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RESEARCH ARTICLE

Cotton Stalk and Tea Residue Biochar as Organic Amendments to Boost Maize Performance

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Abstract

Soil degradation and declining crop productivity are major challenges in modern agriculture, especially in areas with intensive farming and limited access to synthetic fertilizers. The use of organic waste materials as soil amendments offers a promising strategy to enhance soil fertility, improve crop yield, and promote sustainable agricultural practices. This study aimed to investigate the potential of biochar derived from agricultural residues, specifically tea residue and cotton stalks, as organic amendments to improve soil health and maize (*Zea mays* L.) performance. A field experiment was conducted using four treatments: TEB1 (tea residue biochar), TEB2 (cotton stalk biochar), TCC (positive control), and TCN (negative control). Plant growth parameters including plant height, number of leaves, root development, number of ears per plant, grain count per ear, kernel rows, and ear weight were measured. In addition, soil properties such as pH, moisture content, water-holding capacity, ash content, and macro-nutrient levels (nitrogen, phosphorus, potassium) were assessed. The results demonstrated that TEB2 significantly enhanced plant growth and yield, achieving the highest plant height (200 cm), grain count (400 per ear), and ear weight (0.85 kg) compared to the control (plant height: 154 cm; yield increase: 13.5%). Biochar treatments also improved soil pH from 11.5 to 7, increased nutrient availability, and enhanced moisture retention. Both biochars, especially cotton stalk biochar, promoted better root development and soil aeration. This study underscores the value of utilizing agricultural waste-derived biochar to improve maize productivity and soil quality, highlighting its potential for sustainable crop production and resource-efficient farming systems. Further research should explore the long-term effects of biochar amendments across varying soil types and climatic conditions.

Keywords: Agricultural residues; biochar; maize yield; soil health; sustainable agriculture

Introduction

Maize (*Zea mays* L.), commonly referred to as “the queen of cereals” is one of the most important staple crops worldwide due to its wide adaptability, nutritional richness, and high productivity. It contains approximately 72% starch, 10.4% protein, 4.8% oil, and a range of essential vitamins and minerals, making it vital for food, feed, and industrial purposes such as biofuel, oil, and starch production (Akhtar et al., 2024; Yaqoob et al., 2019). As the third most important cereal crop worldwide, maize plays a crucial role in global food security, with major producers including the United States, China, Brazil, and the European Union (Erenstein et al., 2022). Despite its global prominence, maize production in Pakistan remains suboptimal. The country ranks 22nd in maize cultivation area but only 68th in total production, underscoring a substantial yield gap (Akhtar et al., 2024). This underperformance is attributed to multiple factors, including low soil fertility, climate variability, limited resources, and unsustainable agricultural practices (Dawar et al., 2022). A major concern is the excessive and imbalanced use of synthetic fertilizers, which, although initially beneficial, has resulted in severe soil degradation, disruption of beneficial microbial communities, depletion of soil organic matter, nutrient leaching, and elevated greenhouse gas emissions (Ali et al., 2025; Rahman et al., 2018; James et al., 2023). These environmental and agronomic challenges necessitate sustainable and integrated nutrient management strategies that enhance crop production, improve soil health and minimize ecological footprints (Feroz et al., 2024).

Among emerging sustainable soil amendments, biochar has gained attention for its potential to improve soil quality and crop productivity. Biochar is a stable, carbon-rich product derived from the pyrolysis of organic biomass under limited oxygen conditions. Its porous structure, large surface area, and diverse functional groups contribute to improve water retention, nutrient availability, pH buffering, and stimulation of beneficial microbial activity (Colantoni et al., 2016; Liu et al., 2025). However, the properties and agronomic effectiveness of biochar vary widely depending on the type of biomass feedstock and pyrolysis conditions (Islam et al., 2019; Cao et al., 2020). Previous studies have confirmed the benefits of biochar in enhancing soil fertility and plant growth, but relatively few have investigated biochars derived from locally available agricultural residues such as tea residues and cotton stalks, both of which are abundant and often discarded as waste in South Asian farming systems. This presents an opportunity to convert agriculture waste into a valuable resources (Venkatesh et al., 2013). While the beneficial effects of biochar on soil and crop performance are well documented, field-based evidence comparing the performance of tea residue and cotton stalk biochars under local agro-climatic conditions remain limited. Moreover, previous studies have focused on biochars general properties rather than its influence on specific plant physiological traits, nutrient uptake, and yield components under integrated nutrient regimes (Tao et al., 2024).

Therefore, this study aims to evaluate the agronomic and soil health benefits of tea residue and cotton stalk-derived biochars on maize (*Zea mays* L.) growth and productivity under field conditions. The objectives of this study were: (1) to characterize the physicochemical properties of biochar derived from tea residue and cotton stalks, (2) to evaluate the effects of biochar application on maize growth parameters (plant height, root development, leaf number), yield and quality. We hypothesize that biochar derived from tea residue and cotton stalks, when applied to soil, will enhance maize growth and yield by improving soil nutrient availability, structure, and water-holding capacity, with cotton stalk biochars expected to yield superior results due to its higher ash and porosity content.

