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Biochar-Assisted Amelioration of Saline Soil for Optimal Growth and Yield of Okra (*Abelmoschus esculentus* (L.) Moench)

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ABSTRACT

Saline soil poses a significant challenge to agricultural productivity, particularly in coastal regions. In this study, a field experiment at the agriculture research field of Noakhali Science and Technology University, Noakhali was conducted where three doses of biochar were applied using RCBD with 3 replications in the soil to investigate the potential of biochar as a sustainable solution to enhance Okra growth and yield under saline conditions. To impose the salinity, 0.1M of NaCl solution were applied in each plot at the seedling stage. The findings demonstrated that the application of biochar significantly improves the growth and yield-contributing factors of okra. As the biochar dosage increased, notable increases in plant height, number of leaves per plant, lamina length, and petiole length were observed. Additionally, biochar-treated plants exhibited reduced time to first flowering (DAS), indicating enhanced early reproductive development. Chlorophyll content in okra leaves also showed a positive correlation with biochar application, suggesting improved photosynthetic efficiency and stress tolerance in saline conditions. Notably, biochar application positively influenced okra fruit characteristics. Higher biochar doses significantly increased the single fruit's length, diameter, and weight. Moreover, the number of fruits per plant and overall yield per plot were notably higher in biochar-treated plants. Among the various biochar doses tested, the 4 tons/ha treatment proved the most effective, resulting in remarkable improvements in all growth and yield parameters. The findings indicate that using biochar might help the farmers of the coastal region to mitigate the salinity problem.

1. INTRODUCTION

Okra (*Abelmoschus esculentus* (L.) Moench, 2n = 130), a widely recognized and economically significant vegetable, belongs to the family Malvaceae cultivated in various regions worldwide (Khandaker et al., 2017; Arapitsas, 2008; Siemonsma, 1982). It serves multiple purposes, being consumed raw, canned, or used for its seeds. This crop is a highly nutritious and rich source of protein and is considered a low-fat food and also contains fibres, minerals, vitamin C, folate, Vitamin B1, B6 and K. It also contains bioactive components such as flavonoids (Khan et al., 2023). In every 100 grams of edible portion, fresh okra contains approximately 35 calories, 89.6 grams of water, 6.4 grams of carbohydrates, 1.9 grams of protein, 0.2 grams of fat, and 1.2 grams of fibre (Gopalan et al., 2007). Okra also offers significant antioxidant properties, carotenoids, and flavonoids, it possesses healing properties against diabetes, hyperlipidemia, microbes, ulcers and neurodegenerative diseases (Uwiringiyimana et al., 2024). It thrives as a warm-season crop and is abundantly grown in Bangladesh during summer. For optimal growth, flowering, and pod development, okra requires a well-drained, fertile, organic-matter- and nutrient-rich soil with a preferred pH range of 6.6 to 8.0. Germination typically occurs above 16°C, and a monthly temperature range between 21°C to 30°C is considered ideal (Tindall, 1983). The okra crop is classified as sensitive to salinity, whose salinity threshold is below 1.3 dS/m in the saturation extract (Costa et al., 2022).

Cultivating okra can be challenging in the context of saline soil due to the adverse effects of high salt concentrations on plant growth and yield. Elevated salt levels interfere with essential physiological processes, like water status, ion balance, mineral nutrition, photosynthetic efficacy and stomatal behaviour, resulting in reduced growth and production (Munns, 1993). Salinity stress delays germination, generates ROS and oxidative stress, causing macromolecule damage and lowering okra development and pod yield (Haq et al., 2023).To manage crops grown in saline soils, several approaches can be employed: (i) selecting crop varieties that can tolerate high salinity, (ii) adjusting planting methods, (iii) using suitable irrigation systems, (iv) preparing the land appropriately, (v) implementing leaching processes, and (vi) applying special treatments like soil amendments. These methods can be implemented individually or in combination to enhance soil and plant conditions (Tejada et al., 2006; Hashan et al., 2023).

