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Research Article

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Posted Date: October 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11043993/v1>

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Additional Declarations: No competing interests reported.

Coconut Shell Biochar as a Sustainable Amendment for Soil Quality and Tomato (*Solanum lycopersicum* L.) Plant Growth

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Abstract

Growing concerns about environment sustainability and food security have encouraged the adoption of sustainable soil amendments that enhances soil quality and improve crop growth. This study assessed the effect of coconut shell waste derived biochar as a sustainable soil management strategy to improve tomato (*Solanum lycopersicum* L.) growth while supporting agricultural resource utilisation. Following controlled slow pyrolysis of coconut shell waste, the resulting biochar was comprehensively characterised to assess its physiochemical properties, such as surface morphology, porosity, pH, and nutrient availability. The experiment was designed and set up as a randomised complete block design with 3 replicates per treatment. Tomato plants were cultivated under greenhouse conditions for 120 days and subjected to four biochar application rates 0%, 2%, 4% and 6%, designated as T1 (control), T2, T3 and T4, respectively. The coconut shell-derived biochar (CSB) exhibited a mildly alkaline nature (pH 7.23), whereas the experimental soil was moderately acidic (pH 6.16). The ANOVA (Analysis of variance) indicated that biochar application significantly influenced soil quality and tomato plant growth, indicating its potential for sustainable crop production. Consequently, tomato plants exhibited better growth, stronger root development, and higher fruit yield and quality than those grown in untreated soil, highlighting the potential of biochar to better crop yield and soil management.

Keywords: Coconut Shell Biochar, Soil Quality, Sustainable Food Production, Nutrient dynamics, Tomato.

31 Graphical abstract:



32

33 Highlights

- 34 1. Coconut shell biochar (CSB) improved soil fertility and enhanced tomato plant growth.
- 35 2. Biochar enhanced Soil Carbon, Nutrient availability, Water retention and CEC.
- 36 3. Biochar response varied with the application rate, revealing a nonlinear dose effect.
- 37 4. At 6% biochar rate maximized fruit yield, while 4% rate enhanced biomass accumulation.
- 38 5. Agricultural waste was valorised into a functional soil amendment.

39

40 1. Introduction

41 Global food security and sustainable agricultural production are under growing threat from soil
 42 degradation, declining soil quality, and progressive soil fertility loss. Soil quality is largely
 43 governed by soil organic matter (SOM), electrical conductivity (EC) and soil depth; imbalances
 44 in these indicators often result in salinization, erosion, nutrient loss and compaction [1, 2].
 45 Hence, rising food demand and climate change highlight the urgent need for green and
 46 sustainable solutions in order to enhance as well as restore soil quality while mitigating the
 47 ecological impacts of agricultural practices to achieve higher crop productivity. In this context,
 48 organic amendments offer a promising strategy to enhance SOM content, maintain soil
 49 structure as well as promote soil fertility and plant productivity [3]. Biochar, an emerging
 50 recalcitrant, carbon-rich material produced via pyrolysis of organic feedstocks under anoxic

conditions has gained significant attention in this regard [4-7]. Traditionally practiced in India and some other Asian regions, the use of biochar as a soil amendment has diminished with increased reliance on inorganic fertilizers [8]. Renewed interest in biochar has emerged because agricultural waste can be converted into locally available soil amendment, providing an opportunity to simultaneously manage biomass waste and improve soil functions [9].

Literature reports indicate that biochar improves soil functionality by increasing water-holding capacity, enhancing nutrient availability, stimulating microbial activity, balancing soil pH, and facilitating the immobilization of soil contaminants [10-14]. Its recalcitrant nature makes biochar a suitable candidate for long-term carbon sequestration in soils and helps to mitigate greenhouse gas emissions as well [15]. Additionally, the skeletal, sponge-like framework of biochar facilitates retention of soil nutrients thereby limiting their leaching into the environment [16, 17]. Owing to diversity in potential biomass sources for biochar production, there arises variability in their physical and chemical properties [18, 19], which together, with production conditions significantly affect functional properties such as adsorption, surface area, porosity, alkalinity and carbon content [20, 21]. Coconut shell is a lignin rich abundant biomass feedstock, serves as a promising resource for biochar production as it possesses high carbon content, porosity and strong structural stability [8]. Its surface functionality and nutrient retention capacity can further be enhanced by surface modification, which ultimately increases its efficiency as soil amendment.

Tomato (*Solanum lycopersicum* L.) is an economically important vegetable crop whose growth and productivity are strongly influenced by soil fertility and water availability. Tomato offers substantial nutritional benefits owing to the presence of abundant antioxidants which play an important role in maintaining good health and reducing the cardiovascular disorder and cancer [22-25]. Global production of tomatoes in 2024 was recorded to be 188.5 million tons, spanning over 5.1 million hectares of cultivated land [26]. However, improper and excessive use of fertilizers, coupled with poor agronomic practices have exacerbated the exposure of tomatoes to environmental challenges, resulting in a decline of yield. Current research indicates that biochar amendment can substantially promote tomato growth, productivity and overall fruit quality. For example, Kumari et al. reported significant enhancements in vegetative growth (plant height, branches number and leaf area), fruit yield and quality parameters ((size and weight) under both field and laboratory conditions. They observed that with 200 kg/acre biochar, 3.47 kg per plant and 12.83 kg per meter square yield was obtained [27]. Yadav et al. studied the effect of biochar on tomato plant in the kharif season of 2024 in an organic farm and

reported that application of biochar significantly improved plant height, stem diameter, number of leaves, number of flowers, fruits per plant, weight of fruit along with harvest stage of tomato [28]. From meta-analysis, Lei et al. reported that use of biochar increased tomato yield by 29.55%, total soluble solid (TSS) by 4.28%, and vitamin C (VC) by 6.77% in comparison to control treatments without biochar [29]. Similarly, Adekiya et al. carried out a 120-day study on effect of biochar amendment for growth, yield, quality and self-life of tomato. The results showed increase in these parameters due to increase in soil quality on addition of biochar and percentage weight loss of tomato was also controlled [30].

Although much progress has been made, the study of underlying mechanisms which govern the interactions of biochar, soil properties and plant physiological processes remain a gap. Also, the effectiveness of CSB to regulate nutrient availability and improvement in crop productivity across different soil types needs further investigation. Therefore, this study evaluated graded CSB application rates (0, 2, 4 and 6%) for their effects on soil pH, EC, WHC, CEC, Moisture content, organic carbon and nutrient availability, along with tomato morphological, physiological, biomass and productivity responses. Integrating biochar functionality with soil and plant responses, this study provides insights into rate dependent biochar soil plant interactions and the valorization of agricultural residues into a value-added carbonaceous material for sustainable soil management. The study also contributes to the objectives of United Nations sustainable development goals (SDGs), SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land) through sustainable crop production, agricultural waste management and improved soil fertility management.

2. Materials and methodology

2.1. Preparation of biochar from coconut shell waste

Slow pyrolysis was carried out in a muffle furnace (Metrex Scientific Instruments Limited, 101) with crucibles containing coconut shell and sealed to limit the presence of oxygen at temperature of 500 °C (Process shown in Figure 1). Before pyrolysis, the feedstock was processed by drying at 105 °C for 24 hours and sieving to a particle size of less than 5mm. the pyrolysis process was maintained for 2 hours, ensuring consistent heating and a stable inert environment. The resultant biochar was allowed to cool within the reactor to minimize oxidation and ground to pass through 2 mm sieve afterwards as outlined by Antonangelo et al. [31]. 5g biochar was mixed with 50 mL deionized water (w/v, 1:10).

2.2. Proximate and ultimate analysis

The moisture, ash, and volatile matter content of the biochar was determined using the standard procedures described in ASTM D1762-84 (2009). Fixed carbon (%) was calculated from the difference of moisture, ash, and volatile matter [32]. The element (C, H, N, and S) contents were analyzed by Elemental analyzer (Elementar Vario EL Cube). Biochar that undergoes extensive carbonization will exhibit reduced O/C and H/C ratios, indicating that it consists predominantly of carbon and has a smaller amount of oxygen and hydrogen [33]. These ratios are significant in determining the biochar's stability and reactivity in the environment.



