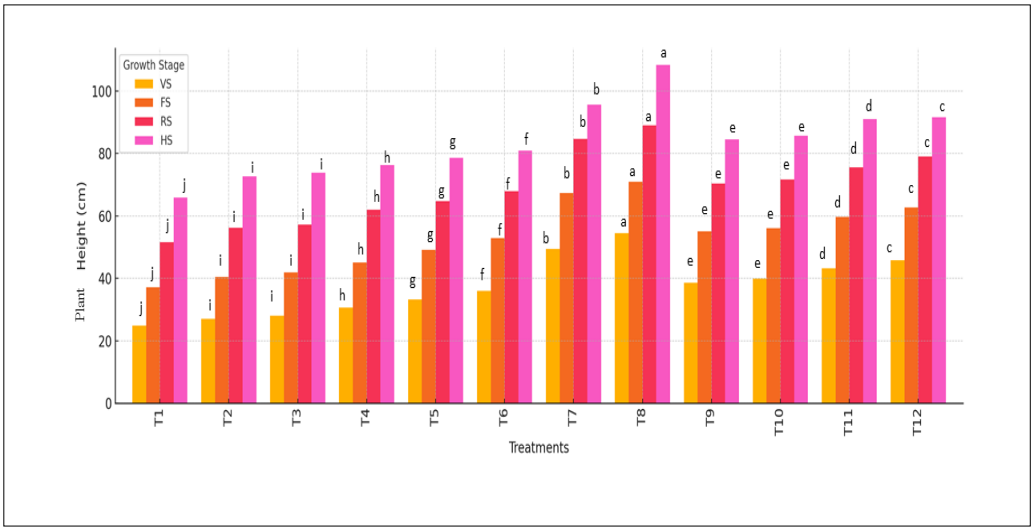

Fig. 1a. Plant height of tomato as recorded at various physiological stages.

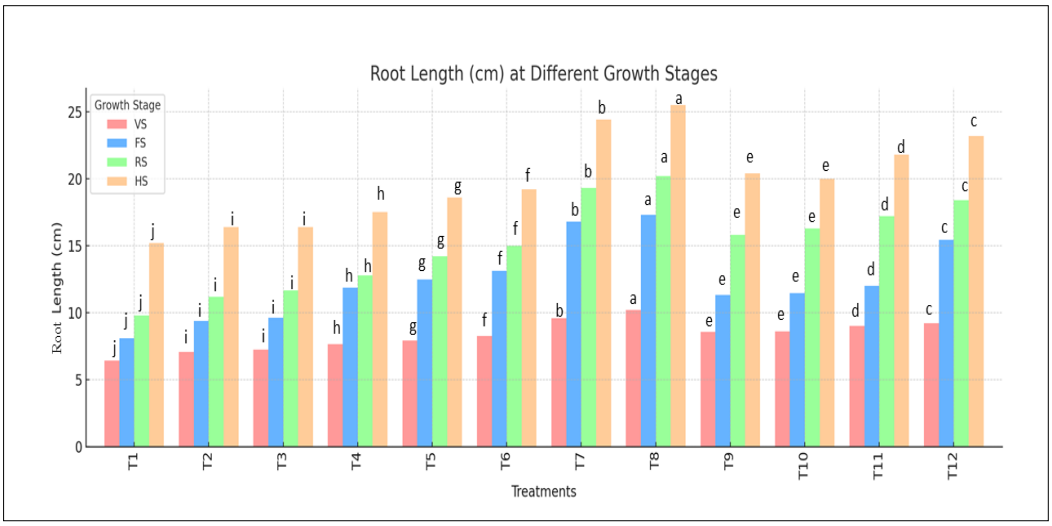

Fig. 1b. Root length of tomato as recorded at various physiological stages.

A comparison between T_7 and T_8 revealed that the higher fertilizer application rate in T_8 (28 kg ha^{-1}) led to superior growth compared to T_7 (14 kg ha^{-1}). However, T_7 performed better than the other treatments, likely due to the presence of biochar and HA coated fertilizer. T_1 had the least value which shows that though often neglected but micronutrient application is critical to crop growth and development.