Material and methods

Experimental Site

The experimental study was conducted in 2024 at the Pakistan Council of Scientific and Industrial Research (PCSIR) Institute, located in Lahore, Punjab, Pakistan (latitude 31°32′ N, longitude 74°19′ E). The region experiences a subtropical monsoon climate with moderate rainfall. The average annual temperature ranges from 24°C to 26°C, and average annual precipitation is approximately 178 mm, with the majority of rainfall occurring during the monsoon season.

Experimental design and treatments

The field experiment was conducted in a 500 m² area at PCSIR. Hybrid maize seeds (*Zea mays* L., variety 'Neelam') were sown in late April 2024. The experimental layout included four main plots with plant-to-plant spacing of 25cm, row-to-row spacing of 40cm, and inter-plot spacing of 110cm. During the experimental period, ambient temperature ranged between 35-40 °C, and the photoperiod varied from 9 to 11 hours. The experimental plots TEB1, TEB2, TCN, and TCC were subdivided into three subplots each, and biochar was applied at three concentrations: C1 = 2g, C2 = 6g, and C3 = 8g. TEB1 and TEB2 plots received biochar derived from tea residue and cotton stalks, respectively. The positive control (TCN) was treated with NPK fertilizer at three concentrations (25g, 50g, and 75g) according to PAC guidelines (J82_F; cabidigitallibrary.org). The negative control (TCC) received only water. Biochar treatments were prepared by dissolving the appropriate quantity of biochar in 1000ml of distilled water and applied to the soil through irrigation. Each treatment was applied three times 15, 45, and 75 days after seedling emergence. Plant growth parameters such as plant height (cm), number of leaves, and number of roots were recorded one week after each treatment.

Soil Analysis

Soil samples were collected and analyzed for various health indicators at PCSIR, with results verified by the Soil Testing Laboratory in Thokar Niaz Baig, Lahore. Soil properties analyzed included texture, organic matter content, moisture saturation, electrical conductivity (EC), total nitrogen (N), and extractable potassium (K), following AOAC (1995) guidelines (Table 1).

Table 1. Initial soil properties of the experimental location

Soil Properties	Values
Moisture content (%)	7.19
Ash content (%)	18.21
Texture	Loam
pH	7.91
Total N (mg/kg)	0.96
Total P (mg/kg)	9.5
Total K (mg/kg)	64
EC $mScm^{-1}$	0.93
Saturation (%)	38
Bulk density (g/cm^3)	30

Note: E.C = Electrical Conductance, % = percentage, mg/kg = milligram per kilogram, mScm-1 = miliSiemens per centimeter.

Biochar synthesis

Two types of biochar were prepared using locally sourced household and agricultural waste materials: tea residue and cotton stalks. Tea residue was collected from tea stalls in Jubilee Town, Lahore, and cotton stalks were obtained from nearby cotton fields. The biomass was subjected to pyrolysis in a muffle furnace under limited oxygen conditions at temperatures between 600-650 °C for 24 hours to produce biochar.

Yield of biochar

Biochar samples were characterized for pH, water-holding capacity, electrical conductivity, nitrogen content, moisture content, and ash content. Morphological analysis was performed using Scanning Electron Microscopy

(SEM), following the methods outlined by Sahoo et al. (2021) and Shenbagavalli et al. (2012). Biochar yield was calculated as the ratio of the mass of biochar produced to the mass of raw biomass, following the method described by Sahoo et al. (2021), using Equation 1.

$$(\text{Biochar yield } (\%)) = \frac{\text{Mass of Biochar (g)}}{\text{Mass of raw biomass (g)}} \times 100 \text{ .... Equation (1)}$$

Growth attributes of *Z. mays* crop

Morphological and yield-related attributes of maize (*Zea mays*) were recorded to evaluate plant growth and productivity. Observations were taken at 15 days after sowing (DAS) from randomly selected plants within each replication, followed by subsequent assessments at 45 DAS and 75 DAS**.** Plant height (cm) was measured from the base of the plant at the soil surface to the tip of the main stem using a meter ruler. The number of leaves and roots per plant was determined by counting these parameters on three randomly selected plants from each replication, after which mean values were calculated to represent each treatment. At physiological maturity, yield-related parameters were recorded. These included the number of ears per plant**,** number of kernel rows per ear (counted manually), number of grains per ear (counted manually), average ear weight (kg), and the total grain yield per treatment plot. The ear weight was measured using a high-precision electronic weighing balance to ensure accuracy.