Fig. 1 Process flow of synthesize of biochar from coconut shell waste

The biochar yield was determined as the ratio of the mass of the biochar product to the mass of the biomass, using the following equation:

$$\text{Biochar yield}(\%) = \frac{\text{Weight of biochar (g)}}{\text{Weight of coconut shell (g)}} \times 100 \quad (1)$$

The bulk density was calculated as per using eq. 2 (Khater et al., 2024):

$$\text{Bulk density} = \frac{\text{Mass of biochar}}{\text{Bulk volume of biochar}} \times 100 \quad (2)$$

2.3.Biochar characterization techniques

The crystal structures of biochar were analyzed by X-ray diffractometer (XRD) (Smart lab 3kw/ Rigaku) with operational parameters set at Scan range 1-157 and angle speed per minute 2-10. The surface morphologies of CSB were observed by a scanning electron microscope (SEM) (7610F Plus/JEOL) equipped with energy-dispersive X-ray spectrometer (EDS). SEM imaging was performed under a high vacuum at a resolution of 0.8 nm and accelerating voltage of 15 kV. Functional groups were identified using a Fourier transform infrared spectrometer (FTIR) (Spectrum 2, Perkin Elmer, India) over the range of 400–4000 cm^{-1} . The specific surface area and pore size of CSB was calculated by the Brunauer-Emmett-Teller (BET) method using an automated surface area and porosity analyzer (Quantochrome Autosorb1 QC-MP). Before test, the biochar samples were degassed at 200 °C for approximately 3 hr under vacuum atmosphere. The charge on the surface of CSB was determined using a Zeta potential measurement (Malvern, Nano zs). The thermogravimetric analyses (TGA) of CSB were performed using a Shimadzu TGA-60 thermal analyzer under an N_2 atmosphere at 50 mL min^{-1} . The samples were placed in aluminum crucibles, and the analyses were conducted within a temperature range of 100 °C to 1000 °C, with a heating rate of 10 °C min^{-1} , using a 10 min plateau at 105 °C. Other details of characterization techniques of biochar is given in S1 of supporting information file.

2.4. Soil sampling and analysis

Soil samples were collected from Myna village in Rohtak, Haryana, India. The study area is characterized by a predominantly dry climate, with recorded temperatures ranging from approximately 16 °C in March to 40.5 °C in July. The soil used in the experiment is a sandy clay. The region's soil depths vary from shallow to deep, the topmost soil is coarsely textured, contains little organic matter, and is severely deteriorated in certain places, which results in low soil fertility. Soil samples from the upper layer (0 to 20 cm) of the experimental pots were collected prior to the initiation of the experiment and after crop harvest, following standard protocols for subsequent physicochemical analysis. Samples were homogenized thoroughly to exclude any plant roots and debris. The collected samples were air-dried, pulverized, sieved through a 2 mm mesh and stored in clean plastic bags. The details of analysis for the soil samples are given in supporting information file S2.

2.5. Experimental design and field description

The pot experiment was carried out in a greenhouse at the Maharshi Dayanand University, Rohtak, Haryana, from March 2024 to June 2024 to evaluate the impact of biochar on the growth and yield of tomato (*Solanum lycopersicum* L.). The experimental design followed a completely randomized design with four treatments and three replicates for each treatment. The pots (18 cm length, 16 cm width, and 30 cm height) were filled with 8.0 kg biochar-soil mixtures at a 2% (T2), 4% (T3), and 6% (T4) (w/w) ratio, with non-biochar soils serving as controls (T1). Biochar was applied manually to each experimental pot at the prescribed rate and uniformly incorporated into the soil to ensure consistent distribution prior to transplanting. A constant distance of 5.0 cm was maintained between the soil surface and the upper border of each potted plant in the experiment to ensure irrigation conditions. The tomato seeds of INDAM Nanda (Indo-American) variety were obtained from the Haryana Nursery, Rohtak and the plants were cultivated under greenhouse conditions for experimental purposes following standard cultivation practices recommended by IARI (Indian Agricultural Research Institute). The tomato growth cycle was of 120 days and the average temperature was 35 °C /25 °C (day/night). The healthy seedlings were transplanted into the pots at the early growth stage. All treatment were mentioned under uniform experimental conditions, with irrigation, ploughing and weeding carried out at regular intervals.

2.6. Plant sampling and growth parameter analysis

At harvest, the height of the tomato plants was measured from the soil surface to the tip of the longest leaf, the number of leaves and branches per plant was determined. Internodal distance was also measured. After destructive harvesting and thorough cleaning with distilled water, shoot and root length along with the fresh weights were determined and stored at -80 °C until chlorophyll measurement. Root and above-ground dry weights were determined after oven drying at 70 °C for 48 hr [34]. Chlorophyll contents were calculated using the equations described by Arnon, (1949). 1 g of fresh leaves were homogenized in 20 ml of 80% acetone for chlorophyll extraction. Then, the mixture was filtered, and the optical density (OD) of Chlorophyll-a (Chla) and Chlorophyll-b (Chlb) was measured at 663 nm and 645 nm, respectively. Tomato yield per plant was calculated by measuring total weight of harvested fruit.

2.7. Statistical analysis

The data were collected and subjected to one-way analysis of variance (ANOVA) followed by a comparison of multiple treatment levels with controls using Tukey's honest significant

difference test [35]. Differences between means were considered significant for p values < 0.05. GraphPad Prism version 8.0.2 for Windows, GraphPad Software, Boston, Massachusetts USA was used for all statistical analyses.

3. Results and discussion

3.1. Biochar characterisations

The physicochemical properties of the biochar were analyzed via proximate and ultimate analysis to determine its structural, elemental, and functional characteristics, as given in Table 1. The biochar yield is 37.5% and is within the normal range of biochar produced at 500 °C. The biochar found to have a slightly alkaline pH of 7.70, making it suitable for improving acidic soils, EC of 417 (uS/cm) and CEC of 46.3 (meq/100 g) indicating its moderate ionic content. The CSB was comprising of lower bulk density (0.60 g/cm³) and higher WHC (60.4%) influencing soil aeration and porosity. High carbon content (79.72 %) of the CSB indicate its suitability for applications emphasizing carbon stability, such as soil amendment and long-term carbon sequestration [36]. Moisture content, ash content, volatile matter, and fixed carbon were found to be 3.20%, 3.80%, 28.5%, and 64.5%, respectively. CSB contains a significant amount of fixed carbon can be used as a powerful CO₂ sequester and climate change mitigation strategy. Oxygen and nitrogen contents in biochar can affect its stability and reactivity, while hydrogen, sulfur, and carbon contents can affect its energy content and combustion properties.

Table 1: Basic physical-chemical properties of biochar.

Parameter	Results
Yield	37.5 %
pH	7.70
EC	417 μ S/cm
Bulk density	0.60 g/cm ³
CEC	46.3 meq/100g
Water holding capacity	60.4 %
Proximate analysis	
Moisture content	3.20 %
Ash content	3.80 %
Volatile matter	28.5 %
Fixed carbon	64.5 %

Ultimate analysis	
Carbon	79.72 %
Hydrogen	3.13 %
Nitrogen	0.28 %
Sulfur	0.05 %
Atomic ratios	
H/C	0.468
O/C	0.16
C/N	332
Specific surface	255.24 m ² /g
Average Pore size/diameter	2.6 nm (mesoporous)
Total Pore volume	0.156 cm ³ /g

212

213 Thermo gravimetric analysis (TGA) evaluates the thermal degradation performance of the
 214 biochar. Figure S1 (supplementary information) shows the thermal decomposition curve of
 215 biochar up to 1000°C. The biochar demonstrated greater thermal stability, according to the
 216 findings. In particular, for biochar, the first mass loss occurred up to 350 °C, and the second up
 217 to 900 °C. The total weight loss was 94.72% and the residual mass percentage was 5.28% for
 218 biochar.