T_8 also had the most significant SPAD values as shown in Fig. 2, which indicate chlorophyll concentration and photosynthetic efficiency. It has been demonstrated that biochar and HA coated micronutrients protect it from leaching or binding to other agents and improve their uptake by the crop. Chlorophyll requires micronutrients like iron, zinc, manganese as cofactors in biosynthetic pathways and therefore its availability improves the SPAD values (25-27). The absence of these nutrients reduces the photosynthetic capability as demonstrated by the consistently low values throughout all growth stages for T_1 (control). Additionally, treatments containing other coated fertilizers also performed well than the control. Overall, the application of SRFs in combination with biochar induced increments in morphological and physiological parameters of tomato (28).

On the other hand, when we see antioxidant activity such as peroxidase, we observe that T_8 outperform the rest in all the growth stages of the crop followed by T_7 and the least performing treatment was T_1 (Fig. 3). This is because micronutrients play a significant role as enzyme cofactors. Iron is essential for heme group present in peroxidase and without

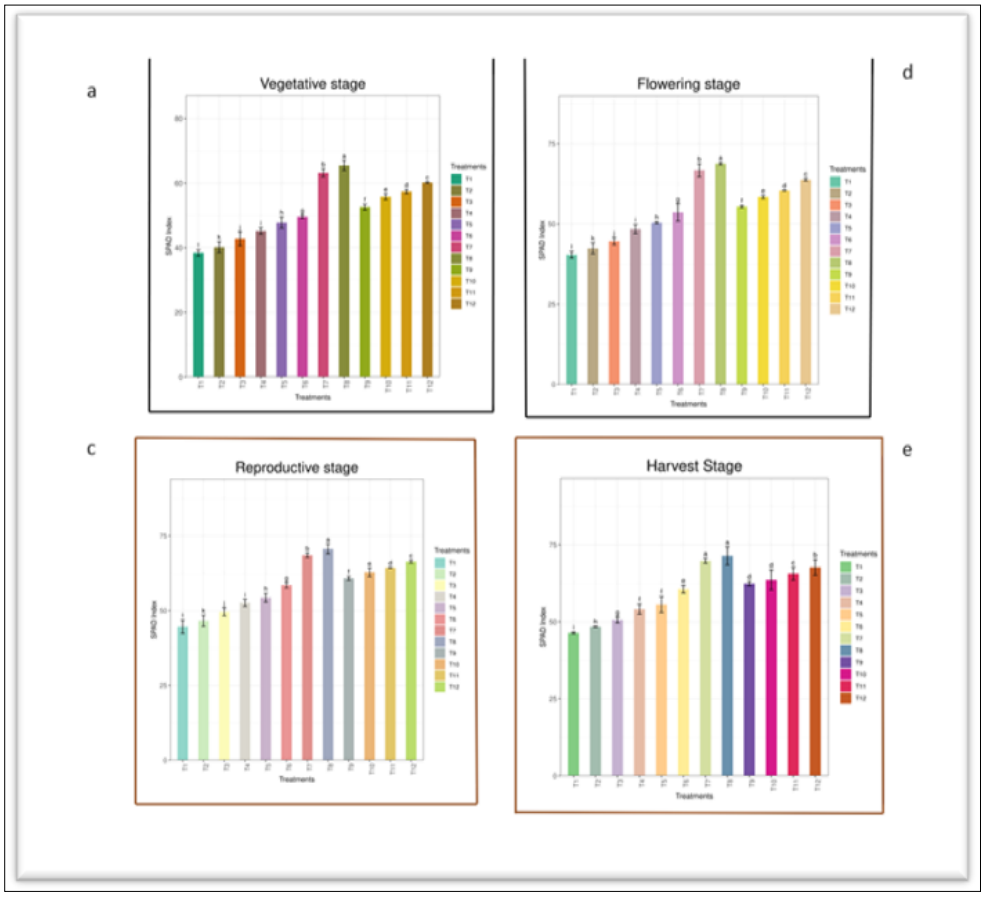

Fig. 2. Chlorophyll content (SPAD) as recorded at different physiological stages.
a. Vegetative stage; b. Flowering stage; c. Reproductive stage; d. Harvest stage