Biochar, a soil amendment, is a form of black carbon created by heating biomass in an oxygen-deprived or low-oxygen environment, resulting in a lack of complete combustion. When used to enhance soil quality and crop yield, it is known as biochar, whereas when it is used to generate energy, it is referred to as charcoal. (Lehmann & Joseph, 2009; Lehmann, 2007). Biochar technology is especially advantageous for soils with minimal levels of organic carbon. (Dar et al., 2019). Despite variable outcomes depending on soil type, biochar feedstock, pyrolysis temperature, and environmental factors, biochar as a soil amendment offers several potential benefits. These include increased availability and uptake of nutrients by plants (Sigua et al., 2015), enhanced fertilizer use efficiency (Schulz & Glaser, 2012), reduced leaching losses of nutrients and fertilizer requirements (Ding et al., 2016), improved various soil physical properties like water holding capacity, porosity, aeration, bulk density, infiltration rate, hydraulic conductivity, and aggregate stability (Mukherjee & Lal, 2013; Atkinson et al., 2010), increased liming effect and base saturation on acidic soils (Wang et al., 2014), and reduction of salinity, drought, and heat stresses' impact on plant growth and soil properties (Ali et al., 2017; Drake et al., 2016; Fahad et al., 2016). Due to its carbon-rich and stable nature, biochar can store carbon and capture soil nutrients that crops have not received (Li and Tasnady, 2023). Biochar improves soil pH, cation exchange capacity, and organic carbon content by 46%, 20%, and 27%, respectively, especially in coarse and fine-textured soils (Singh et al., 2022; Gairhe, 2024). The high surface area and CEC of biochar (soil amendment) make it ideal for saline soils since it absorbs salt well (Khatun et al., 2024).

Despite substantial studies on the effects of biochar on a variety of crops, including those mentioned in the literature, a significant knowledge gap exists regarding its influence on okra growth and yield. To address this gap, the present study was conducted to evaluate the effect of biochar on okra production in saline soil. While several research works related to this topic have been conducted worldwide, there is a lack of specific studies in the coastal region of Bangladesh. Consequently, the purpose of this study was to figure out the potential of biochar in enhancing okra growth as well as yield under soil salinity stress. The research evaluated the effect of biochar application on okra's growth as well as yield in saline conditions. The investigation thoroughly examined the specific effects of biochar on okra plants, offering valuable information on optimising yield and encouraging the cultivation of this valuable crop in saline-affected areas. From this research, one can have valuable insights that can contribute to existing knowledge and promote sustainable agricultural practices.

2. MATERIALS AND METHOD

The experiment was conducted at the Agricultural Research Field (22.7916° N, 91.1028° E) of NSTU (Figure 1). To conduct the research, Green Finger F_1, a hybrid variety of Okra from Lal Teer Seed Ltd. was used as the plant material, and biochar from the Christian Commission for Development in Bangladesh (CCDB), Mirpur 10 Roundabout, Dhaka 1216, was used as treatment.

Chemical properties of the soil and biochar

The physical and chemical properties of the soils of the experimental field and the applied biochar are presented in Table 1. Data on soil properties are obtained from the Soil Resource Development Institute (SRDI) in Noakhali and the biochar properties are obtained from CCDB.

Treatments and layout of the experiment

The research was set up with three replications utilizing a Randomized Complete Block Design (RCBD). During land preparation, the recommended dosage of urea (150 kg/ ha), TSP (112 kg/ ha), MOP (75 kg/ ha) and cow dung were applied. Three biochar doses (T_1: Control, T_2: 2 tons/ha, and T_3: 4 tons/ha) were applied under non-saline conditions. In total, the research had 9-unit plots of 1x1 m^2 area, three plots per block. The seedlings were planted at a 45cm x 45cm distance with a 0.50 cm gap between each plot. The treatments were randomly assigned within a plot.