219 Surface morphology and porosity characteristics were analyzed by SEM. The SEM
 220 micrographs (Figure 2) reveal the heterogeneous surface morphology of CSB at varying
 221 magnifications (10,000x to 50,000x) indicative of its suitability for soil amendment. At lower
 222 magnification the surface exhibited prominent macropores and fissures, likely formed by
 223 devolatilization during pyrolysis, which can enhance soil aeration, water infiltration, and
 224 microbial colonization. At higher magnification, a network of meso- and micropores was
 225 observed, contributing to increased internal surface area, beneficial for nutrient adsorption. The
 226 presence of sharp edges and fragmented particles also indicates high reactivity and potential
 227 for cation exchange, making this biochar highly suitable for agronomic applications.
 228 Examination of the chemical composition of CSB using EDS analysis revealed that in addition
 229 to carbon CSB included Na, O, Ca, K and Au (Figure S2).

To further quantify porosity and specific surface characteristics, BET surface area analysis was conducted. BET analysis confirmed a moderate surface area ($255.24 \text{ m}^2/\text{g}$) and pore volume ($0.156 \text{ cm}^3/\text{g}$), highlighting the potential of low-temperature biochar for applications where structural integrity and moderate adsorption capacity are desirable.

From FTIR analysis (Figure S3), it was observed that the main characteristic peaks for CSB appeared at 3417 , 2920 , 1618 , and 1127 cm^{-1} , which correspond to the stretching vibration of O-H, the bending vibration of C-H, the bending vibration of C=C, and the bending vibration of C-O, respectively [37]. These functional groups are crucial for enhancing nutrient retention, water retention and aromatic stability in soil.

X-ray diffraction (XRD) analysis of the CSB exhibited broad, diffuse peaks centered around 22° and $42^\circ 2\theta$ (Figure S4), characteristic of a predominantly amorphous carbon structure. The prominent hump at $\sim 24^\circ$ corresponds to the (002) plane of disordered graphitic carbon, which is a common feature in biochar derived from lignocellulosic biomass. This lack of crystallinity enhances the material's surface reactivity, ion exchange capacity, and sorption potential, making it well-suited for applications such as soil amendment and root-zone improvement. These observations are consistent with the findings of da Silva et al. [38], who reported similar amorphous patterns in coconut shell-derived biochar pyrolyzed at 500°C for soil remediation purposes.

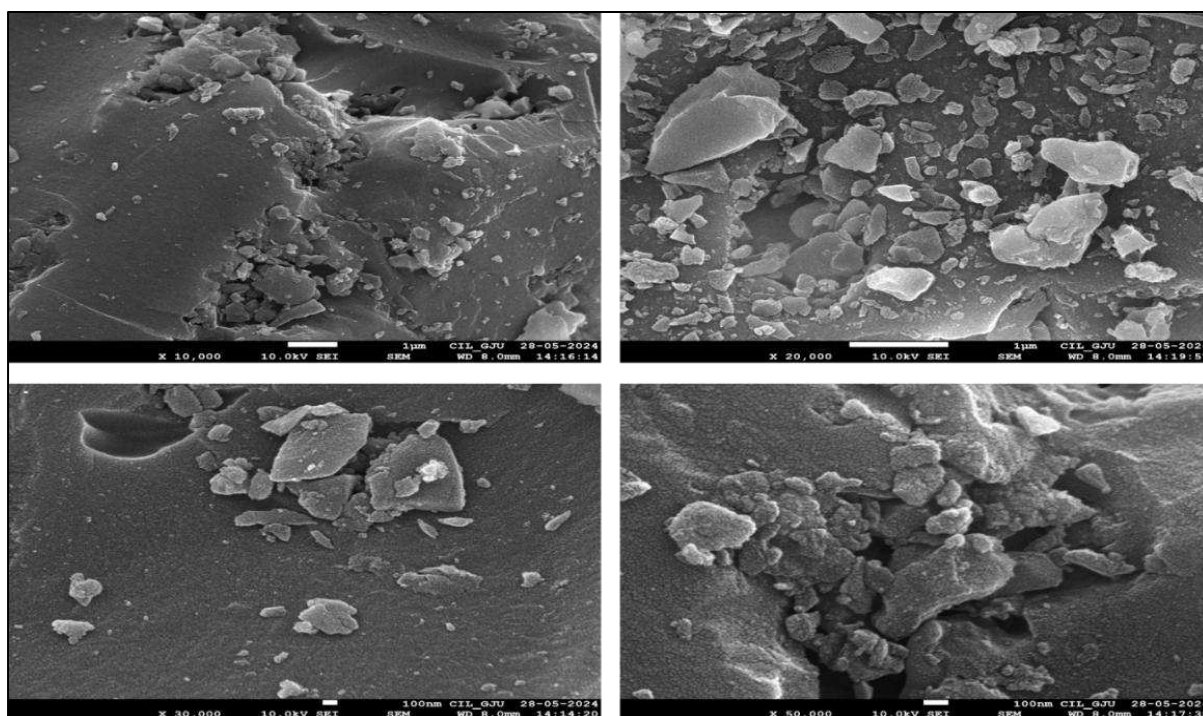


Fig. 2 SEM images show microscopic views of the CSB, revealing its three-dimensional, multilayered, hollow structure with large porous holes at 0.1 to 1.0 $\mu\text{m}/100\text{-}1000\text{ nm}$

Zeta potential analysis (Figure S5) indicated a surface charge of -12.1 mV for the CSB, suggesting a moderately stable colloidal suspension with a tendency for limited agglomeration. This level of surface negativity supports cation exchange potential, beneficial in nutrient-deficient and acidic soils. Particle size analysis (Figure S6) showed a multimodal distribution with a Z-average diameter of $5.3\text{ }\mu\text{m}$ (5295 nm) and a polydispersity index (PDL) of 0.250 , indicating moderately dispersed micro-sized particles suitable for soil incorporation. These results align with the findings of Sani et al. [39], who demonstrated that CSB with zeta potentials in the range of -10 to -30 mV and $\text{PDL} < 0.4$ exhibited strong agronomic performance and colloidal behavior suitable for sustainable agriculture.

3.2. Impact of biochar addition on soil physiochemical properties

The soil has a sandy clay texture with a bulk density of 1.53 g/cm^3 . In the cultivation of tomatoes, a notable increase in soil pH was observed in T2, T3 and T4 (6% CSB w/w) treatments compared to the control (6.16). This liming effect is attributed to the alkaline nature of biochar and the presence of basic cations such as Ca^{2+} , K^+ , and Mg^{2+} which can contribute to the buffering of soil acidity. Additionally, there was overall average CEC increase of 77% rising from 9 to 18.33 meq/100g affirming biochar's ability to influence soil CEC positively, especially in coarse-textured soils with inherently low CEC. The highest increase (103.67%) was observed in T4. This enhancement is likely due to the high surface area and functional groups of biochar, which promote ion retention and nutrient exchange. EC showed a nonlinear trend, initially decreasing slightly in T2 ($119\text{ }\mu\text{S/cm}$), followed by a marked increase in T3 ($215.2\text{ }\mu\text{S/cm}$) and T4 ($261\text{ }\mu\text{S/cm}$). This suggests an increase in the release of soluble ions with high biochar rates. A sharp rise in organic carbon was recorded, from 0.40% in T1 to 1.43% (T2), 1.69% (T3), and 2.43% (T4), reflecting up to a six-fold increase at the highest dose. Similarly, SOM content improved significantly, from 0.68% to 4.17% . These changes highlight biochar's role in carbon sequestration and aggregate stability, contributing to long-term soil health. WHC and moisture content increased with biochar application, reaching 59.06% and 22.52% in T4 respectively, indicating enhanced soil porosity and water retention.