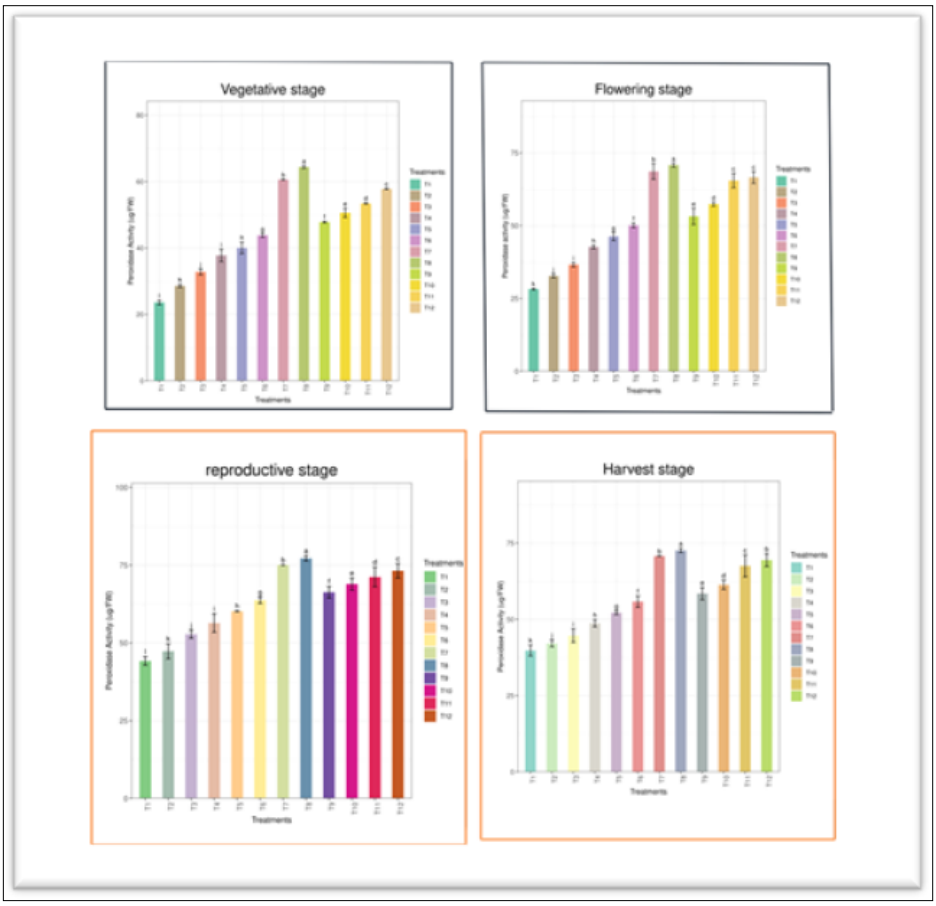

Fig. 3. Enzymatic activity as recorded at different physiological stages.
a. Vegetative stage; b. Flowering stage; c. Reproductive stage; d. Harvest stage

it; enzyme's active site cannot bind with H_2O_2 and catalyse its breakdown. Likewise, copper stabilizes the enzyme structure and enables electron structure in enzymatic reactions. Similarly, zinc and manganese are also involved indirectly in holding the membrane integral and protein structures under oxidative stress. Therefore, deficiency of any micronutrient may lead to significant loss and reduction in peroxidase activity in the crop (25,29). Henceforth, it can be suggested that the application of micronutrients, whether through traditional fertilization or innovative approaches like slow/controlled systems delivery can significantly enhance peroxidase activity and overall antioxidant capacity in tomato plants.

Conclusion

The use of biochar and HA as coating materials for slow-release fertilizer development has demonstrated significant agronomic and nutritional benefits which was represented by treatment T_8 followed by T_7. This study presents that the utilization of biomass derived biochar and HA coated SRFs are a novel approach for better utilization and uptake of micronutrients which often remains a subject of quite negligence. Additionally, their porous and functionalized surfaces enable gradual nutrient desorption, synchronizing nutrient release with plant uptake demand. The incorporation of biochar with micronutrients in the core and coating with HA showed positive impact in sustained release. This was evident from the uniform increments visible in morphological and physiological parameters such as plant height, root length, chlorophyll content and antioxidant activity throughout the growth stages of the crop. It is more likely that biochar seems to influence the mechanical properties and hydrophobicity of the formulation and micronutrient release behaviour through the coated fertilizer. Therefore, biochar and HA are effective, sustainable and synergistic carriers for the controlled release of nutrients in modern agricultural systems.