Sowing and Saline solution applications

The okra seeds were sown following the line-sowing method. After placement of seeds in pits, seeds were covered with soil, followed by light pressure by hand. After sowing, each plot was irrigated properly to ensure consistent soil moisture. Then, 0.1 M NaCl solution was prepared and applied to each plot in the field uniformly after the seed emergence.

Data collection

Data were taken from three plants that were selected at random from each plot, with the parameters as follows: Plant Height (cm), Number of Leaves Per Plant, Lamina Length (cm), Petiole Length (cm), Days of 1st Flowering (DAS), Chlorophyll Content (μmol m^2), Single Fruit Length (cm), Single Fruit Diameter (cm), Weight of a Single Fruit (gm), Number of Fruits Per Plant, Yield Per Plot (gm), and Yield (ton/ha). The parameters were assessed using a measuring tape and weighing machine in accordance with the specified requirements, while the chlorophyll content was quantified using a chlorophyll meter (SPAD-502Plus KONICA MINOLTA, Japan) from randomly selected plant leaves of each plot.

Statistical analysis

The analysis of variance, Tukey's pairwise comparison and correlation studies were conducted with the assistance of the Minitab 21 statistical software tool. Graphs were generated through Microsoft Excel - 2016.

3. RESULTS

The study found that the application of biochar significantly improved various plant growth parameters and yield-contributing factors. In contrast, the control treatment (without biochar) showed lower performance. The analysis of variance (ANOVA) for all the characters showed highly significant ($P \leq .001$) variation among treatments except WSF and CC (Table 2). WSF showed a significant difference at $P \leq .01$ and CC at $P \leq .05$.

Effect of Biochar on Plant Growth Parameters:

The analysis showed that biochar has a significant impact on growth parameters e.g. plant height, the number of leaves per plant, lamina length (cm), and petiole length (cm) of okra plants in saline soil (Figure 2). It was found that the parameters showed a positive response with the increased doses of biochar application. The data for growth parameters were recorded at 30, 45 and 60 DAS respectively. According to the result, the highest plant height (Figure 2a) (18 cm, 36.67 cm, and 72.67 cm), leaf number (Figure 2b) (10.33, 14.33, and 16.33), leaf length (Figure 2c) (10.67cm, 14.00cm, and 18.73cm), and petiole length (Figure 2d) (7.23cm, 12.77cm, and 15.50cm) at 30, 45 and 60 DAS were recorded from T_3 which is followed by T_2. On the contrary, the lowest plant height (Figure 2a) (12.33cm, 24.67cm, and 53.83cm), leaf number (Figure 2b) (5.67, 8.00, and 11.33), leaf length (Figure 2c) (7.00cm, 10.33cm, and 13.53 cm) and petiole length (Figure 2d) (4.70cm, 9.27cm, and 11.63cm) were recorded from T_1.

Effect of Biochar on Days to Flowering:

The result showed that days to the first flowering of okra in saline soil differed significantly as a consequence of biochar doses. The minimum days (43.33 days) required to flower were found in T_3, followed by T_2 (46.33 days), while the T_1 treated plot took the maximum (47.33 days) days to flower (Figure 3a).

Effect of Biochar on Chlorophyll Content:

The effect of biochar on the chlorophyll content of okra leaves was evaluated as well, and it was found that it significantly increased the chlorophyll content. The highest amount of chlorophyll content in leaves (54.43 µmol m^2) was observed from the T_3 treated plots, followed by T_2 (49.73 µmol m^2), and the lowest amount of chlorophyll content in leaves (46.17 µmol m^2) was found in T_1 (Figure 3b).

Effect of Biochar on Yield-contributing Parameters:

In this study, it was found that the use of biochar has an impressive effect on the yield contributing traits like the number of fruits per plant, single fruit length (cm), single fruit diameter (cm), and weight of a single fruit (gm) of okra in saline soil (Figure 4).