Impact of soil physicochemical properties with varied amount of biochar (BC) viz. 2% , 4% and 6% , was analyzed using ANOVA and depicted in Figure 3 as well as Table S2 of supplementary file. A gradual increase in soil pH was seen from control to BC- 6% in Figure

3a. However, the differences were statistically non-significant ($p > 0.05$), indicating that even though biochar helps in neutralizing soil acidity, the magnitude of change was not sufficient to produce statistically significant variation among treatments. The slight increase in pH with increase in amount of BC can be ascribed to the alkaline nature of biochar and the presence of basic cations such as Ca^{2+} , Mg^{2+} and K^{+} in its ash. Similarly, Teng et al. based on a global meta-analysis, observed a 12.60% increase in soil pH after biochar application in highly acidic soils [40]. Electrical conductivity (EC) exhibited a significant increase with biochar dose of 4% and 6% exhibiting $p < 0.0001$ as compared to control (Figure 3b). This rise in EC is due to the release of soluble salts and mineral ash content from biochar. The higher ionic concentration enhances soil solution conductivity, but the EC values remain within acceptable limits, indicating no salinity stress for plant growth. Biochar application increased soil EC by 70.30% overall, while biochars particularly with less nitrogen content increased EC by 61.27%, indicating that biochar characteristics influence soil ionic conductivity [41, 42]. The water holding capacity (WHC) shows significant improvement in biochar-amended soil at higher doses ($p < 0.01$ to $p < 0.001$) (Figure 3c). The BC-6% treatment showed highest WHC which attributes to the increased soil porosity and water retention capacity owing to the porous structure and high surface area of biochar. These findings are consistent with studies carried out by Khan et al., who reported that biochar increased soil porosity and water retention by 8.4% and 15.1% respectively, based on meta-analysis of 74 studies [43]. Rise in biochar concentration increases the soil moisture content. The BC-4% and BC-6% treatment exhibited significant differences ($p < 0.001$ to $p < 0.0001$) as shown in Figure 3d. The enhanced moisture retention is due to the hygroscopic nature and presence of internal pore network of biochar. A slight decrease was seen in BC-2% as compared to control, indicating that lower biochar doses may not be sufficient to modify the soil structure. Biochar induced changes in soil porosity highly varied with application rates and soil type [44]. A statistically significant increase in soil organic carbon (SOC) was observed with biochar addition, particularly at higher concentration ($p < 0.01$ to $p < 0.0001$) as depicted in Figure 3e. Since, biochar itself is carbon-rich and contributes directly to SOC levels, hence this trend was observed. Further, its recalcitrant nature enhances long-term carbon sequestration [45, 46]. With addition of biochar, the cation exchange capacity (CEC) increases showing highly significant differences with $p < 0.0001$ (Figure 3f). This increase in CEC is attributed to the enhancement of nutrient retention and ion exchange capacity due to the presence of functional groups such as carboxylic, phenolic, etc. on biochar surfaces. The improved CEC has been reported to facilitate better nutrient availability for plants [47]. Organic matter content showed a significant statistical increase with

rise in biochar dose from 2% to 6% ($p < 0.001$ to $p < 0.0001$) (Figure 3g). This increase is due to the addition of stable carbon fractions through biochar incorporation. Also, biochar may stimulate microbial activity, further contributing to SOM accumulation as reported previously [48].

Table 2: The effect of CSB on soil properties for tomato production.

Soil Parameters	Treatments			
	Control (T1)	BC-2% (T2)	BC-4% (T3)	BC-6% (T4)
Soil texture	Sandy clay	-	-	-
Bulk density (g/cm ³)	1.53	-	-	-
pH	6.16	6.76	7.13	7.23
EC (μS/cm)	128.6	119	215.2	261
Moisture content (%)	12.03	8.55	20.42	22.52
CEC (meq/100g)	9	13	16.46	18.33
Organic carbon (%)	0.40	1.43	1.69	2.43
Organic matter (%)	0.68	2.45	2.90	4.17
WHC (%)	51.66	58.20	57.36	59.06

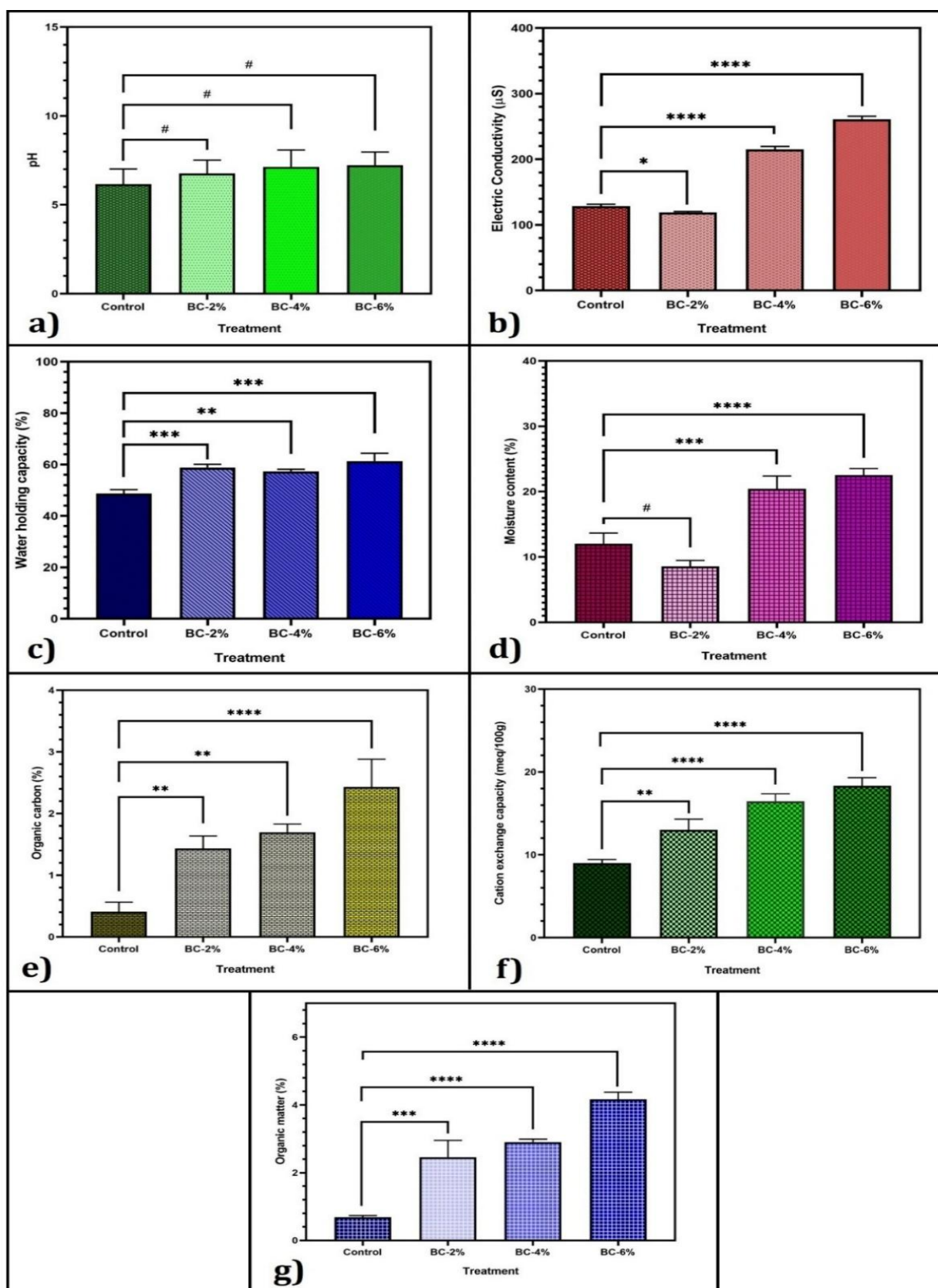


Fig. 3 Comparison of different soil characteristics after biochar treatment a) pH, b) electric conductivity, c) water holding capacity, d) moisture content, e) organic carbon, f) cation

exchange capacity, g) organic matter. (Values represent mean $\pm$ standard deviation with # = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = $p < 0.0001$)