Acknowledgements

Thanking the Department of Soil Science and Agricultural Chemistry, Tamil Nadu Agricultural University for providing financial support in carrying out the field trial and for all the time-to-time assistance required during the research work.

Authors' contributions

AK was responsible for writing and formulating the original draft. ME played a key role in conceptualization, data validation, methodology. PJ contributed to data curation and review and editing of the draft. SS focused on visualization, re-drafting and editing while AS and EP made major contributions by correcting the final version of the manuscript. SKB contributed to reviewing and final proofreading of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

References

1. United Nations, Department of Economic and Social Affairs, Population Division. World population prospects 2022: summary of results. New York: United Nations; 2022. World population prospects series No. 2022/1.
2. FAO. Global agriculture towards 2050. In: Proceedings of the High Level Expert Forum – How to Feed the World in 2050; 2009 Oct 12–13; Rome, Italy. Rome; 2009.
3. Purnomo CW, Saputra H. Manufacturing of slow and controlled release fertilizer. In: Fahad S, Hasanuzzaman M, Fujita M, Ok YS, Saeed M, Adnan M, editors. Controlled release fertilizers for sustainable agriculture. Amsterdam: Elsevier; 2021. p. 95–110 https://doi.org/10.1016/B978-0-12-819555-0.00006-6
4. Bose U, Tripathi S. Effect of micronutrients on growth, yield and quality of tomato cv. Pusa Ruby in MP. Crop Res. 1996;12:61–4.
5. Mondal S, Bose B. Impact of micronutrient seed priming on germination, growth, development, nutritional status and yield aspects of plants. J Plant Nutr. 2019;42:2577–99. https://doi.org/10.1080/01904167.2019.1655032
6. Welch RM, Shuman L. Micronutrient nutrition of plants. Crit Rev Plant Sci. 1995;14:49–82. https://doi.org/10.1080/07352689509701922
7. Khoshgoftarmanesh AH, Schulin R, Chaney RL, Daneshbakhsh B, Afyuni M. Micronutrient-efficient genotypes for crop yield and nutritional quality in sustainable agriculture. Agron Sustain Dev. 2010;30:83–107. https://doi.org/10.1051/agro/2009017
8. Graham RD. Micronutrient deficiencies in crops and their global significance. In: Alloway BJ, editor. Micronutrient deficiencies in global crop production. Dordrecht: Springer; 2008. p. 41–61 https://doi.org/10.1007/978-1-4020-6860-7_2
9. Liu G, Zotarelli L, Li Y, Morgan K. Controlled-release and slow-release fertilizers as nutrient management tools [Internet]. Gainesville (FL): University of Florida IFAS Extension; 2017. https://edis.ifas.ufl.edu/publication/HS1255
10. Ranganathan DS, Perumal R. Effect of micronutrients with/without organics and biofertilizers on growth and development of tomato in inceptisol and alfisol. South Indian Hort. 1995;43(3–4):89–92.
11. Mihalache G, Peres CI, Bodale I, Achitei V, Gheorghitoaie MV, Teliban GC, et al. Tomato crop performances under chemical nutrients monitored by electric signal. Agronomy. 2020;10:1915. https://doi.org/10.3390/agronomy10121915
12. Azeem B, Kushaari K, Man ZB, Basit A, Thanh TH. Review on materials and methods to produce controlled release coated urea fertilizer. J Control Release. 2014;181:11–21. https://doi.org/10.1016/j.jconrel.2014.02.020
13. Trenkel ME. Slow- and controlled-release and stabilized fertilizers: an option for enhancing nutrient use efficiency in agriculture. Paris: International Fertilizer Industry Association; 2010.
14. Govil S, Long NV, Escribà-Gelonch M, Hessel V. Controlled-release fertiliser: recent developments and perspectives. Ind Crops Prod. 2024;219:119160. https://doi.org/10.1016/j.indcrop.2024.119160