The data related to the growth attributes of the *Zea mays* crop were recorded based on plant height (cm)**,** number of leaves, and number of roots per plant. In addition, the number of corns per plant was also counted to assess the overall growth performance of the crop. The data related to the yield attributes of the *Z. mays* crop were recorded based on the number of plants germinated within the given experimental area. The grain yield was calculated by using the equation 2.

$$(\text{Yield t ha} - 1) = \frac{\text{Average ear Weight} \times \text{number of ears per m2} \times 10{,}000}{10{,}000} \text{ .... Equation (2)}$$

Chlorophyll content analysis (mg/g)

The determination of chlorophyll a, b, and c contents was carried out by using fresh maize (*Zea mays*) leaves collected from each treatment, following the protocol of Evensen et al., 1992 with minor modifications. Approximately, 1.0 g of fresh leaves were weighed and grind with pestle and mortar. The homogenized sample was then mixed with 10-20 mL of a hexane and acetone solution (6:4, v/v). The mixture was agitated on a magnetic stirrer for 2 hours and subsequently filtered through Whatman filter paper (No. 1). However, the resulting filtrate was diluted with the same solvent mixture (hexane and acetone) as required. The optical density (OD) of the supernatant was measured at 663 nm, 645 nm, 505 nm, and 453 nm using a spectrophotometer. The concentrations of chlorophyll a, b, and c (mg/g fresh weight) were then calculated using the equation 3, 4 and 5.

Chlorophyll a (mg/100ml) = 0.999 A663 – 0.0989 A645 ……………. Equation (3)

Chlorophyll b (mg/100ml) = -0.328 A663 + 1.77 A645 ……………..Equation (4)

Chlorophyll c ((mg/100ml) = Chlorophyll a (mg/100ml) + Chlorophyll b (mg/100ml)…Equation (5)

Statistical analysis

A one-way analysis of variance (ANOVA) was used to assess differences among treatment groups. Statistical analyses were performed using Statistix 8.1 and Microsoft Excel. The significance level of $p < 0.05$ was considered statistically significant.

Results

Biochar characterization

Yield of biochar

The successful synthesis of all experimental biochar samples was visually confirmed. Both biochars exhibited a porous, granular, powdery appearance with a black to dark brown colour. The appearance of visible pores and cavities indicated a high surface area, a desirable characteristic for biochar. Among the samples, the highest biochar yield was recorded for TEB2 (86%), followed by TEB1 (80%).

Proximate and ultimate analysis of biochar

The proximate analysis revealed clear differences among the biochar samples. The highest ash content after pyrolysis was recorded in TEB2 (38.29%), whereas TEB1 exhibited the lowest (6.5%). These variations in ash content likely reflect differences in the feedstock and pyrolysis conditions. The ash content in TEB1 and TEB2, within optimum ranges, contributed positively to plant growth. In terms of moisture content, TEB2 exhibited the highest value (6%), followed by TEB1 (5%), showing a clear distinction in moisture retention among the samples (Figure 1; Table 2).

Table 2. Proximate and Ultimate analysis of biochar.

Parameters	TEB1	TEB2
pH	8.22	9.1
EC (dSm^{-1})	320	1185
Water holding capacity (%)	75	90
Moisture content (%)	5	6
Ash Content (%)	6.5	38.2
Total Nitrogen content (%)	0.96	0.5
Total Na (%)	79	44
Calcium (%)	30	78
Total potassium (%)	135	65

Note: TEB1 = Treated Experimental Biochar1 (Tea residue),
TEB2 = Treated Experimental Biochar2 (Cotton stalk)
EC = Electrical conductance, % = percentage,
dSm-1 = deciSiemens per meter.