3.3. Effect of coconut shell engineered biochar on soil nutrient availability

3.3.1. Influence on Soil Macronutrient Dynamics

Biochar showed increased concentrations of Nitrogen (N), calcium (Ca), phosphorus (P), potassium (K), copper (Cu), zinc (Zn), and magnesium (Mg). Among the most pronounced effects was an increase in N content, which ranged from 452.03 to 514.76 kg/ha. This may also reflect the biochar's role as a habitat for nitrogen-fixing microbes. Phosphorus concentration, however, showed considerable variability across treatments (28.5-61.81 kg/ha). In some cases, biochar application appeared to reduce P availability, possibly due to P immobilization via sorption onto biochar surfaces or formation of insoluble complexes, particularly under alkaline conditions. This aligns with reports that biochar's influence on P dynamics is often site and pH specific. Potassium (K) levels increased consistently across all treatments, with values ranging from 161.45 to 210.06 kg/ha. This enhancement can be attributed to both the inherent K content of the CSB and its ability to minimize K losses via improved retention in the soil matrix. These findings confirm that biochar acts as a slow-release source of K, especially in tropical soils where leaching is prevalent. Soil Ca and Mg concentration also reflected moderate improvements following biochar application. Ca levels ranged between 840 and 1120 ppm, while Mg varied from 142 to 192 mg/kg. These changes are likely due to the alkaline nature of the biochar, which improved the availability of base cations through increased pH buffering and mineral dissolution. Sulfur (S) content did not exhibit a consistent trend, fluctuating within a narrow range (21.27–25.36 mg/kg). This result may reflect the limited interaction between biochar and sulfur, given sulfur's mobility in the soil and its dependency on microbial transformations.

Results from ANOVA revealed that with increase in biochar amount, a rise in soil nitrogen content was observed with BC-6% exhibiting highest value (Figure 4a). Although some non-significant comparisons were obtained ($p > 0.05$), others showed moderate to high significance ($p < 0.05$ to 0.0001). The increase in nitrogen level can be ascribed to enhanced nitrogen retention, reduced leaching, and enhanced microbial activity. Studies have shown that biochar reduce nitrogen losses by adsorption and by improving soil structure, thereby increasing nitrogen use efficiency [49]. A notable variation of treatments can be observed for the calcium content, where BC-4% showed the highest calcium level and BC-2% with reduced value

compared to control ($p < 0.0001$) (Figure 4b). However, for higher biochar concentrations, viz. 4% and 6%, non-significant ($p > 0.05$) results were obtained. The increased calcium concentration at moderate biochar levels can be attributed to the release of Ca^{2+} from biochar ash and improved cation retention capacity via increase in CEC [50]. The reduction in calcium content at lower BC dose (2%) may occur due to initial adsorption or immobilization processes. At lower biochar amendment (BC-2%), a decrease in soil phosphorus content was observed, followed by a gradual increase at higher doses (BC-4% and BC-6%). However, these values were much lower than that of control (Figure 4c) with highly significant differences ($p < 0.0001$). The initial reduction may be due to phosphorus immobilization or adsorption onto biochar surfaces, mainly via interactions with Ca, Fe, or Al. However, at higher biochar concentration, the rise in phosphorus level may result from enhanced mineralization and improved microbial activity [51]. The potassium content increased significantly with increase in biochar dosage, BC-6% showing the highest value ($p < 0.0001$) (Figure 4d). This may occur due to the high potassium content in biochar derived from plant biomass (here coconut shell), which facilitates the release of K^+ ions and contributes directly to soil fertility [52].

Moreover, improved cation exchange capacity enhances potassium retention and thus reduces leaching losses. A decrease in Mg content was observed at BC-2% and BC-4%. Although at BC-6%, a slight increase in Mg level was obtained, it was lower than that of the control with highly significant differences of $p < 0.0001$ (Figure 4e). The initial decrease may occur due to cation competition or adsorption onto the biochar surfaces, while rise in Mg content at higher biochar dose indicates the contribution of Mg from biochar ash [53]. Sulfur content showed moderate variation among treatments, where BC-2% exhibits slightly higher values compared to control, while that of BC-4% and BC-6% showed a declining trend (Figure 4f). From statistical analysis, significant differences ($p < 0.01$) and non-significant differences ($p > 0.05$) were obtained. The variation in sulfur content may be due to its transformation between organic and inorganic forms and its interaction with soil microorganisms. Biochar can also influence sulfur cycling by altering microbial activity and redox conditions [54].

3.3.2. Influence on Soil Micronutrient Dynamics

The impact of biochar on soil micronutrients was element specific. Notably, iron (Fe) levels increased with biochar application, reaching up to 14.63 mg/kg. Zinc (Zn) concentrations, however, decreased in some treatments, with values as low as 0.66 mg/kg. This decline may be explained by strong adsorption of Zn onto biochar surface, reducing its availability to plants.

389 This phenomenon is particularly relevant in high pH soils, where biochar may bind
 390 micronutrients more strongly. Copper (Cu) showed a steady increase (0.113-0.232 mg/kg),
 391 indicating improved availability likely due to chelation and complexation facilitated by organic
 392 functional groups present in biochar. Boron (B) content remained largely unchanged (0.48-0.53
 393 mg/kg), which is consistent with previous reports suggesting that B availability is weakly
 394 influenced by biochar amendments due to its high solubility and low sorptive affinity.

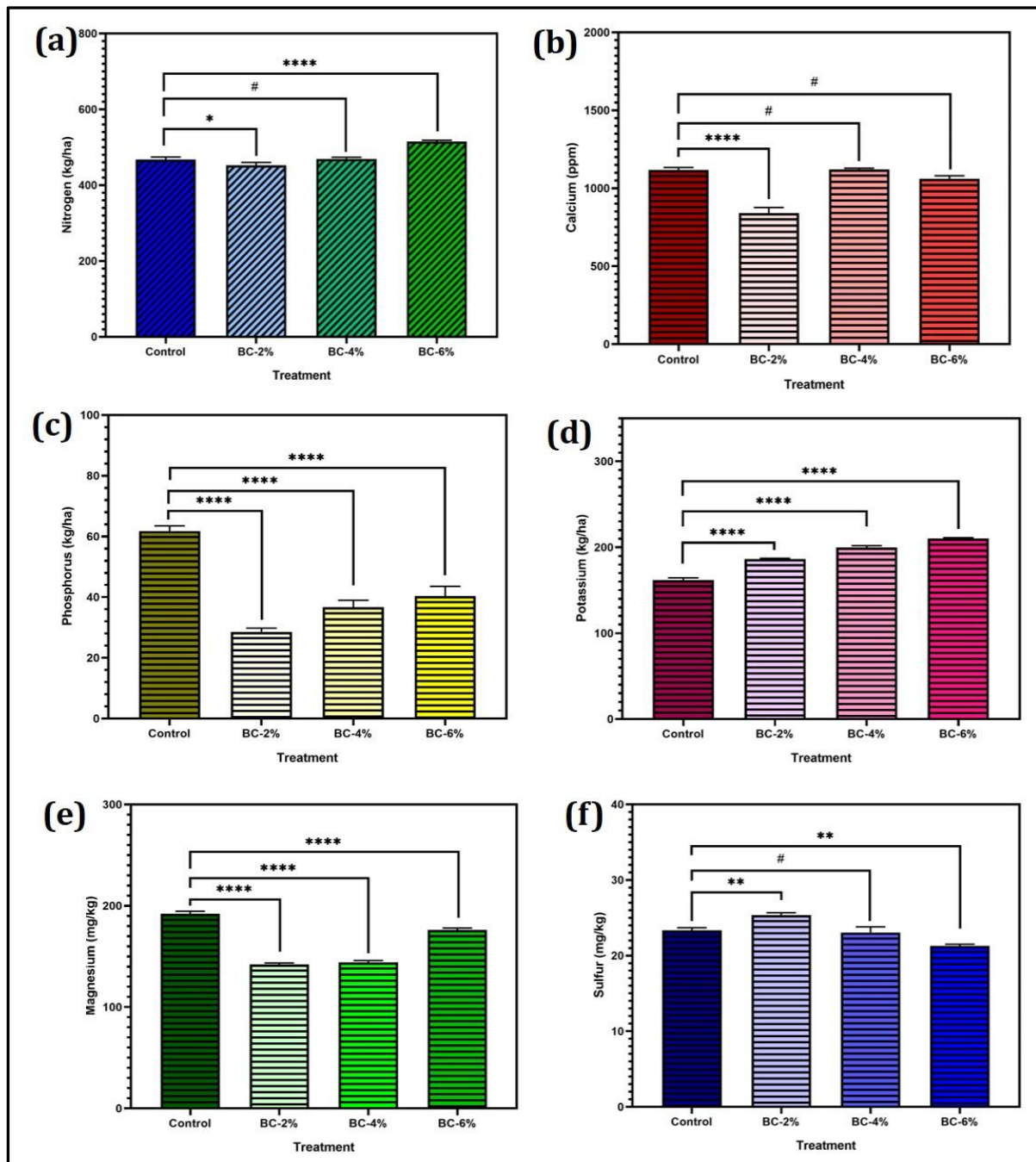


Fig. 4 Comparison of different soil nutrients after biochar treatment a) nitrogen, b) calcium, c) phosphorus, d) potassium, e) magnesium, f) sulfur. (Values represent mean $\pm$ standard deviation with # = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = $p < 0.0001$)