15. Lawrencia D, Wong SK, Low DYS, Goh BH, Goh JK, Ruktanonchai UR, et al. Controlled release fertilizers: A review on coating materials and mechanism of release. Plants (Basel). 2021;10(2):238. https://doi.org/10.3390/plants10020238
16. Eghbali BF, Yunus R, Masoudi SS, Shotipruk A. Release mechanisms and kinetic models of gypsum–sulfur–zeolite-coated urea sealed with microcrystalline wax for regulated dissolution. ACS Omega. 2021;6:11144–54.
17. Tapia-Hernández JA, Madera-Santana TJ, Rodríguez-Félix F, Barreras Urbina CG. Controlled and prolonged release systems of urea from micro- and nanomaterials as an alternative for developing a sustainable agriculture: a review. J Nanomater. 2022;2022:5697803. https://doi.org/10.1155/2022/5697803
18. Chatzoudis GK, Rigas FP. Combined action of hydrogel and controlled-release fertilizers on growth of tomato plants. Acta Hortic. 2003;613:193–6.
19. Kalita A, Elayarajan M, Janaki P, Suganya S, Sankari A, Parameswari E. Organo-monomers coated slow-release fertilizers: current understanding and future prospects. Int J Biol Macromol. 2024;133320. https://doi.org/10.1016/j.ijbiomac.2024.133320
20. Brewer K, Clulow A, Sibanda M, Gokool S, Naiken V, Mabhaudhi T. Predicting the chlorophyll content of maize over phenotyping as a proxy for crop health in small holder farming systems. Remote Sens. 2022;14(3):518. https://doi.org/10.3390/rs14030518
21. Singh AK, Verma SK, Rai GK. Effect of humic acid and micronutrient mixture on growth, yield and quality of tomato (*Solanum lycopersicum* L.). J Appl Nat Sci. 2016;8(1):373–6. https://doi.org/10.31018/jans.v8i1.1369
22. Homayoonzadeh M, Torabi E, Talebi K, Allahyari H, Nozari J. Micronutrient fertilization amplified the antioxidant capacity in tomato plants with improved growth and yield. InBiol Life Sci Forum. 2021;11(1):62.
23. Patil VK. Effect of foliar application of micronutrients on growth, yield and quality of tomato (*Lycopersicon esculentum* Mill.) cv. Phule Raja. Horticulture, Master's [thesis]. Parbhani (IN): Vasantrao Naik Marathwada Krishi Vidyapeeth; 2009.
24. Rosa D, Petruccelli V, Iacobbi MC, Stanzione F, Forte A, Iovino P. Functionalized biochar from waste as a slow-release nutrient source: application on tomato plants. Heliyon. 2024;10(4):e25861. https://doi.org/10.1016/j.heliyon.2024.e25861
25. Karakurt Y, Hıdıroğlu İ, Aslantas R. Effects of foliar applied humic acid and microelements on yield, fruit quality, nutrient content and growth of tomato (*Lycopersicon esculentum* L.). J Plant Nutr. 2009;32(1):146–57. https://doi.org/10.1080/01904160802592774
26. Li Y, Zhu M, Duan X, Zhang J, Yang Y, Zhang Z. Biochar improves tomato growth and photosynthetic traits under drought and salinity stress. BMC Plant Biol. 2024;24(1):120. https://doi.org/10.1186/s12870-024-05058-9
27. Meena DC, Maji S, Meena J, Govind, Kumawat R, Meena RK, et al. Improvement of growth, yield and quality of tomato (*Solanum lycopersicum* L.) cv. Azad T-6 with foliar application of zinc and boron. Int J Bio-resour Stress Manag. 2015;6:598. https://doi.org/10.5958/0976-4038.2015.00091.3
28. Pérez-Labrada F, López-Vargas ER, Ortega-Ortiz H, Cadenas-Pliego G, Benavides-Mendoza A, Juárez-Maldonado A. Responses of tomato plants under saline stress to foliar application of copper nanoparticles. Plants. 2019;8(6):151. https://doi.org/10.3390/plants8060151
29. Chowdhury AK. Studies on effect of foliar application of zinc humate on growth, yield and quality of tomato (*Solanum lycopersicum* L.) in laterite soil of West Bengal. Horticulture, Master's [thesis]. Mohanpur (IN): Bidhan Chandra Krishi Viswavidyalaya; 2017.

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

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