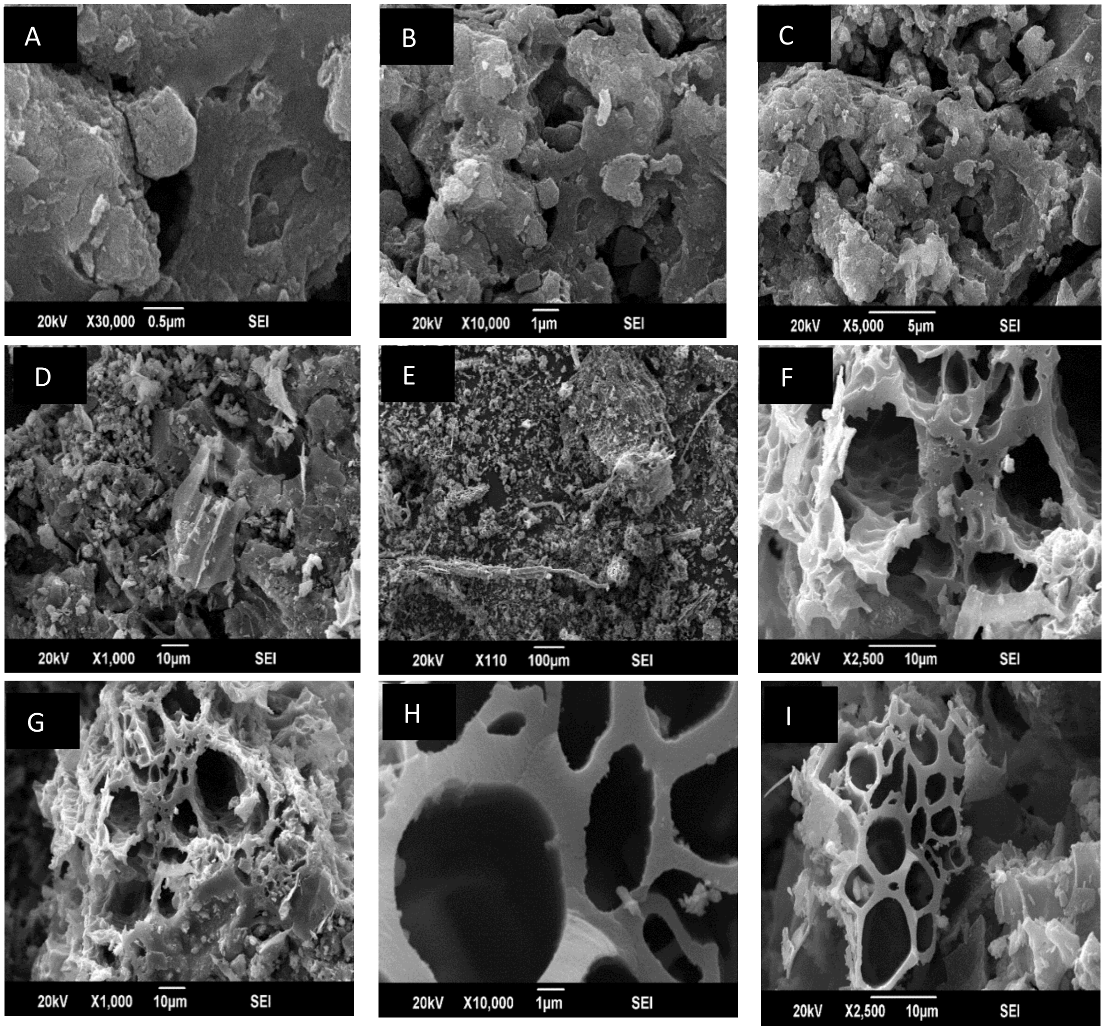

Figure 1: Scanning electron microscope images of TEB2 (Cotton stalk Biochar)

Furthermore, the water holding capacity was greatest in TEB2 (90%), followed by TEB1 (75%). The higher water holding capacity of TEB2 is attributed to its porous structure and larger internal voids, as confirmed by SEM analysis. This enhanced porosity facilitates improved soil moisture retention and nutrient availability. The chemical and elemental analysis of the biochars showed variation in nutrient content. The total nitrogen content was generally low across all samples due to the loss of volatile components during pyrolysis. The highest nitrogen content was found in TEB1 (0.96%). The sodium content was highest in TEB1 (79%) and lowest in TEB2 (44%). Elevated sodium levels in biochar can increase soil salinity and promote photosynthesis by facilitating stomatal opening through Na^+ ions. Potassium content was highest in TEB1 (95%), followed by TEB2 (65%). High potassium availability aids in regulating water uptake, enhancing photosynthesis, and improving plant resilience under drought conditions (Figure 2; Table 3).

Table 3. Proximate analysis and carbohydrate content of corn

Sr. No	Proximate analysis	TEB1	TEB2
1	Moisture content (%)	15.8	14
2	Ash content (%)	0.23	0.29
3	Protein content (%)	6	7
4	Nitrogen content (%)	0.5	0.1
5	Fat (%)	2.71	2.72
6	Fiber (%)	0.3294	0.31126
7	Total carbohydrate	74.9306	75.679

Note: TEB1= Treated Experimental Biochar1 (Tea residue), TEB2= Treated Experimental Biochar2 (Cotton stalk)