The ANOVA results indicated a non-linear response of soil zinc content to biochar amendment. BC-4% showed highest zinc level, while BC-2% and BC-6% showed reduced values compared to control with statistically significant differences ($p < 0.05$ to 0.01) (Figure 5a). The increased zinc content at moderate biochar levels may be due to improved micronutrient retention and enhanced microbial activity [55]. The decline in zinc concentration at higher biochar doses may occur due to zinc immobilization caused by rise in pH or adsorption onto biochar surfaces (Figure 5b). A gradual increase in Cu concentration was observed (Figure 5c) with increase in biochar dose from 2% to 6% exhibiting significant differences compared to control ($p < 0.0001$). This rise in Cu content can be ascribed to the inherent micronutrient content of biochar such as carboxyl and hydroxyl groups as well as its ability to enhance metal retention capacity through surface complexation and adsorption mechanisms [40]. Figure 5d shows the variation of boron content with application of different biochar concentration with statistically non-significant differences among treatments ($p > 0.05$). The marginal increase shown by BC-2% and BC-6% additions can be ascribed to the contribution of boron from biochar ash and improve retention owing to improvement in soil adsorption capacity. However, lack of statistical significance suggests that boron dynamics are less sensitive to biochar addition or may be governed by complex soil-solution mechanism [56].

The data clearly demonstrate that CSB has the potential to improve soil fertility by enhancing the availability of selected macronutrients (N, K, Mg) and micronutrients (Fe, Cu), while the availability of others (P, Zn) may be reduced due to surface interactions (Table 3). The variability in nutrient response further highlights the importance of tailoring biochar application strategies based on specific soil and crop requirements. A similar nutrient specific response was reported by Ninlaphong et al. reported a proportional increase in soil exchangeable K and Ca at 5% biochar, while P and Mg decreased across biochar treatments [57].

Table 3: Macro and Micro Nutrients content in biochar amended soil.

Macronutrients	Control (T1)	BC-2% (T2)	BC-4% (T3)	BC-6% (T4)
N (Kg/ha)	467.99	452.03	469.08	514.76
P (kg/ha)	61.81	28.5	53	40.33

K (kg/ha)	161.45	186.16	199.59	210.06
Ca (ppm)	1118	840	1120	1040
Mg (mg/kg)	192	142	144	176
S (mg/kg)	23.34	25.36	23.06	21.27
Micronutrients				
Fe(mg/kg)	10.42	13.18	13.66	14.63
Zn (mg/kg)	1.09	0.68	1.03	0.66
Cu (mg/kg)	0.113	0.179	0.229	0.232
B (mg/kg)	0.48	0.53	0.49	0.51

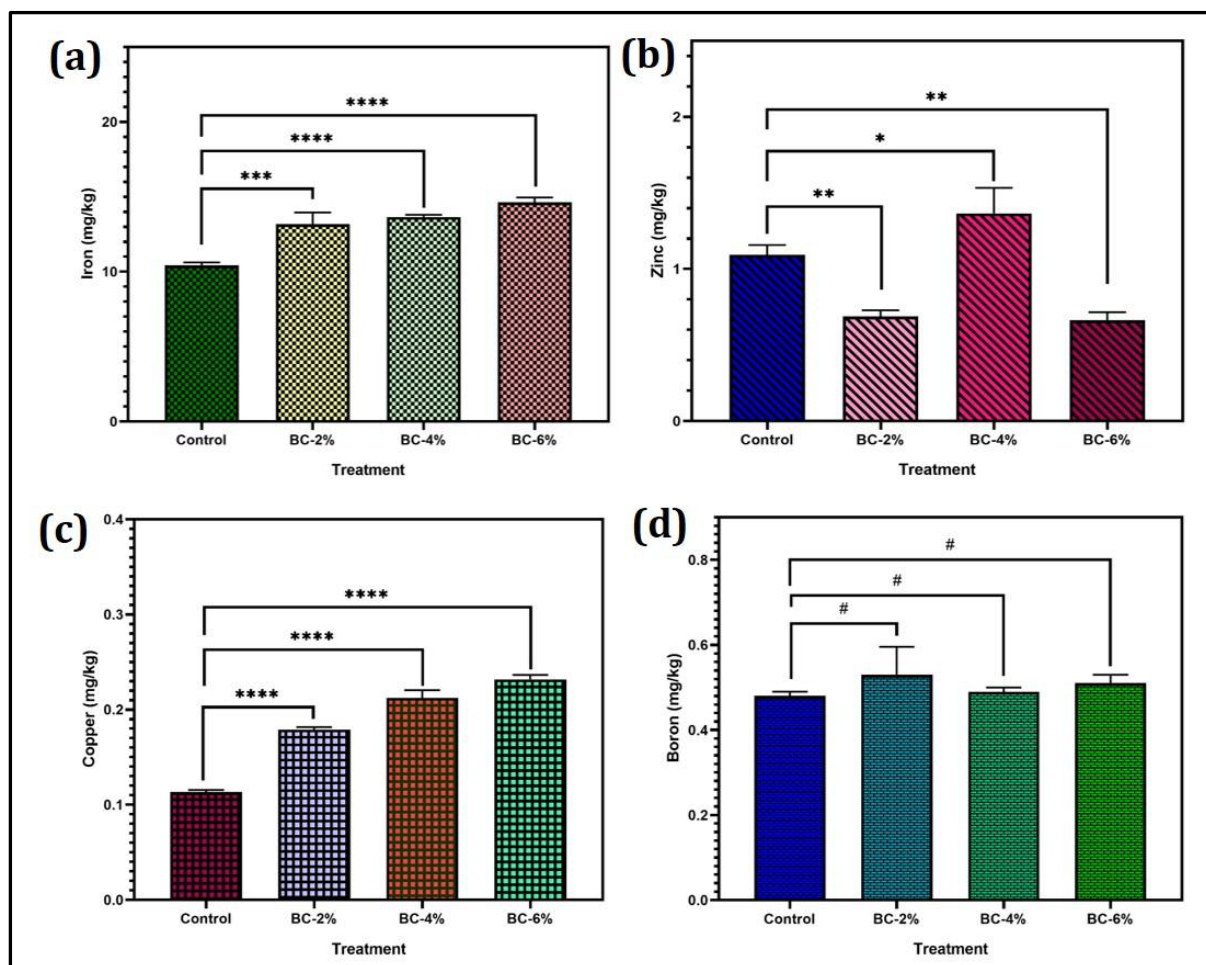


Fig. 5 Comparison of different soil nutrients after biochar treatment a) iron, b) zinc, c) copper, d) boron. (Values represent mean $\pm$ standard deviation with # = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = $p < 0.0001$)

3.4. Effect of coconut shell engineered biochar on plant growth and yield

From proximate and ultimate analysis, it was found that the maximum values for plant height (39 cm), number of leaves (70), number of branches (16) and total leaf chlorophyll content (0.280 mg) were observed in T3 (4% CSB w/w) followed by T4 (6% CSB w/w) as shown in

Table 4. The treatments T3 (4% CSB w/w) exhibited the maximum root length (21.5 cm), shoot length (30.5 cm), fresh shoot weight (34.52 g), fresh root weight (3.87 g), dry shoot and root weight (3.90 and 3.02 g respectively). Based on the results, the application of CSB had positive impact on all the yield parameters of tomatoes. Likewise, the highest values for total weight of fruit per plant (35.4 g) were noted in T4 for tomato, followed by T3.

