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Research article

Valorizing oil palm EFB as biochar for improved soil properties and early Maize growth

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Abstract: Oil palm empty fruit bunches (EFB) are abundant biomass residues that can be converted into biochar to simultaneously address agricultural waste management and soil fertility challenges. In this study, we investigated the effects of EFB biochar, alone and with organic fertilizer, on soil properties and maize growth in two soil types. The experiment comprised five treatments: control soil, biochar + soil (20:80, w/w), soil + organic fertilizer, biochar + soil + organic fertilizer (20:70:10, w/w), and biochar + soil + organic fertilizer (20:60:20, w/w), evaluated under two soil types, Reddish Brown Earths (RBE, S1) and Red-Yellow Podzolic Soils (RYP, S2). After 48 days, plant height, number of leaves, collar diameter, and root mass were measured. Results showed that biochar-based treatments significantly improved plant height, collar diameter, and root mass, with the biochar + soil + organic fertilizer (20:70:10, w/w) treatment producing the greatest improvements. Plant height increased up to 81.7% in S1 and 69.4% in S2, while collar diameter increased by up to 76.0% in S1 and 90.5% in S2. Root mass increased by 114.8% in S1 and 107.6% in S2 compared with the respective controls. In contrast, the number of leaves was not significantly affected by treatment ($p = 0.2993$), indicating that

the response to biochar amendment varied among growth parameters. These findings demonstrate the effectiveness of biochar derived from EFB as a sustainable soil amendment that enhances nutrient cycling, promotes soil structure, and supports plant growth, contributing to improved soil health and agricultural productivity.

Keywords: biochar; empty fruit bunch (EFB); soil amendment; maize growth; sustainable agriculture

Abbreviations

The following abbreviations are used in this manuscript:

BC	Biochar
EC	Electrical Conductivity
HU	Humidity
BD	Bulk Density
C	Carbon
$N\text{-}NO_3$	Nitrate Nitrogen
$N\text{-}NH_4$	Ammonium Nitrogen
P	Phosphorus
K	Potassium
P-AL	Available Phosphorus
K-AL	Available Potassium
Ca	Calcium
Mg	Magnesium
Na	Sodium
S1	Soil Type 1 (Reddish Brown Earths)
S2	Soil Type 2 (Red Yellow Podzolic Soils)
RBE	Reddish Brown Earths
RYP	Red, Yellow Podzolic Soils

1. Introduction

The oil palm tree (*Elaeis guineensis*) is one of the most important plantation crops cultivated in tropical regions such as Indonesia, Malaysia, and Sri Lanka [1,2]. Due to its high oil productivity, palm oil has become one of the major sources of vegetable oil used in both food and non-food industries worldwide [3,4]. However, the processing of fresh fruit bunches (FFB) for crude palm oil (CPO) production generates considerable quantities of biomass residues including empty fruit bunches (EFB), fibers and shells [5,6]. It has been reported that approximately 2.3 tons of palm biomass residues are generated per ton of palm oil produced. This estimate comprises approximately 1.0 ton of EFB, 0.7 tons

of palm fiber, 0.3 tons of palm kernels, and 0.3 tons of palm shells per ton of palm oil produced [7]. Traditionally, EFB has been utilized as a mulching material in plantations. However, the slow decomposition rate and the associated methane emissions during degradation have increased the interest in developing sustainable utilization pathways for EFB [8].

Among the available biomass conversion technologies, pyrolysis has received considerable attention as an effective method for energy and resource recovery from lignocellulosic biomass. Pyrolysis is a thermochemical conversion process carried out under oxygen-limited or oxygen-free conditions, producing biochar, bio-oil, and syngas as the major products [9,10]. Biochar (BC), particularly produced through slow pyrolysis, has gained attention due to its potential applications in agriculture and environmental management [11–13]. Application of biochar to agricultural soils has been widely reported to modify soil physicochemical properties and, under suitable soil and management conditions, improve crop growth and productivity [14–18]. However, the magnitude and direction of these effects depend on biochar properties, application rate, soil characteristics, and crop type. Biochar can also influence soil biological processes by modifying the soil environment and providing surfaces that support microbial interactions, although these effects depend on biochar characteristics and soil conditions [19–21].

The porous structure and surface characteristics of biochar contribute to improvements in soil structure, water dynamics, nutrient retention, and soil pH, while potentially reducing bulk density and nutrient losses from the soil system [22–24]. Studies further demonstrate that the effects of biochar on soil properties and plant responses can vary substantially with soil type, biochar characteristics, and application rate [25,26]. Therefore, the utilization of EFB-derived biochar presents a dual benefit by addressing biomass waste management issues while simultaneously improving soil productivity and sustainability in agricultural systems [27–29].

Maize (*Zea mays* L.) is an important cereal crop in Sri Lanka and is cultivated mainly during the Maha and Yala seasons. National statistics indicate substantial annual maize production, with approximately 196,871 t produced during the 2024 Maha season from 65,300 ha and a further 26,626 t during the 2024 Yala season from 7,401 ha [30]. At the global scale, maize is one of the major cereal crops in terms of cultivated area and production [31]. Maintaining soil fertility and improving nutrient-use efficiency are therefore important for sustaining maize productivity, particularly in soils affected by low fertility and other physicochemical constraints.

Although studies have demonstrated that biochar can improve soil physicochemical properties and crop performance, responses vary with feedstock, pyrolysis conditions, application rate, and soil characteristics [2,32,33]. In particular, limited information is available on the performance of EFB-derived biochar in contrasting Sri Lankan agricultural soils and its interaction with organic fertilizer for early maize growth.

Accordingly, in this study, we evaluate EFB-derived biochar under two contrasting Sri Lankan soil types and compare biochar alone with combined biochar–organic fertilizer amendments to identify soil- and treatment-specific responses in early maize growth.

2. Materials and methods

Figure 1 summarizes the overall methodology of the study.

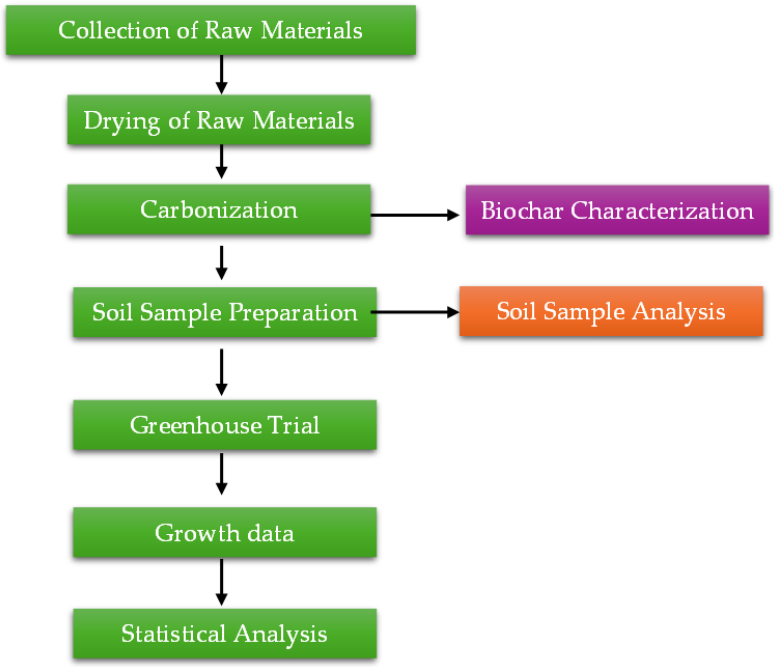


Figure 1. Summary flowchart of the methodology.