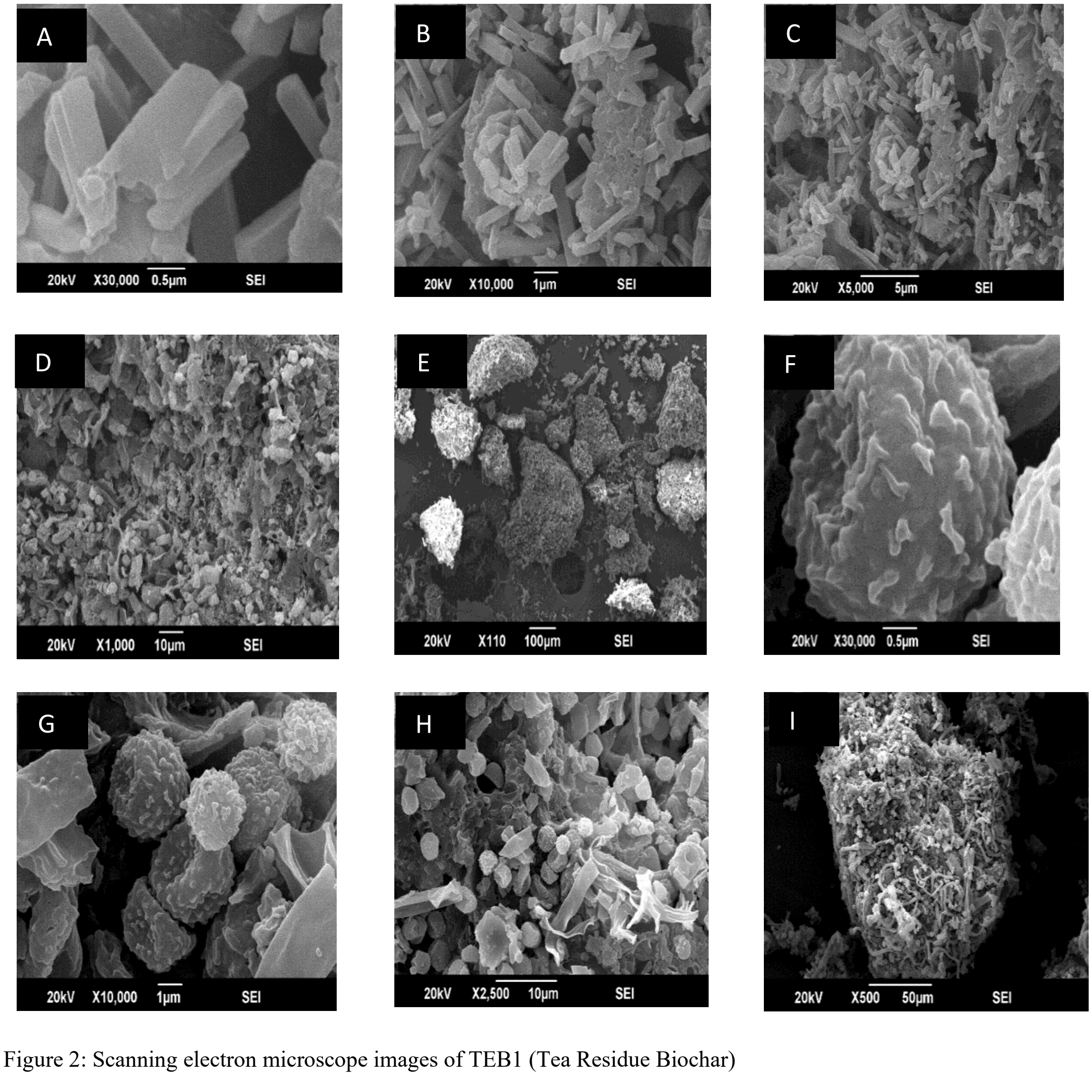

Figure 2: Scanning electron microscope images of TEB1 (Tea Residue Biochar)

pH, Electrical Conductivity (EC), and calcium content

Soil nutrient availability is closely influenced by pH, and the addition of biochar typically increases soil pH. In this study, all biochar samples exhibited alkaline pH values above 7. TEB2 recorded the highest pH (9.1), whereas TEB1 had the lowest (8.22). To stabilize the soil pH at around 7, dilute ammonium nitrate was added during application. Electrical conductivity (EC), indicative of soluble salt content, nutrient availability, texture, and water retention capacity, varied significantly among samples. TEB2 showed the highest EC value (1185 dS/m), followed by TEB1 (320 dS/m). Elevated EC values suggest improved nutrient availability and enhanced soil carbon levels, both of which contribute to better soil health and crop productivity. Regarding calcium content, TEB2 had the highest value (78%), followed by TEB1 (30%). High calcium levels improve soil structure, support chlorophyll formation, and contribute to overall soil and plant health.

Scanning electron microscope (SEM) analysis of biochar

SEM analysis of TEB2 revealed variations in particle size across different magnification levels, ranging from ×30,000 to ×250. The particles were non-spherical and irregular in shape. At ×30,000 magnification, the average particle size was 1µm; at ×10,000, it was 0.5µm; at ×5,000, 5µm; at ×1,000, 10µm; and at ×500, 100µm. At magnifications of ×110, ×2,500, and ×250, particle sizes were consistently around 10µm and 100µm. Structural observations showed plate-like fragments with irregular surfaces (×100), porous and interconnected voids with sharp edges (×110), uneven and porous particle structures (×250), and large cavities and macro-porous channels (Figure 1) at higher magnifications (×5,000 to ×30,000). Similarly, SEM analysis of TEB1 also indicated non-spherical and irregular particle shapes. At ×30,000 magnification, the average particle size was 0.5µm; at ×10,000, 1µm; at ×5,000, 5µm; and again 0.5µm at ×30,000. Larger structures were observed at ×500 (100 µm), ×110 (50µm), ×2,500 (10µm), and ×250 (10µm). These images revealed large cavities, micro-pores, and rough, irregular surfaces. The SEM results confirmed that both TEB2 and TEB1 biochar possess complex porous structures that contribute to their water and nutrient retention capabilities.