The maximum number of okra fruits per plant (10.67) (Figure 4a), single fruit length (14.67 cm) (Figure 4b), single fruit diameter (5.93 cm) (Figure 4c), and weight of a single fruit (16.13 g) (Figure 4d) was found in T_3 followed by T_2, while T_1 had the lowest number of okra fruits per plant (5.4) (Figure 4a), single fruit length (10.7 cm) (Figure 4b), single fruit diameter (5.0 cm) (Figure 4c), and weight of a single fruit (11.2 g) (Figure 4d).

Finally, in terms of yield the maximum yield (6.87 tons/ha) was obtained in plots treated with T_3, followed by T_2 (4.67 tons/ha), while T_1 had the lowest yield (2.42 tons/ha) (Figure 5).

Correlation among growth and yield contributing parameters

The correlation matrix **(Figure 6)** shows the relationships between different plant characteristics and yield-related variables. Overall, there are strong positive correlations among plant growth parameters (plant height, number of leaves per plant, leaf length and petiole length), chlorophyll content and yield contributing traits (single fruit length, single fruit diameter, weight of a single fruit, number of fruits per plant, yield). This suggests that plants with higher chlorophyll content, larger fruits, more fruits per plant, taller height, and more leaves tend to have better overall productivity. On the other hand, the variable representing days of 1st flowering exhibits strong negative correlations with other variables, implying that early flowering is associated with higher productivity. This correlation matrix provides valuable insights into the interdependencies of plant characteristics and yield, which can be useful for agricultural practices, breeding programs, and crop improvement strategies.

4. DISCUSSIONS

Soil salinity poses a significant challenge for agricultural crop production. especially in coastal regions elevated salt levels raise osmotic pressure, hindering water absorption by plant roots (Haque et al. 2024; Shahid et al., 2011). This stress is toxic to plant cells and disrupts their ion balance as well as their production. (Abbas et al., 2014). Because of this salinity issue, okra production is encountering the same scenario, leading to decreased yields. To ameliorate the effects of salt stress, biochar was employed as a soil conditioner at different levels. Our study found that applying biochar had a significant effect on all the traits we examined (Table 2), indicating its ability to lessen the harmful effects of salt stress.

Effect of Biochar on Plant Growth Parameters

Salinity possesses a significant detrimental effect on the growth parameters of Okra (Haque et al. 2024). In this study, it was observed that all the studied growth parameters (Plant height, Number of Leaves Per Plant, Lamina Length and Petiole Length) showed improved performance in biochar-treated plots compared to control plots. It was also found due to the increased dosage of biochar performance of T_3 was better than T_2. Because the application of biochar can improve the condition of saline soil (Huang et al., 2019). Adding biochar in saline soil can enhance the availability of essential mineral nutrients and improve soil characteristics, including bulk density, hydraulic properties, aggregate structure, ion exchange capacity, and microbial activity, making the soil more suitable for plant growth **(**Lehmann et al., 2011, Hossain et al., 2020, Hui et al., 2021) which leads to better performance in terms of growth parameters of okra. Several researcher's work also indicates that the application of biochar improved plant growth parameters in saline conditions, (Adeyemi et al., 2022; Elshaikh et al., 2018; William and Qureshi, 2015; DeLuca et al., 2009).

Effect of Biochar on Days to 1st Flowering

In saline soil, ion toxicity reduces water potential in okra roots, hindering nutrient uptake and delaying development (Cramer, 2003; Tester & Davenport, 2003). Control plots showed delayed flowering, while biochar-treated plots had faster development and earlier flowering. In an experiment carried out by Ali et al., (2017) it was also found that biochar can alleviate the negative effects of salt stress flowering days. By improving soil structure, reducing salinity, enhancing nutrient availability, supporting beneficial microbial activity, and regulating pH, biochar mitigates the stresses associated with saline soils and fosters conditions that promote timely and robust flowering in okra plants.