2.1. Feedstock collection and pretreatment

EFB fiber was collected from the processing mill as part of the standard production process. The process began with the sterilization of fresh FFB using steam to loosen the fruit and prevent enzymatic degradation. After sterilization, the bunches were transferred to the stripping section, where a threshing drum separated the fruits from the bunches. The residual empty bunches were shredded, and the resulting fiber was pressed to extract EFB fiber, which was then stored in a designated fiber storage area (Figure 2).

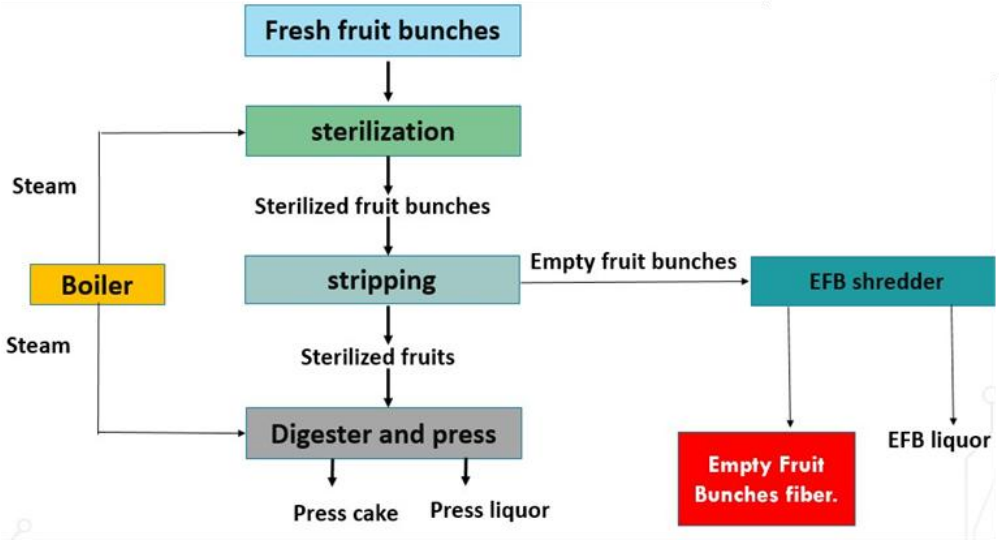


Figure 2. EFB fiber collection from a processing mill and the standard production process.

To prepare the EFB fiber for pyrolysis, the raw fiber was dried using the oven-dry method to reduce moisture content. This drying step is critical, as high moisture levels can promote fungal growth (e.g., orange fungi) and adversely affect the pyrolysis process, impacting the calorific value and flash point of the resulting bio-oil. The dried fiber was then cut into small pieces to ensure uniform particle size, facilitating efficient thermal decomposition during pyrolysis. Proximate and elemental analysis of EFB waste compared to common biomass feedstocks are available in Table 1.

Table 1. Proximate and elemental analysis of EFB waste.

	Proximate Analysis (wt.%)				Ultimate Analysis (wt.%)				
Sample	Moisture	Fixed Carbon	Ash	Volatile	C	H	N	S	O
Oil palm EFB	13.84	18.86	9.32	57.98	40.05	5.64	1.67	0.21	43.11

2.2. Pyrolysis experiment

The pyrolysis experiments were conducted using a laboratory-scale Updraft Double Chamber (UDDC) batch-type pyrolysis reactor, as illustrated in Figure 3. The reactor consisted of a cylindrical stainless-steel chamber measuring approximately 1.0 m in length and 0.30 m in diameter. Approximately 130 g of oven-dried EFB fiber was loaded into the reactor for each experimental run. Prior to heating, the reactor was tightly sealed to establish an oxygen-limited environment, and no external inert carrier gas or catalyst was employed throughout the pyrolysis process.

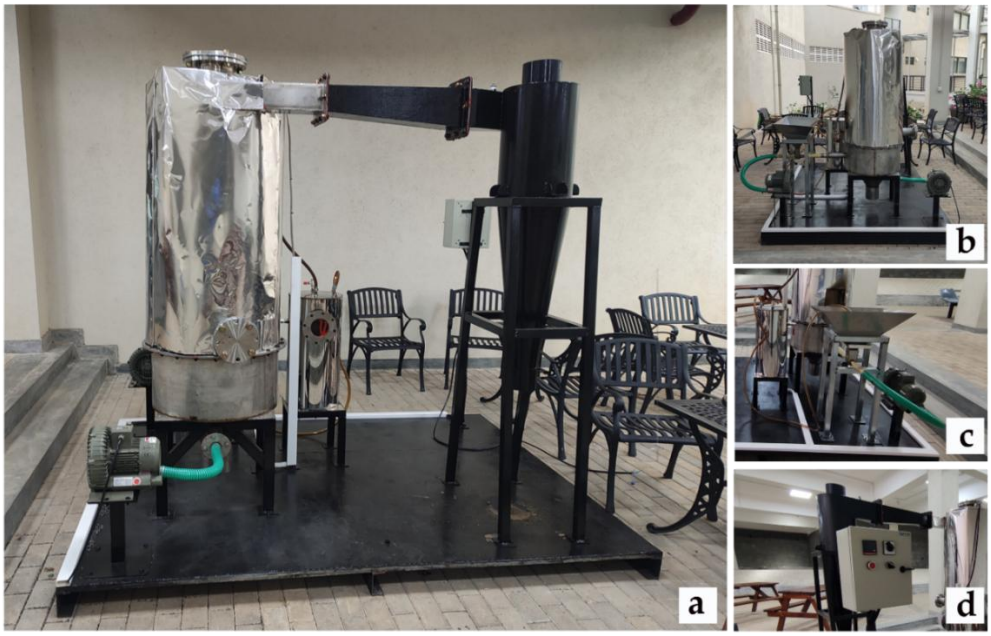


Figure 3. Updraft Double Chamber (UDDC) pyrolysis reactor setup; (a,b) Reactor, (c) Feed hopper, and (d) Control panel.

The reactor was heated from an initial temperature of 26 °C to 450 °C over approximately 60 min, corresponding to an average heating rate of approximately 7.1 °C min^{-1}. After reaching the target

temperature, the biomass was maintained at 450 °C for 30 min to ensure complete thermal decomposition and carbonization of the feedstock. Following the reaction period, the reactor was allowed to cool naturally while remaining sealed to minimize oxidation of the produced biochar.