Biochar effects on plant growth

Biochar treatments significantly influenced maize growth parameters at 15, 45, and 75 days after sowing. At 75 days, TEB2 recorded the highest mean plant height (200cm), mean number of leaves (19), and mean number of roots (18.3). TEB1 showed mean height of 184cm, 16 leaves, and 14.3 roots. TCN recorded 177cm height, 13 leaves, and 13 roots. TCC, the water control, had the lowest values (154cm, 13 leaves, 14 roots). Statistical analysis confirmed that TEB2 had highly significant effects ($p < 0.05$) on all three parameters: plant height ($p = 0.03$), number of leaves ($p = 0.04$), and number of roots ($p = 0.02$). The results highlight the potential of cotton stalk biochar in enhancing vegetative growth (Table 4).

Table 4. Effect of Biochars application on plant height, number of leaves, and number of roots.

Treatments	Levels (g)	Plant height (cm)			Plant no. of leaves			Plant no. of roots		
		15d	45d	75d	15d	45d	75d	15d	45d	75d
TEB1	2	92	164	180	6.7	9	15	6.7	8	14
	6	95	162	184	6.7	8.67	16	9	9	14.7
	8	83	166	181	7	8	15	7	8	13.3
TEB2	2	96	188.7	192	8.7	13.67	19	6.7	8	14
	6	83	189.5	200	6	11	19	9	9	14.7
	8	92	186.9	199	6.7	10	19	7	8	13.3
TCC	2	83	118.9	154	6.7	7.67	12	9	14	18.3
	6	87	122	149	6.7	8	12	8	9	18.3
	8	87	125	153	7.3	8.33	13	9	10	18.3
TCN	2	83	118.9	154	6	7	11	7.7	8	13.7
	6	87	122	149	6.3	7.33	10	7.3	8	14
	8	87	125	153	6.7	7	10	7.7	9	12.3

Biochar effects on chlorophyll content

The chlorophyll content of *Zea mays* varied significantly across the treatments. The highest chlorophyll concentration (45%) was recorded in TEB4, followed by TEB3 (40%). In contrast, lower values were observed in TEB1 (35%) and TEB2 (30%) (Figure 3). These results demonstrate that biochar application, particularly from tea residue and cotton stalks, positively influences chlorophyll synthesis and content in corn plants, likely contributing to improved photosynthetic activity and plant vigor (Arisha et al., 1999; Arisha et al., 2003).

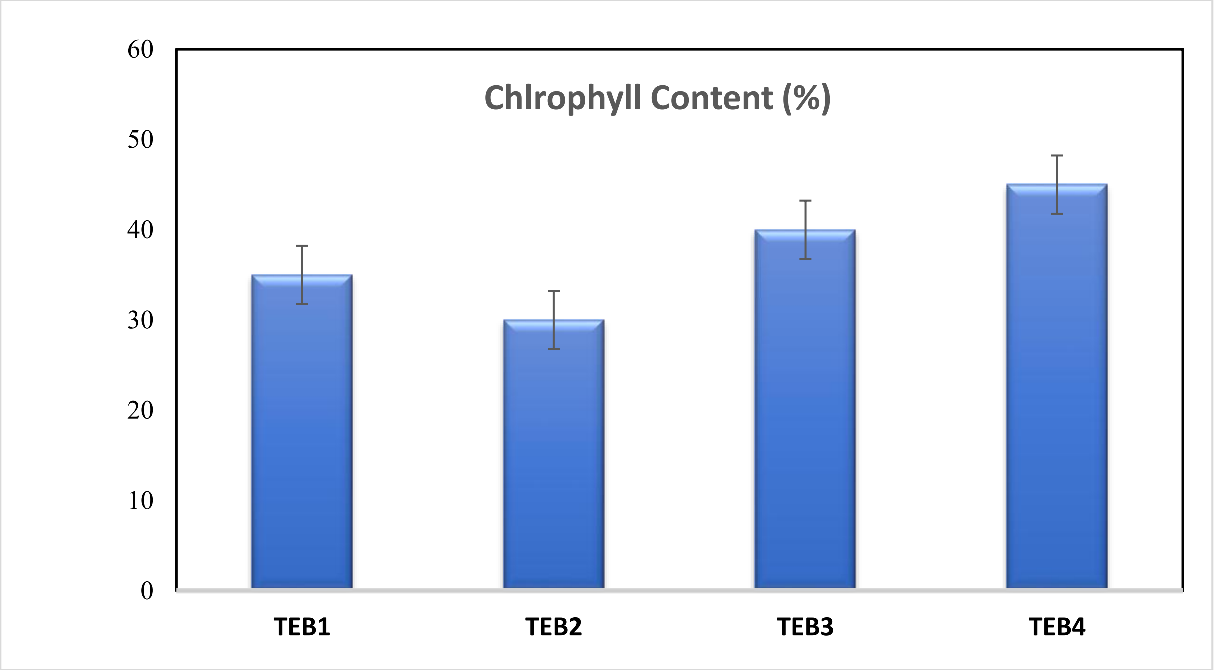

Figure. 3 Chlorophyll content observed in four different treatments (TEB1–TEB4)