Effect of Biochar on Chlorophyll Content

Salinity stress damages the photosynthetic process in leaves, reducing chlorophyll content, causing chlorosis, and leading to early leaf senescence (Jabborova et al., 2023). In our study, biochar application significantly mitigated salt stress, enhancing chlorophyll content. Similarly, William and Qureshi (2015) found that biochar increased chlorophyll content in vegetables under saline conditions. Biochar attracts additional Na^+ in saline soils, releases nutrients, and lowers osmotic stress by increasing water-holding capacity and CO_2 absorption. This leads to improved photosynthesis, stomatal conductance, and transcription rates (Ibrahim et al., 2021).

Effect of Biochar on Yield-contributing Parameters

In our study, we observed that biochar had a significantly positive impact on various parameters influencing the yield of okra, including Single Fruit Length, Single Fruit Diameter, Weight of a Single Fruit, Number of Fruits Per Plant, and overall Yield. Compared to conditions with salt stress, plots treated with increased dosages of biochar exhibited notably improved performance across these metrics. These findings are consistent with previous research (Khatun et al. 2024; Acharya et al., 2022; de Freitas et al., 2020; Riaz et al., 2018), which also highlighted the beneficial effects of biochar on crop yield. Salt stress negatively affects plants by causing oxidative stress, reducing leaf water content, nutrient uptake, photosynthesis, and overall growth and yield (Gupta & Huang 2014; Noman et al., 2015; Siddiqui et al., 2015). However, biochar treatments mitigate these effects by enriching soil nutrients (N, P, K, humus) and enhancing soil enzyme activities (catalase, invertase, urease). Additionally, they improve physiological factors such as leaf area, photosynthesis, transpiration, and chlorophyll content, ultimately enhancing crops growth and yield (Huang et al., 2022).

Correlation among growth and yield contributing parameters

Yield is a complex polygenic characteristic with numerous associated component traits. Consequently, it is essential to comprehend the nature of the interaction between and among these yield-related parameters by evaluating the correlation coefficient to increase yield. The correlation analysis was conducted to observe the association between the studied growth and yield contributing parameters in these saline conditions. It was found that all the growth parameters are positively correlated with yield-contributing parameters. However, days to 1st flowering showed a negative association with all other traits, which indicates the negative influence of delayed blooming on the growth and yield of okra. Mohammed et al. (2020) also found similar association while evaluating 36 okra cultivars for different morphological parameters.

5. CONCLUSION

This study demonstrated the transformative potential of biochar in enhancing okra growth and yield in saline soil. Diverse growth parameters, including plant height, leaf count, lamina and petiole length, and the initiation of flowering, were appreciably enhanced by the application of biochar. In addition, the research showed that biochar had a beneficial effect on chlorophyll quantity, which indicates that it improved photosynthetic efficiency and stress tolerance in okra plants that were subjected to salinity stress. Positive effects were also seen in the okra’s yield and yield-contributing characteristics compared to control conditions. These findings underscore the potential of biochar as a long-lasting and effective solution to mitigate the negative effects of soil salinity on crop performance. Further research is needed to integrate biochar application in agricultural practices, which holds great promise for ensuring food security and supporting resilient farming systems in especially the salt-affected coastal regions of Bangladesh.