Upon completion of the pyrolysis process, the solid biochar and condensed bio-oil fractions were collected separately and weighed. The gaseous product yield was determined by difference based on the mass balance of the pyrolysis products. On a dry biomass basis, the pyrolysis process produced 31.75 wt.% biochar, 38.12 wt.% bio-oil, and 30.13 wt.% permanent gases. These product distributions were consistent with the expected product yields obtained from slow pyrolysis of lignocellulosic biomass at approximately 450 °C.

To ensure reproducibility, 18 independent pyrolysis experiments were conducted under identical operating conditions. The biochar produced from these experiments was homogenized and subsequently used for physicochemical characterization and greenhouse evaluation.

2.3. Soil, biochar amendment, and biochar-amended soil analysis

Two soil types commonly used for maize cultivation in Sri Lanka were selected for this study. Soil type 1 represented the Reddish-Brown Earth (RBE, S1) soil group, while soil type 2 represented the Red Yellow Podzolic (RYP, S2) soil group. Physicochemical characterization of the soils, biochar and biochar-amended soils were carried out using standard analytical procedures. Moisture content (HU) was determined by the gravimetric method through oven drying of samples at 105 °C until a constant weight was obtained. Soil pH was measured using the potentiometric method with a solid-to-liquid ratio of 1/2.5 (w/v) for non-amended and biochar-amended soils, whereas a ratio of 1/10 (w/v) was used for biochar. Electrical conductivity (EC) was determined by the conductometric method using a solid-to-liquid ratio of 1/5 (w/v) for soils and biochar-amended soils, while a ratio of 1/10 (w/v) was applied for biochar samples. Bulk density (BD) was calculated as the ratio between the dry mass and the measured volume of the sample, including non-amended soils, biochar and biochar-amended soils. Soluble nitrate nitrogen ($N\text{-}NO_3$) and ammonium nitrogen ($N\text{-}NH_4$) contents were determined spectrophotometrically at a wavelength of 420 nm using a CECIL 2041 Spectrophotometer (Buck Scientific, Norwalk, CT, USA), following extraction at a solid-to-liquid ratio of 1/5 (w/v). Phosphorus (P) concentration was measured using the same spectrophotometer at 720 nm, whereas potassium (K) concentration was analyzed using a Sherwood 410 Flame Photometer (Sherwood Scientific, Cambridge, UK) with a solid-to-liquid ratio of 1/5 (w/v). Available phosphorus (P-AL) and potassium (K-AL) were determined using the Egner–Riehm–Domingo extraction method at a solid-to-liquid ratio of 1/20 (w/v). Ammonium acetate-lactate solution was used as the extracting medium and the extracted phosphorus and potassium were quantified using spectrophotometric and flame photometric techniques, respectively. Available calcium, magnesium, and sodium (Ca, Mg, and Na) were extracted using ammonium acetate solution at a solid-to-liquid ratio of 1/50 (w/v) and subsequently analyzed using an Optima 8300 ICP-OES system (PerkinElmer, Waltham, MA, USA). Total carbon (C) content of the samples was determined using an EA3100 Elemental Analyzer (Eurovector, Pavia, Italy). The physicochemical properties obtained were used to evaluate the effects of biochar incorporation on the selected soil types and their suitability for maize cultivation.

2.4. Impact of biochar amendment on Maize growth

A greenhouse experiment was conducted for a period of 48 days (Figure 4) to evaluate the effects of biochar (BC) application on the growth and development of maize plants. The experiment was carried out under controlled conditions at the greenhouse facility of the Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya, Sri Lanka. All experimental activities, including the collection and use of plant materials, were performed in accordance with the relevant institutional, national, and international guidelines and regulations. Maize seeds used for the experiment were obtained from a local supplier.

A factorial greenhouse experiment was conducted using two soil types (Reddish Brown Earth, S1, and Red Yellow Podzolic soil, S2) and five treatment combinations (Table 2). Each treatment was replicated three times, with one maize plant grown per pot. Individual pots were considered independent biological replicates, resulting in 15 experimental units for each soil type and a total of 30 experimental units across the study. The pots were randomly arranged within the greenhouse to minimize positional effects and environmental variation. Three independent pots were used for each treatment, with one maize plant maintained per pot, resulting in three biological replicates per treatment.

Table 2. Experimental scheme for the greenhouse experiment.

Code	Treatment	Soil Types	Biological Replicates
S	Soil (Control)	S1, S2	3
SBC	Biochar + Soil (20:80, w/w)	S1, S2	3
SOF	Soil + Organic Fertilizer	S1, S2	3
BCSOF1	Biochar + Soil + Organic Fertilizer (20:70:10, w/w)	S1, S2	3
BCSOF2	Biochar + Soil + Organic Fertilizer (20:60:20, w/w)	S1, S2	3

The experimental treatments were designed to distinguish the individual and combined effects of biochar and organic fertilizer on maize growth. A biochar incorporation rate of 20% (w/w) was selected because similar amendment rates have been widely used in controlled pot experiments and are sufficiently high to induce measurable improvements in soil physicochemical properties while maintaining suitable growing conditions [34,35]. The soil-only and fertilizer-only treatments served as controls for evaluating the independent contributions of biochar and nutrient supplementation, respectively. Two organic fertilizer application rates (10% and 20% of the amendment mixture) were included to investigate whether increasing nutrient availability influences the agronomic response when combined with biochar. This treatment structure enabled assessment of potential synergistic interactions between biochar and organic fertilizer under two contrasting soil types. No liquid organic fertilizer was applied through irrigation water during the experiment.



Figure 4. Greenhouse experiment on maize plants.

The total nutrient load per plant provided by the four organic fertilizer applications included 160 mg of phosphorus (P), 80 mg of nitrogen (N), 22 mg of magnesium (Mg), 8 mg of potassium (K), 8 mg of iron (Fe), 2.4 mg of boron (B), 2.2 mg of manganese (Mn), 2 mg of zinc (Zn), and 1.2 mg of copper (Cu). The organic fertilizer mixture also included amino acids, multivitamins, enzymes, growth regulators (such as auxin, cytokinin, and gibberellin), and other essential micronutrients.

2.5. Statistical analysis

Statistical analysis was performed using two-way analysis of variance (ANOVA) to evaluate the effects of soil type, treatment, and their interaction on the measured soil physicochemical and plant-growth parameters. Pearson correlation analysis was conducted to examine linear relationships among the measured soil physicochemical properties. Statistical significance was evaluated at $p < 0.05$.

Statistical analyses were conducted using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). The statistical outputs were subsequently used to interpret the effects of BC amendment on soil quality parameters and their possible influence on plant growth performance.

3. Results and discussion

3.1. Biochar properties

Raw EFB and product biochar are shown in Figure 5. The proximate and ultimate analysis of the oil palm EFB biochar revealed valuable insights into its chemical composition and potential applications as shown in Table 3. The SEM images in Figure 6 reveal a heterogeneous and porous surface structure in the EFB-derived biochar. The presence of visible pores is particularly relevant to its potential use as a soil amendment because the pore network can provide sites for the retention of water, nutrients, and dissolved compounds. Pyrolysis-induced development of porous structures has also been reported for other biomass-derived chars, with pyrolysis temperature influencing pore development and the physicochemical properties of the resulting material [36].