Biochar effects on yield attributes of maize

The application of biochar showed highest number of corns were recorded in TEB2 (20), followed by TEB1 (18), and TCC (15) while the lowest value was observed in TCN (9). Highest value of kernel row per ear was recorded in TEB2 (15), followed by TEB1 (14), and TCC (10) while the lowest value was observed in TCN (12). The increases in number of kernel rows impact on the number of grains highest number of grains per ear was recorded in TEB2 (476), followed by TCC (400) while the lowest value was observed in TCN (390). Highest value of weight of corn was recorded in TEB2 (1kg), followed by TEB1 (0.95kg), and TCC (0.9kg) while the lowest value was observed in TCN (0.8kg). This study showed that cotton stalk biochar revealed increase of total yield, number of corns and number of kernels in a corn as compared to other treatments (Table 5).

Table 5. Yield attributes of the *Z. mays* of all experimental groups.

Treatments	Corns weight (kg)	Grains/Corn	Corn per m^2	No. of kernel rows	Yield (t/ha)
TEB1	0.95	460	18	14	17.1
TEB2	1	476	20	15	20
TCC	0.9	400	15	10	13.5
TCN	0.8	390	9	12	7.2

Note: TEB1 – Tea Residue Biochar; TEB2 – Cotton Stalk Biochar; TCN – Positive Control (NPK); TCC – Negative Control (Water Only).

Quality attributes of maize (*Z. mays*)

Fiber is a crucial component of the human diet, providing both soluble and insoluble dietary fiber. In the current study, the highest fiber content (0.96%) was recorded in the TEB1 treatment, followed by TEB2. The application of tea residue biochar (TEB1) and cotton stalk biochar (TEB2) significantly influenced nutrient uptake by the plants and demonstrated positive effects on crop nutritional value. The highest fat content (3.35%) was also recorded in TEB1, while the lowest fat content (0.311%) was observed in TEB2. Moisture content varied slightly among the treatments, with TEB2 showing the highest moisture content (18%) and TEB1 showing the lowest (17%). These results indicate distinct variations in the moisture retention capacity of the different biochar treatments. Ash content was highest in TEB1 (1.25%), followed by TEB2 (0.59%). Regarding nitrogen content, TEB1 again showed the highest value (5%), followed by TEB2 (1.5%), with the lowest nitrogen value recorded in TEB2 (0.1%). These findings suggest that the use of tea residue biochar leads to improved accumulation of key nutritional components, including carbohydrates, nitrogen, fat, and ash, thereby enhancing the nutritional profile of *Z. mays*.

Discussions

Biochar, a carbon-rich byproduct of pyrolyzing organic matter under limited oxygen, has garnered increasing attention due to its multifaceted benefits in agriculture. It improves soil fertility, enhances soil structure, and boosts plant productivity through its porous architecture, which facilitates water retention and nutrient adsorption (Shakeel et al., 2022). In this study, biochars derived from cotton stalks, tea residue, banana peels, and eggshells were evaluated for their distinct physicochemical properties and their effects on the growth and nutritional quality of *Zea mays*. Cotton stalk biochar, pyrolyzed at 600–650°C, demonstrated the most remarkable results in terms of plant yield (20 t ha^{-1}) and plant height (199.83cm). This superior performance can be attributed to its high pH (9), which ameliorates acidic soils and enhances nutrient availability. Such outcomes align with the findings of Rafat Al Afif et al. (2019), who reported a similar yield boost with cotton stalk biochar application. The observed high alkalinity is likely due to the presence of calcium carbonate and potassium salts, consistent with He et al. (2020). SEM analysis further revealed well-developed micro and macro-pores that provide a favorable habitat for microbial colonization and improved nutrient exchange, corroborating the findings of Du et al. (2013). However, the low nitrogen content in cotton stalk biochar supports previous observations by Xu et al. (2021), indicating nitrogen loss through volatilization during high-temperature pyrolysis, primarily in the forms of HCN and NH_3. Tea residue biochar, produced at 600°C, also demonstrated significant benefits with a yield of 20 t ha^{-1}, second only to cotton stalk biochar. It had a moderate pH of 8.2, closely matching the 7.91 pH reported by Yang et al. (2020) for similar pyrolysis conditions. The relatively high plant performance observed with this treatment can be attributed to its structural integrity and porosity, which aid in moisture retention and nutrient absorption, in line with Wang et al. (2014). The filamentous and irregular pore structures observed via SEM likely contributed to enhanced root-soil interactions and microbial activity. Despite its positive effect on plant growth, the tea residue biochar also exhibited low nitrogen content (0.9%), reinforcing conclusions from Xu et al. (2021) regarding nitrogen loss during thermal decomposition. Notably, the increased yield is consistent with findings by Azeem et al. (2021), who reported yield improvements in legumes upon application of tea residue biochar. In contrast, banana peel biochar, while rich in potassium (85%) and exhibiting a very high pH (11.5), showed the lowest yield impact (8 t ha^{-1}). Although potassium is vital for plant metabolism, excessive concentrations may cause nutrient imbalances, particularly with nitrogen and calcium, which could inhibit optimal plant development. Similar negative yield effects of banana peel biochar have been documented by Islam et al. (2019), highlighting the need for careful nutrient management when using potassium-rich biochars. The low nitrogen content (0.29%) also supports earlier findings by Xu et al. (2021), who attributed nitrogen volatilization during pyrolysis as a major limitation in nutrient-rich biochar applications. Thus, while the biochars chemical composition might appear favorable in isolation, its agronomic performance was suboptimal, possibly due to excessive alkalinity and nutrient antagonism.