Figure 7a-f and Table S2 depict the ANOVA study of the impact on growth and yield parameters of tomato plant with respect to the amount of biochar added to soil. The results obtained demonstrated a dose-dependent enhancement in most of the parameters; yet some characteristics exhibited non-linear responses. Increasing biochar concentration from 2% to 6% increases the chlorophyll content gradually with high differences of $p < 0.01$ to $p < 0.001$ (Figure 7a). This enhancement can be attributed to enhanced nutrient availability, mainly N and Mg essential for chlorophyll synthesis. Moreover, increase in soil moisture and CEC under biochar treatment facilitates better nutrient uptake. Obadi and coworkers also reported the enhancement of chlorophyll content and photosynthesis [58]. A variable trend was obtained for the plant height relative to biochar concentration. BC-4% exhibited slightly improved growth with respect to the control, while that of BC-2% and BC-6% showed reduced values (Figure 7b). Statistical analysis showed significant differences ($p < 0.01$ to 0.001), even though some comparisons were found to be non-significant with $p > 0.05$. A study carried out by Dad et al. reported similar results where plant growth, physiology as well as fruit quality were improved on application of biochar [59].

No significant variation among treatments ($p > 0.05$) was seen for the number of branches (Figure 7c). A slight increase in number of branches was observed at high biochar concentration, i.e., at BC-6%. However, the marginal improvement can be ascribed to better nutrient availability and root development [60]. On addition of biochar, a significant increase in the number of leaves was observed with $p < 0.001$ to 0.0001 (Figure 7d), among which BC-6% showed the highest leaf count value. This increase in number of leaves can occur due to improved vegetative growth and photosynthetic capacity, likely due to enhanced soil moisture, nutrient retention, and microbial activity [61]. A highly significant increase ($p < 0.0001$) in fruit yield can be observed with addition of biochar, where BC-6% showed highest increment followed by BC-4% and BC-2% (Figure 7e). This increase compared to the controlled experiment suggests that biochar improves soil fertility, water retention capacity as well as nutrient use efficiency. The enhanced yield can also be ascribed to the improvement in photosynthetic activity and better reproductive growth [62]. A slight variation ($p < 0.05$ - 0.01)

in internodal distance was observed with BC-4% showing the highest value (Figure 7f). The increase in internodal length suggests enhanced cell elongation and vegetative growth under optimal biochar conditions. However, excessive elongation is not always desirable, as it can have adverse effects on the plant architecture [63]. The results suggest that moderate biochar addition can improve plant growth dynamics without causing structural imbalance.

BC-4% showed highest root fresh weight value followed by BC-6% and BC-2% ($p < 0.0001$) as shown in Figure 7g. The increase in root biomass reveals improved root development owing to better soil aeration, porosity and nutrient availability [64]. Biochar-added soil also supports root penetration and expansion by reducing bulk density and hence improve the soil structure. For the shoot fresh weight, BC-4% recorded the highest value, while that of BC-6% exhibited a slight declination compared to control (Figure 7h). Statistical analysis revealed significant differences ($p < 0.01$ to 0.0001), even though some comparisons showed non-significant ($p > 0.05$) values. The increased shoot fresh weight at moderate BC concentration can be ascribed to enhanced nutrient uptake and water availability, whereas the slight reduction at higher dose (BC-6%) can occur due to increased salinity or nutrient imbalance. Such observations were also reported by Kawanna et al. [65]. A significant variation was exhibited by root dry weight where BC-4% showed improved results as compared to that of BC-2% and BC-6% ($p < 0.01$ to 0.0001) (Figure 7h). The control experiment showed relatively higher dry weight indicating that biochar influences water content and root composition. The increase in dry biomass content at optimal levels indicates improved carbon allocation and root structural development [66].

With BC-2% and BC-4% ($p < 0.0001$), a significant rise in shoot dry weight was obtained where BC-4% shows the highest value (Figure 7j), indicating enhanced biomass accumulation and photosynthetic efficiency. The increase in dry matter further indicates enhanced assimilation and translocation of photosynthates. Enhancement in above ground biomass compared with control was also reported by Nicolas et al. [67]. This is further supported by enhanced soil fertility and moisture availability in biochar amended soil [67]. Figure 7k shows increase in root length with increase of biochar application where BC-2% shows highest root length, followed by BC-4% and BC-6% exhibiting $p < 0.01$ to $p < 0.0001$. The enhanced root elongation at lower biochar concentration indicates that moderate biochar amendment improves soil structure and reduces mechanical resistance [68]. Yet, at higher BC concentrations, root elongation may be slightly inhibited owing to increased salt concentration or altered soil chemistry. Highest shoot length value was obtained for BC-4%, followed by control and BC-2%, while BC-6% showed a declination in shoot length with significant

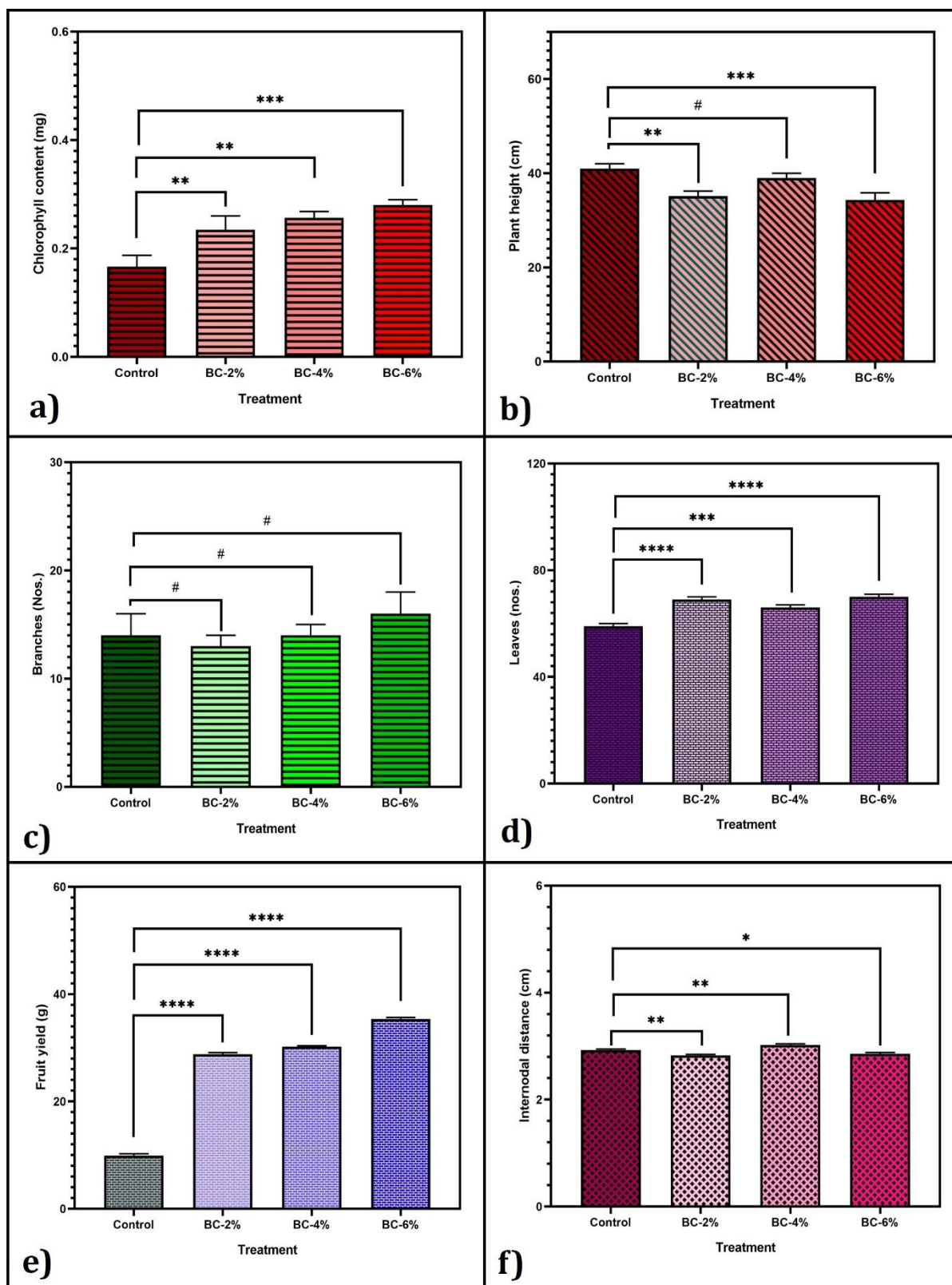
differences ($p < 0.001$) (Figure 7l). The results showed that moderate biochar addition enhances vegetative growth, whereas its excess amount can negatively affect elongation due to possible osmotic or nutrient imbalances [69]. The plant growth was monitored at different stages of experimental set up as shown in Figure 6.