Table 3. Proximate and elemental analysis of biochar.

	Proximate Analysis (wt.%)				Ultimate Analysis (wt.%)				
Sample	Moisture	Fixed Carbon	Ash	Volatile	C	H	N	S	O
EFB Biochar	6.24	53.32	26.3	14.14	55.76	2.92	2.18	0.34	12.50



Figure 5. Raw EFB and biochar from pyrolyzed EFB.

The oil palm EFB biochar demonstrates a promising chemical composition with high fixed carbon and moderate levels of volatile matter, making it suitable for soil amendment and bioenergy applications. The relatively high ash content suggests the presence of valuable minerals, while the low nitrogen and sulfur contents imply that the biochar may be more beneficial for improving soil structure and promoting carbon sequestration than for providing significant nutritional value to plants [37].

Although we focused on evaluating the agronomic performance of EFB-derived biochar, future investigations should incorporate a comprehensive mass and energy balance of the pyrolysis process to assess the overall process efficiency and support scale-up and techno-economic evaluations.

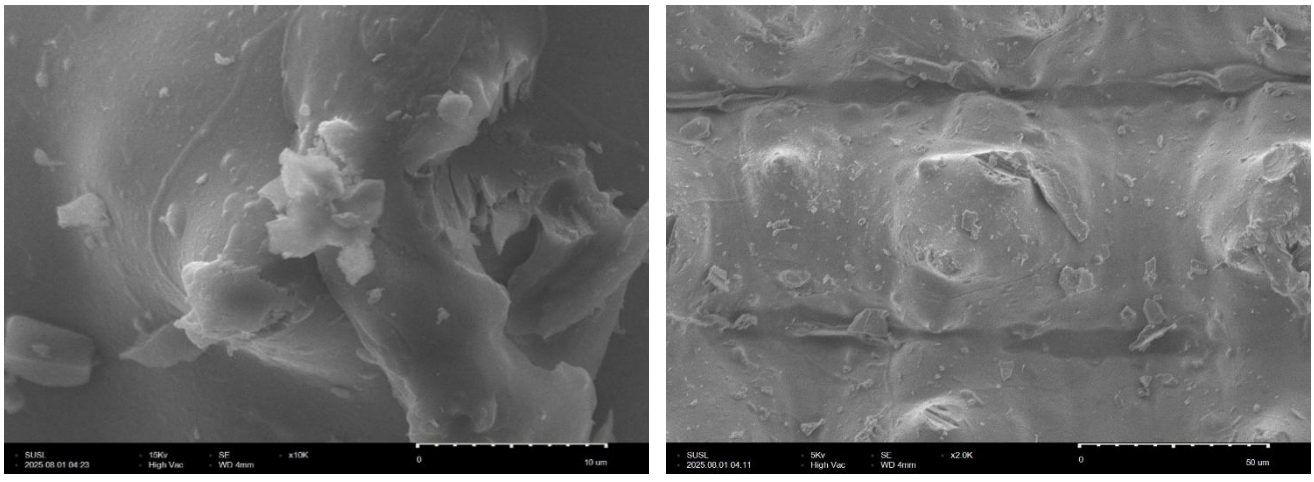


Figure 6. Scanning Electron Microscopy (SEM) images of the EFB biochar.

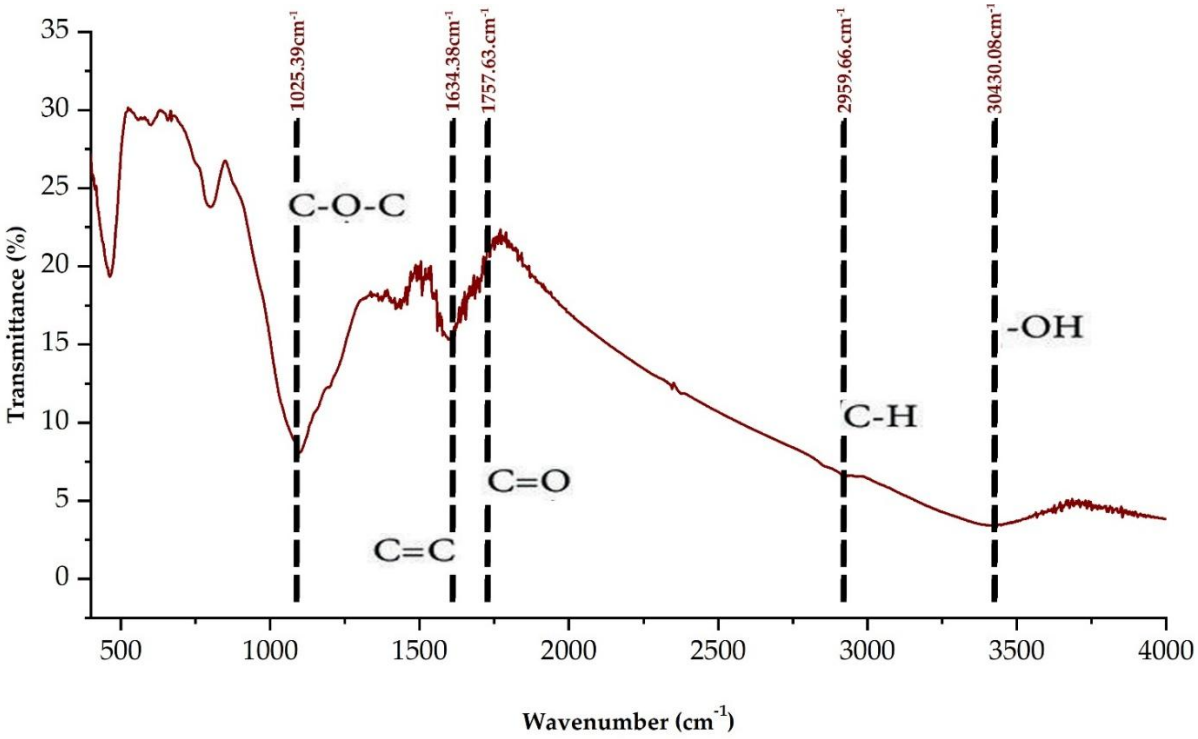


Figure 7. FTIR spectrum of EFB-derived biochar.

The FTIR spectrum in Figure 7 further confirms the presence of several oxygen-containing and carbon-based functional groups. The broad absorption around 3430 cm^{-1} can be associated with O–H stretching, while the band observed around 2959.66 cm^{-1} indicates aliphatic C–H stretching. The band at approximately 1757.63 cm^{-1} can be associated with carbonyl (C = O) stretching, while the band around 1634.38 cm^{-1} may be attributed to aromatic C = C and/or carbonyl-associated vibrations. The bands in the lower wavenumber region are associated with C–O and other oxygen-containing structures. These functional groups indicate that, despite the thermal transformation of EFB, chemically active surface functionalities remained in the resulting biochar. Such surface functionalities are important because they contribute to interactions between biochar and surrounding soil constituents. Reviews have highlighted the role of biochar surface functionalities and physicochemical characteristics in determining its interaction with contaminants and other environmental components [38].