Eggshell biochar, characterized by a high pH (8.78) and substantial calcium content, exhibited intermediate performance in crop yield. Although the pH aligns with He et al. (2020), who reported a pH of 12 at higher pyrolysis temperatures, the yield response was less favorable. This could be attributed to its comparatively lower potassium content (22%) and low nitrogen availability (0.5%), again supporting Xu et al. (2021) regarding the limitations imposed by nitrogen volatilization. These findings are echoed by Sebonela LK et al. (2024), who emphasized the importance of potassium availability in determining biochars effectiveness in enhancing crop productivity. Furthermore, the calcium dominated composition of eggshell biochar, while beneficial for ameliorating acidic soils, may not be sufficient to drive yield gains when other nutrients are suboptimal or imbalanced. The nutritional profiling of *Zea mays* further supports the efficacy of tea residue and cotton stalk biochars. Enhanced nitrogen, fat, ash, and carbohydrate contents in plants treated with TEB1 and TEB2 suggest improved nutrient uptake and metabolic activity. These findings support the role of biochar in enhancing soil-plant nutrient dynamics and align with previous work highlighting biochars role in improving crop quality parameters (Azeem et al., 2021; Wang et al., 2014). The increased chlorophyll content observed in TEB2 (45%) and TEB1 (40%) indicates enhanced photosynthetic efficiency, likely due to improved nitrogen and micronutrient availability, which are critical for chlorophyll synthesis. This aligns with Arisha et al. (1999, 2003), who reported higher chlorophyll content in crops grown under improved soil fertility and nutrient management.

Overall, the biochars derived from cotton stalk and tea residue emerged as the most effective soil amendments among the tested treatments. Their moderate-to-high pH, porous microstructure, and favorable nutrient profiles contributed to better crop performance and enhanced nutritional quality. Conversely, while banana peel and eggshell biochars were rich in specific minerals, their agronomic benefits were limited, possibly due to extreme pH values, nutrient imbalances, or low nitrogen retention. These findings emphasize the importance of selecting appropriate raw materials and optimizing pyrolysis conditions to tailor biochar properties for specific soil and crop requirements. Future research should explore the synergistic effects of combining different biochars or integrating them with organic or inorganic fertilizers to maximize their benefits in sustainable crop production systems.

Conclusion

This study comprehensively evaluated the effects of biochars produced from different organic wastes on maize growth, yield, and quality. Among the biochars tested, those derived from tea residue and cotton stalk consistently demonstrated superior performance by significantly enhancing crop growth and final yield. The beneficial effects of these biochars are attributed to their ability to improve soil water-holding capacity and increase nutrient availability, which in turn promoted better plant development and physiological health. Moreover, the application of tea residue and cotton stalk biochars positively influenced important quality parameters of maize, indicating their role in not only boosting productivity but also improving crop nutritional value. These findings underscore the promising potential of cotton stalk and tea residue biochars as sustainable, cost-effective soil amendments for enhancing soil fertility and agricultural productivity. The results advocate for the wider adoption of such biochars in sustainable farming practices aimed at improving crop performance while promoting environmental stewardship.

Declaration

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Consent for publication: All authors consent to the publication of this manuscript.

Data availability Statement: Data will be available on a formal request from the corresponding authors.

Author's contribution: Rehana Badar[2] helps in conceptualization, supervised and gave final approval for publication; Muqadas Asghar[1] performed experimental analysis and wrote first draft, Aiza Ashfaq[2], and Arooj Afzal[1] helps in formal Analysis, Huma Fatima[1], Tehmoor Aliyan[1] and Farman Ullah[4] help in review and editing, Muafia Shafiq[3], Tehniat Fatima[1], Sunbal Jehan[5] helps in Data collection. All authors have read and agreed to the published version of the manuscript.

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