Table 4: The effect of CBS biochar on growth parameters and yield of tomatoes.

Plant parameters	Control (T1)	BC-2% (T2)	BC-4% (T3)	BC-6% (T4)
Plant height (cm)	41	35.16	39	34.33
Number of branches	14	13	14	16
Number of leaves	59	69	66	70
Shoot length (cm)	32.5	29.5	30.5	23.5
Root length (cm)	16.16	25.9	21.5	19.23
Shoot fresh weight (g)	33.86	33.57	34.52	31.36
Root fresh weight (g)	2.14	3.05	3.87	3.39
Shoot dry weight (g)	3.13	3.61	3.90	3.35
Root dry weight (g)	0.66	0.42	0.58	0.53
Internodal distance (cm)	2.92	2.82	3.02	2.85
Total chlorophyll content (mg)	0.190	0.207	0.240	0.280
Fruit yield (g)	9.9	28.8	30.2	35.4



Fig. 6 Experimental setup and growth of tomato plants under different coconut-shell biochar application rates



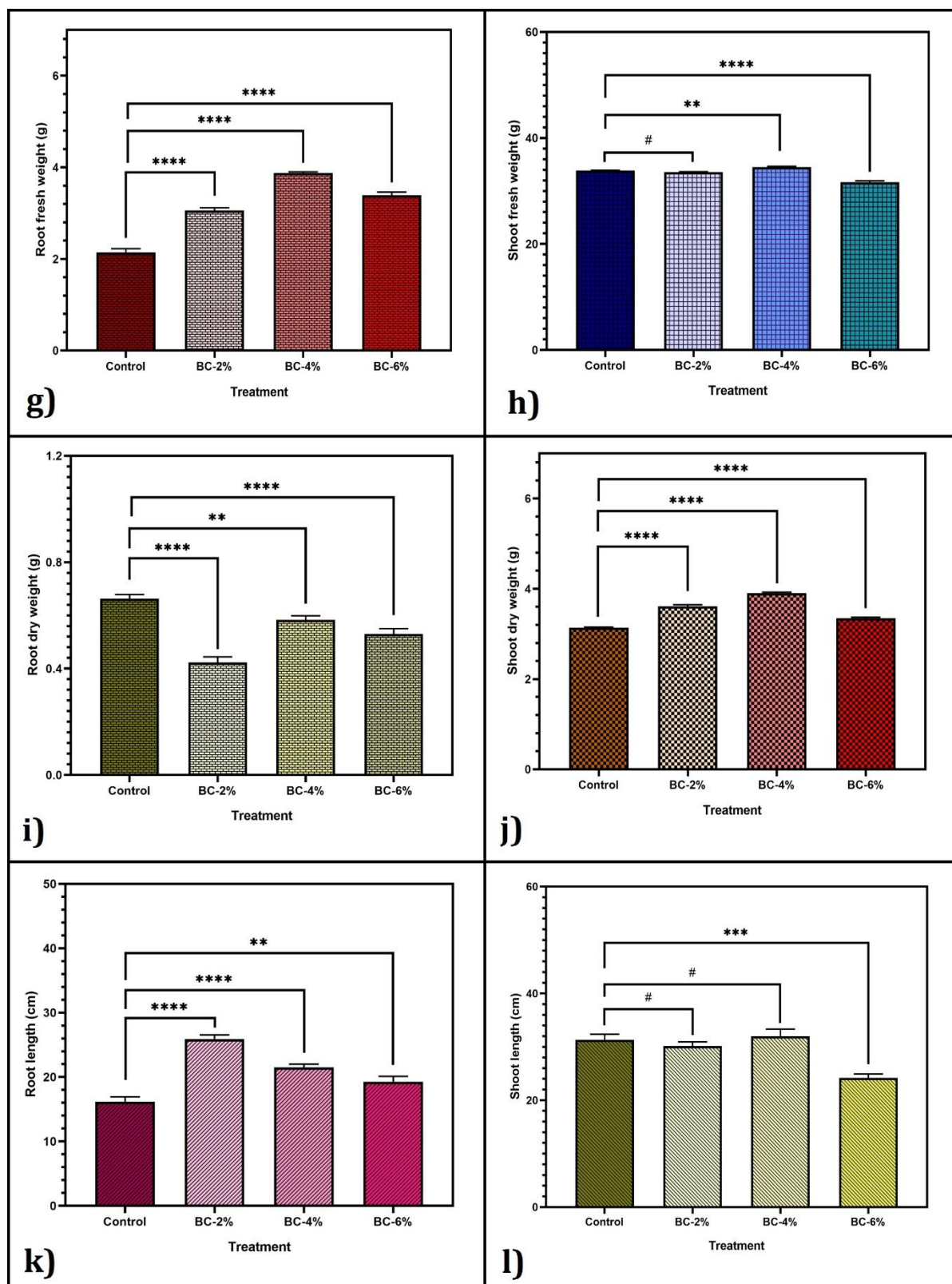


Fig. 7 Comparison of different plant characteristics after biochar treatment a) chlorophyll content, b) plant height, c) branches, d) leaves, e) fruit yield, f) internodal distance, g) root fresh weight, h) shoot fresh weight, i) root dry weight, j) shoot dry weight, k) root length, l) shoot

length. (Values represent mean $\pm$ standard deviation with # = $p > 0.05$, * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = $p < 0.0001$)

4. Conclusion

The current study demonstrates that CSB can modify soil physiochemical functioning and nutrient dynamics, and improving tomato growth and productivity. Biochar amendment increased soil organic carbon, organic matter, CEC, Water holding capacity while also modifying the availability of essential macro and micro nutrients. Nutrient response were element specific with increasing N, K, Fe and Cu, whereas P, Mg and Zn showed variable responses as per different biochar application rates in determining soil plant interactions. Improved soil conditions were reflected in increased plant growth, biomass accumulation, chlorophyll content and fruit production. The response varied with application rate, with 4% CSB showing better growth and biomass parameters, while 6% CSB resulted in highest fruit yield (35.4g plant⁻¹), indicating a dose-dependent but nonlinear response to biochar amendment. CSB represents an approach for converting agricultural waste, supporting improving soil-plant interactions and resource efficient tomato cultivation under tropical conditions. Studies across different agroecosystems are needed for broader environmental benefits of CSB application.

Author contributions:

MY contributed to the study design and concept. MY, AK and RM contributed to data processing and statistical analysis, writing, and formulating the manuscript draft. RB in critical revision of the manuscript. All authors contributed to the article and approved the submitted version.

Funding: This work was funded by UGC, New Delhi, India (UGC-Ref.No.-230510236690).

Data Availability Statement: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

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

Ethics, Consent to Participate, and Consent to Publish: Not applicable.

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