3.2. Characterization of soils following biochar amendment

The mean physicochemical properties of the non-amended soils (S1 and S2), EFB-derived biochar (BC), and biochar-amended soils (S1BC and S2BC) are presented in Table 4. Here, S1BC represents the SBC treatment containing 20% biochar and 80% Reddish Brown Earth (S1) soil, while S2BC represents the corresponding 20% biochar and 80% Red Yellow Podzolic (S2) soil treatment. Biochar incorporation altered several physical and chemical properties of both soils, particularly bulk density, pH, electrical conductivity, carbon, and nutrient concentrations.

Table 4. Mean values of physicochemical properties of soils (S), BC, and BC-enriched soils (S + BC).

No.	Property	S1	S2	BC	S1BC	S2BC
1	Humidity (%)	14.75	10.51	3.47	12.22	9.54
2	Bulk Density (g/cm³)	1.061	0.978	0.324	0.791	0.843
3	pH	7.94	6.28	9.85	8.28	7.14
4	EC (dS/m)	0.23	0.11	2.02	0.34	0.22
5	C (%)	2.91	2.03	75.98	11.03	10.34
6	N-NO_3 (mg/kg)	30.9	14.7	5.5	25.8	11.5
7	N-NH_4 (mg/kg)	12.1	11.5	15.4	14.1	12.2
8	P (mg/kg)	6.4	2.2	15.8	13.5	14.6
9	K (mg/kg)	24.1	5.6	3133	131.2	130.5
10	P-AL (mg/kg)	103.2	16.7	1614	226.2	168.2
11	K-AL (mg/kg)	359	199	8195	1041	859
12	Ca (mg/kg)	2988	2942	2040	2761	2441
13	Mg (mg/kg)	372.1	308.1	471.8	386.3	334.1
14	Na (mg/kg)	31.3	31.1	88.1	35.5	34.8

Note: S1-SBC represents the SBC treatment (20% biochar + 80% RBE soil, w/w), while S2-SBC represents the SBC treatment (20% biochar + 80% RYP soil, w/w).

Among the measured physical properties, bulk density decreased following biochar incorporation. Bulk density declined from 1.061 to 0.791 g cm^{-3} in S1 and from 0.978 to 0.843 g cm^{-3} in S2, corresponding to reductions of approximately 25.4% and 13.8%, respectively (Table 4). This reduction can be attributed to the inherently low density and porous structure of the EFB-derived biochar, as observed in the SEM images (Figure 6). Incorporation of low-density biochar can increase pore space and reduce soil compaction, thereby modifying the physical structure of the amended soil [28].

Gravimetric moisture content was also lower in the amended soils at the time of sampling, decreasing from 14.75% to 12.22% in S1 and from 10.51% to 9.54% in S2. However, water-holding capacity and field capacity were not directly measured in this study. Therefore, these differences should be interpreted only as differences in moisture content at the time of sampling and should not be taken as evidence of changes in the soil's water-holding capacity. The observed moisture differences may be associated with changes in soil pore structure and water distribution following biochar incorporation.

Soil pH increased following biochar application, from 7.94 to 8.28 in S1 and from 6.28 to 7.14 in S2, corresponding to increases of approximately 4.3% and 13.7%, respectively (Table 4). This increase is consistent with the liming effect commonly associated with biochar and can be attributed to alkaline mineral constituents and exchangeable base cations present in the biochar [31]. The FTIR spectrum (Figure 7) also showed oxygen-containing functional groups, including hydroxyl-, carbonyl-, and carboxyl-related groups, which contribute to the surface reactivity of biochar and its interactions with soil constituents. The increase in pH can influence nutrient availability and other chemical processes in the soil.

EC increased from 0.23 to 0.34 dS m^{-1} in S1 and from 0.11 to 0.22 dS m^{-1} in S2 following biochar incorporation (Table 4). The increase may reflect the release of soluble mineral constituents from the EFB-derived biochar and changes in the retention of dissolved ions within the amended soil matrix. Despite these increases, the measured EC values remained relatively low, indicating that the amendment did not result in excessive salt accumulation under the conditions of the experiment. Similar increases in EC following biochar incorporation have been associated with the release of soluble minerals and changes in soil ion dynamics [39,40].

A pronounced increase in soil carbon content was observed after biochar incorporation. Carbon increased from 2.91% to 11.03% in S1 and from 2.03% to 10.34% in S2, corresponding to approximately 3.8-fold and 5.1-fold increases, respectively (Table 4). The EFB-derived biochar contained 75.98% carbon. Therefore, the increase in soil carbon can largely be attributed to the direct incorporation of the carbon-rich biochar into the soil. The FTIR spectrum (Figure 7) further indicated the presence of aromatic carbon structures and oxygen-containing functional groups, suggesting the coexistence of relatively stable carbon structures and reactive surface sites. The substantial increase in soil carbon demonstrates the potential of EFB biochar to increase soil carbon stocks following amendment [31].

Biochar incorporation also modified the concentrations of inorganic nitrogen. Nitrate nitrogen decreased from 30.9 to 25.8 mg kg^{-1} in S1 and from 14.7 to 11.5 mg kg^{-1} in S2, whereas ammonium nitrogen increased from 12.1 to 14.1 mg kg^{-1} in S1 and from 11.5 to 12.2 mg kg^{-1} in S2 (Table 4). The decrease in extractable nitrate should not be attributed solely to direct adsorption of NO_3^- by negatively charged biochar surfaces. Instead, changes in nitrogen cycling, microbial immobilization, and nitrification may contribute to the observed reduction in extractable nitrate. In contrast, oxygen-containing functional groups and negatively charged sites on biochar surfaces can contribute to the retention of positively charged NH_4^+ through electrostatic interactions and cation-exchange processes [33].

The concentrations of phosphorus and potassium increased substantially following biochar incorporation (Table 4). Phosphorus increased from 6.4 to 13.5 mg kg^{-1} in S1 and from 2.2 to 14.6 mg kg^{-1} in S2. Potassium showed an even larger increase, from 24.1 to 131.2 mg kg^{-1} in S1 and from 5.6 to 130.5 mg kg^{-1} in S2. The high potassium concentration measured in the EFB-derived biochar (3133 mg kg^{-1}) indicates that the biochar was an important source of potassium. The increase in phosphorus may similarly reflect the contribution of mineral constituents in the biochar together with changes in soil chemical conditions. The porous structure observed by SEM (Figure 6) and the surface functional groups identified by FTIR (Figure 7) may also contribute to nutrient retention within the amended soil matrix.

Available phosphorus (P-AL) and potassium (K-AL) also increased markedly after biochar incorporation. P-AL increased from 103.2 to 226.2 mg kg^{-1} in S1 and from 16.7 to 168.2 mg kg^{-1} in S2, while K-AL increased from 359 to 1041 mg kg^{-1} in S1 and from 199 to 859 mg kg^{-1} in S2 (Table 4). These changes indicate that EFB-derived biochar influenced the availability of major nutrients in both soil types. The magnitude of the response differed between S1 and S2, suggesting that the initial physicochemical characteristics of the soil influenced the response to biochar amendment.

The concentrations of calcium and magnesium showed comparatively smaller changes. Calcium decreased from 2988 to 2761 mg kg^{-1} in S1 and from 2942 to 2441 mg kg^{-1} in S2, whereas magnesium increased slightly from 372.1 to 386.3 mg kg^{-1} in S1 and from 308.1 to 334.1 mg kg^{-1} in S2 (Table 4). The relatively modest changes in magnesium indicate that biochar incorporation had a smaller effect

on this element than on phosphorus and potassium. Magnesium is an important soil nutrient, and its maintenance following biochar incorporation may contribute to overall nutrient availability [26].

Sodium concentrations increased slightly following biochar application, from 31.3 to 35.5 mg kg^{-1} in S1 and from 31.1 to 34.8 mg kg^{-1} in S2 (Table 4). Although the increase was relatively small, it may reflect the mineral contribution of the biochar and changes in the ionic composition of the amended soils. The measured sodium concentrations remained relatively low, suggesting that the amendment did not result in substantial sodium accumulation under the conditions investigated [41,42].

To further examine the relationships among the measured soil properties, Pearson correlation analysis was performed, and the resulting correlation matrix is presented as a heatmap in Figure 8. HU exhibited a positive correlation with bulk density (BD) (r = 0.69) and negative correlations with carbon (r = −0.73), pH (r = −0.49), and EC (r = −0.68). Bulk density showed strong negative correlations with pH (r = −0.85), EC (r = −0.86), and carbon (r = −0.89), indicating an inverse relationship between soil density and several chemical properties.

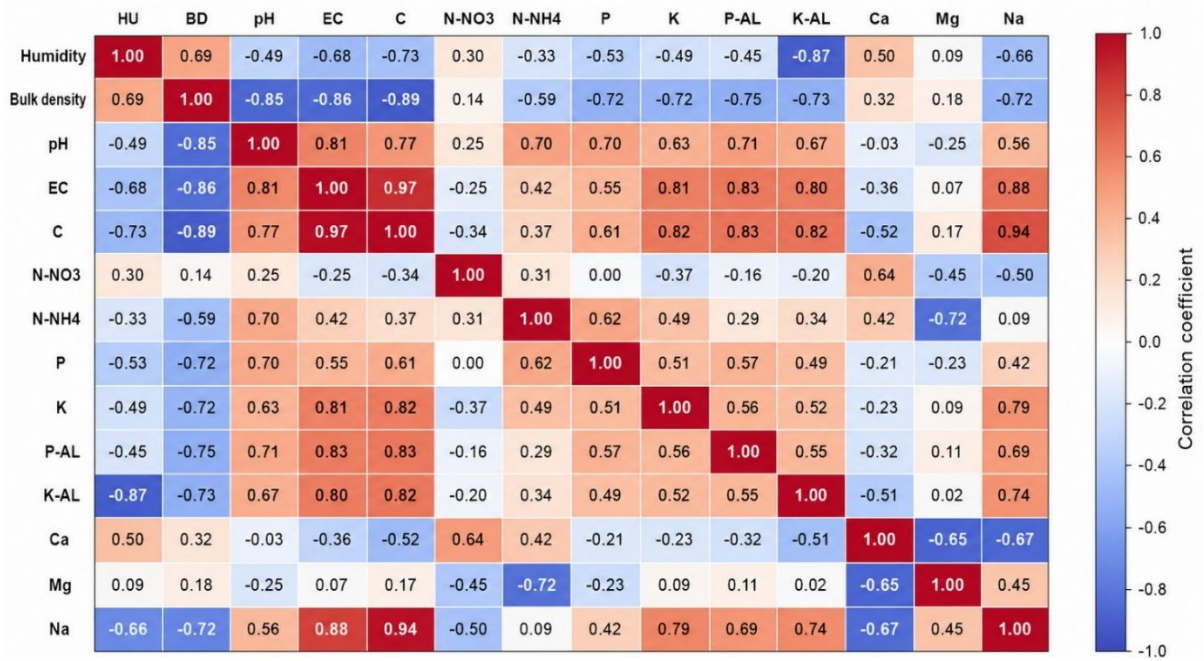


Figure 8. Heatmap for correlations.

Positive correlations were also observed among pH, EC, and carbon. Soil pH was positively correlated with EC (r = 0.81), carbon (r = 0.77), and ammonium nitrogen (r = 0.70), while EC showed a strong positive correlation with carbon (r = 0.97). Nitrate nitrogen showed a weak positive correlation with humidity (r = 0.30) and calcium (r = 0.64), but a negative correlation with carbon (r = −0.34). Ammonium nitrogen was positively correlated with phosphorus (r = 0.62) and pH (r = 0.70).

Phosphorus showed positive correlations with carbon (r = 0.61), P-AL (r = 0.57), and potassium (r = 0.51). Potassium was positively correlated with EC (r = 0.81), carbon (r = 0.82), and P-AL (r = 0.56). Calcium showed a positive correlation with nitrate nitrogen (r = 0.64) and negative correlations with sodium (r = −0.67), carbon (r = −0.52), and magnesium (r = −0.65). Sodium exhibited strong positive correlations with EC (r = 0.88) and carbon (r = 0.94). These relationships indicate that the changes in soil properties following biochar incorporation were interconnected rather than isolated responses.

Overall, EFB-derived biochar substantially modified the measured physicochemical properties of both soils, particularly bulk density, pH, EC, carbon, phosphorus, potassium, and available nutrient fractions. The direction and magnitude of these changes varied between S1 and S2, demonstrating that the response to biochar amendment depends partly on the initial characteristics of the soil. The high carbon content and porous structure of the EFB-derived biochar, together with its mineral composition and surface functional groups, provide plausible explanations for the observed changes in soil physical and chemical properties.

3.3. Effects of BC amendment on Maize growth

The effects of soil type and amendment treatment on maize growth are presented in Figure 9. Plant height, collar diameter, leaf number, and root mass were evaluated after 48 days of cultivation. Two-way ANOVA was used to determine the effects of soil type, amendment treatment, and their interaction on each growth parameter. The corresponding statistical results are summarized in Table 5.

3.3.1. Plant height

Two-way ANOVA revealed that soil type ($F(1,20) = 3538.06$, $p < 0.0001$) and treatment ($F(4,20) = 2137.94$, $p < 0.0001$) significantly affected plant height. Furthermore, a significant Soil × Treatment interaction ($F(4,20) = 87.41$, $p < 0.0001$) indicated that the magnitude of the response to biochar treatments differed between the two soil types.

Among the evaluated treatments, BCSOF1 (20:70:10, biochar: soil: organic fertilizer) produced the greatest plant height in Soil 1 (46.21 cm), representing an 81.7% increase compared with the control (25.40 cm). In Soil 2, the same treatment increased plant height to 34.15 cm, corresponding to a 69.4% improvement over the control (20.15 cm). The SBC treatment also substantially improved plant height, particularly in Soil 2, demonstrating that biochar alone promoted vegetative growth even without supplementary fertilizer. These findings indicate that the combination of biochar and organic fertilizer produced the greatest improvement in plant growth, although the magnitude of the response depended on soil characteristics.

The substantial increase in plant height following biochar and organic fertilizer application suggests that the amendment improved the soil environment sufficiently to support greater vegetative development. The increase coincided with improvements in soil pH, carbon content and nutrient availability observed following biochar incorporation. Similar responses have been reported for maize grown with biochar amendments, where improvements in soil chemical properties and nutrient availability were associated with enhanced plant growth. Increases in maize biomass following the application of water-hyacinth biochar have also been reported, although the magnitude of the response varied with pyrolysis temperature and application rate [43].

3.3.2. Number of leaves

Leaf number was not significantly affected by treatment ($p = 0.2993$). However, the Soil × Treatment interaction approached the significance threshold ($p = 0.0530$), suggesting a possible soil-dependent response that did not reach statistical significance at $\alpha = 0.05$.

Although plants receiving biochar amendments generally produced slightly more leaves than the control, particularly in Soil 2, these differences were relatively small and did not produce a statistically significant treatment effect. The results suggest that leaf production during the 48-day experimental period was influenced more strongly by the inherent properties of the soil than by the biochar treatments.

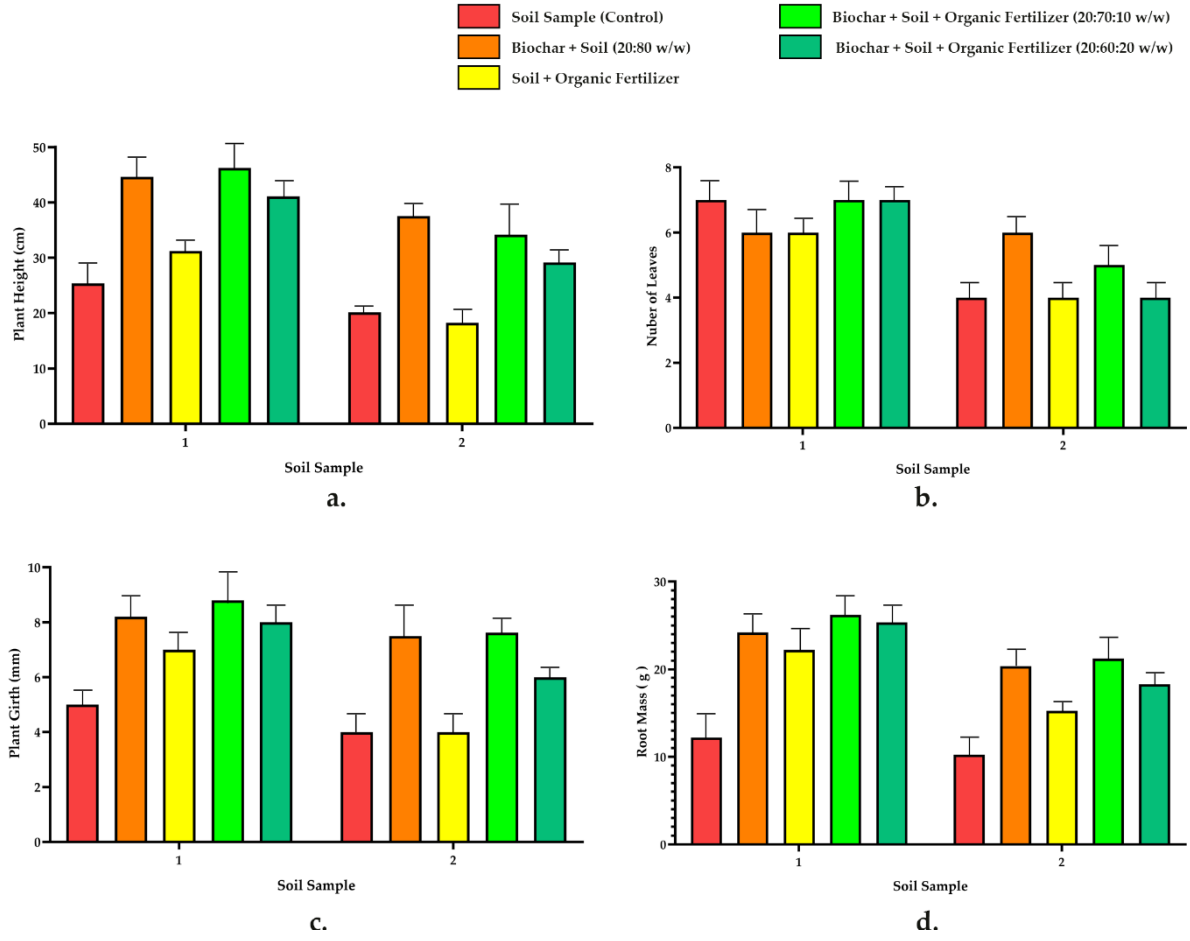


Figure 9. Effect of biochar and organic fertilizer treatments on early maize growth parameters: (a) plant height, (b) number of leaves, and (c) plant girth (collar diameter).

3.3.3. Plant girth (collar diameter)

Plant girth was significantly affected by soil type ($F(1,20) = 465.71$, $p < 0.0001$), treatment ($F(4,20) = 372.52$, $p < 0.0001$), and their interaction ($F(4,20) = 32.47$, $p < 0.0001$). The significant interaction indicates that the influence of biochar treatments on stem development varied between the two soil types.

The BCSOF1 treatment produced the greatest collar diameter in both soils, reaching 8.80 mm in Soil 1 and 7.62 mm in Soil 2. Compared with the control treatments, collar diameter increased by approximately 76% in Soil 1 and 90.5% in Soil 2. Improvements were also observed following biochar application alone, demonstrating that biochar enhanced stem development, while the addition of organic fertilizer further strengthened this response.

3.3.4. Root mass

Root mass exhibited highly significant responses to soil type (F (1,20) = 1706.01, $p < 0.0001$), treatment (F (4,20) = 1386.67, $p < 0.0001$), and the Soil × Treatment interaction (F (4,20) = 64.81, $p < 0.0001$). Figure 10 shows the final root masses in different treatments.

The greatest root biomass was observed under the BCSOF1 treatment, with mean root masses of 26.20 g and 21.23 g in Soil 1 and Soil 2, respectively. These values represented increases of 114.8% and 107.6% relative to the corresponding control treatments. Biochar alone also substantially increased root biomass, indicating that biochar promoted root proliferation through improvements in soil physical conditions and nutrient availability. The significant interaction between soil type and treatment further demonstrates that the extent of root development depended on the physicochemical characteristics of the soil. A summary of ANOVA analysis is given in Table 5.

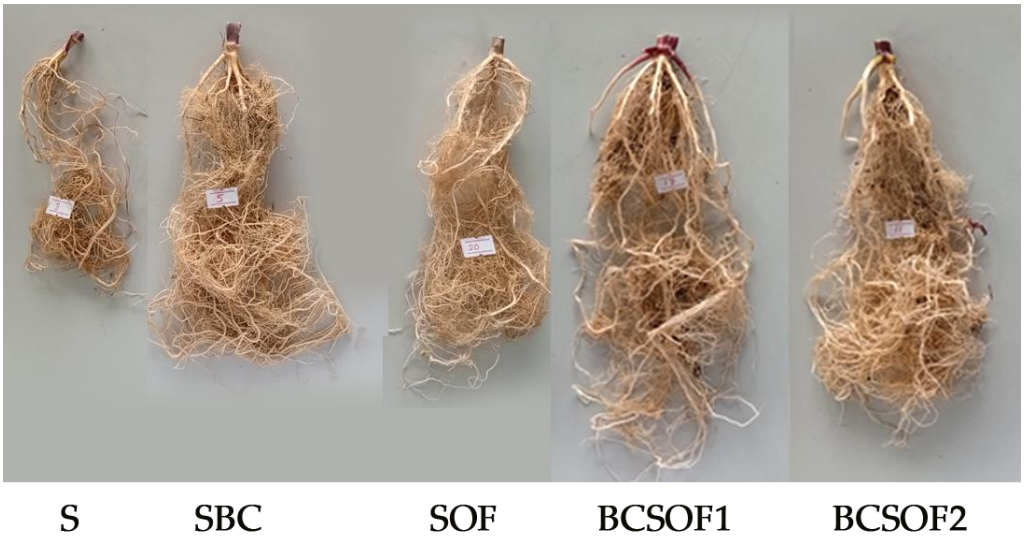


Figure 10. Root mass development in S1 sample after 48 days.

Overall, the combined application of biochar and organic fertilizer consistently produced the greatest improvements in maize growth, particularly for plant height, collar diameter, and root biomass. These findings demonstrate that the agronomic effectiveness of EFB-derived biochar is influenced not only by the amendment but also by the properties of the receiving soil, highlighting the importance of considering soil-specific responses when developing biochar-based soil management strategies.

Although this greenhouse study demonstrates the beneficial effects of EFB-derived biochar on soil quality and early maize growth, the experiment was limited to a 48-day cultivation period under controlled environmental conditions. Consequently, the observed responses primarily represent the short-term effects of biochar application. Since biochar is a relatively stable carbonaceous material capable of influencing soil properties over extended periods, in future investigations, researchers should evaluate its long-term performance under field conditions across cropping seasons. Such studies would provide a more comprehensive understanding of the persistence of biochar-induced improvements in soil fertility, nutrient dynamics, microbial activity, carbon sequestration, and crop productivity under practical agricultural conditions.

Table 5. Summary ANOVA table.

Response Variable	Source	df	F-value	p-value
Plant Height	Soil Type	1	3538.06	<0.0001
	Treatment	4	2137.94	<0.0001
	Soil × Treatment	4	87.41	<0.0001
Number of Leaves	Soil Type	1	37.50	<0.0001
	Treatment	4	1.31	0.2993
	Soil × Treatment	4	2.81	0.0530
Plant Girth	Soil Type	1	465.71	<0.0001
	Treatment	4	372.52	<0.0001
	Soil × Treatment	4	32.47	<0.0001
Root Mass	Soil Type	1	1706.01	<0.0001
	Treatment	4	1386.67	<0.0001
	Soil × Treatment	4	64.81	<0.0001

3.4. Alignment to sustainable development goals

The conversion of oil palm empty fruit bunch, an abundant agricultural residue from the palm oil industry, into biochar provides a potential pathway for integrating agricultural waste management with soil improvement and crop production. Our findings of this study demonstrated that EFB-derived biochar, particularly when combined with organic fertilizer, modified several soil physicochemical properties and improved selected maize growth characteristics. These findings highlight the potential of converting an underutilized biomass residue into a value-added soil amendment rather than relying solely on conventional disposal or low-value utilization pathways.

From the perspective of Sustainable Development Goal 2–Zero Hunger, the observed improvements in soil properties and maize growth indicate the potential of EFB biochar-based amendments to support soil productivity and crop establishment. The combined application of biochar and organic fertilizer is particularly relevant because it integrates a carbon-rich soil amendment with an additional source of plant nutrients, potentially providing a more resource-efficient approach to soil fertility management. However, our results were obtained under controlled pot conditions, and further field-scale studies are required to determine the consistency of these effects under practical agricultural conditions.

The study also contributes to SDG 12–Responsible Consumption and Production through the valorization of EFB. Producing biochar from EFB creates an opportunity to convert a biomass residue into a stable, potentially reusable agricultural input, thereby supporting more circular utilization of resources within the palm oil production system. This approach can contribute to reducing dependence on linear biomass disposal pathways while returning carbon and nutrients to agricultural soils.

The findings are also relevant to SDG 13–Climate Action, because biochar production provides a pathway for retaining a portion of biomass-derived carbon in a relatively stable form when the resulting material is incorporated into soil. In contrast to the short-term cycling of untreated biomass

residues, conversion to biochar can facilitate longer-term carbon retention in soil. Nevertheless, we did not directly quantify carbon sequestration, greenhouse-gas emissions, or the complete life-cycle environmental performance of EFB biochar. Therefore, the potential climate-related contribution should be considered as an implication of the observed biochar properties rather than as a quantified climate benefit [44].

Overall, the results demonstrate the potential for an integrated waste-to-resource approach, in which EFB is converted into a value-added biochar amendment and subsequently utilized for soil and crop management. Such an approach links biomass-residue valorization with sustainable soil management and agricultural production, while supporting the broader objectives of SDGs 2, 12, and 13. Future field-scale and life-cycle assessments would be necessary to quantify the economic, environmental, and climate benefits associated with this approach [45].

4. Conclusions

This study demonstrated the potential of oil palm EFB-derived biochar as a soil amendment for improving selected soil properties and supporting early maize growth. Application of biochar reduced soil bulk density, increased soil pH, and substantially increased soil carbon content in Reddish Brown Earth (S1) and Red Yellow Podzolic (S2) soils. The combined application of biochar and organic fertilizer produced the most pronounced improvements in maize growth, particularly in plant height, collar diameter, and root mass, whereas leaf number was not significantly affected by treatment.

The magnitude of the response differed between the two soil types, indicating that the effectiveness of EFB biochar is influenced by the initial soil conditions. These findings support the potential of converting oil palm EFB into a value-added biochar amendment while providing beneficial use for an abundant agricultural residue. The combined biochar–organic fertilizer treatment appears particularly promising for improving soil conditions and early maize growth under the conditions evaluated in this study.

However, the experiment was conducted under controlled greenhouse conditions over a relatively short growth period. Therefore, the findings should not be directly extrapolated to long-term field performance. Further field-scale studies are recommended to evaluate the persistence of soil improvements, effects on maize yield, nutrient-use efficiency, carbon stability, and the economic and environmental performance of EFB biochar application under practical agricultural conditions.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Author contributions

Conceptualization, methodology, and formal analysis, H.N.; supervision, A.A., E.W. and K.K.; writing–original draft preparation, and validation, H.N.; writing–review and editing, H.N., U.R. E.W., A.A., and K.K. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of interest

The authors declare no conflicts of interest. The funders had no role in the design of the study.

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