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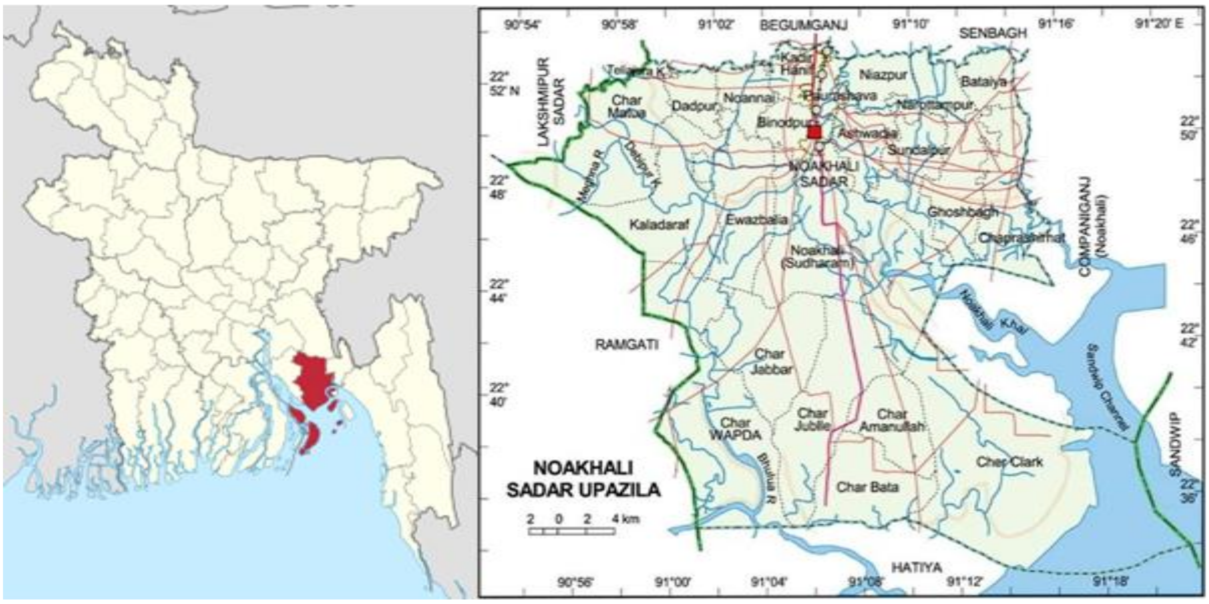

Figure 1: Location of Noakhali District in Bangladesh map (left) and the location of the experimental site marked with a red box in Noakhali district map (right).

Table 1: Characteristics of soil samples analyzed by SRDI, Noakhali

A. Physical properties of the initial soil (0-15 cm depth)		B. Chemical characteristics of soil and Biochar		
Constitutions	**Results**	**Constitutions**	**Soil**	**Biochar**
Sand	21 %	pH	7.5	7.8
Silt	65 %	Organic matter (%)	0.109	4.7
Clay	14 %	Total nitrogen (%)	0.101	1.42
Soil textural class	Silt Loam	Available phosphorus (ppm)	12.00	18
Particle density	2.60 (g/cc)	Electrical conductivity (dS/m)	4.32	
Bulk density	1.35 (g/cc)	Exchangeable potassium (me %)	0.014	0.26
Porosity	46.67 %			

Table 2: Analysis of Variance

SOURCE	df	PH	LN	LL	PL	DF	CC	FN	SFL	SFD	WSF	Y
Days	2	5434.84***	84.70***	125.18***	142.57***	-	-	-	-	-	-	-
Treatment	2	335.29***	87.15***	44***	25.45***	30.11***	51.57*	17.33***	13.44***	0.68***	19.27**	14.9058***
Replication	2	1.51	1.815	0.18	0.351	0.111	4.834	1	0.09	0.00778	0.0878	0.0105
Error		7.46	1.626	0.46	0.569	0.4444	0.4878	0.3333	0.1233	0.004444	0.4261	0.112

df: degree of freedom, PH: Plant Height (cm), LN: Number of Leaves Per Plant, LL: Leaf Length (cm), PL: Petiole Length (cm), DF: Days of 1st Flowering (DAS), CC: Chlorophyll Content (μmol m^2), FN: Number of Fruits Per Plant, SFL: Single Fruit Length (cm), SFD: Single Fruit Diameter (cm), WSF: Weight of a Single Fruit (gm), Y: Yield (ton/ha)

Note: *, ** and *** indicates significant at 5%, 1% and 0.1% level of probability respectively

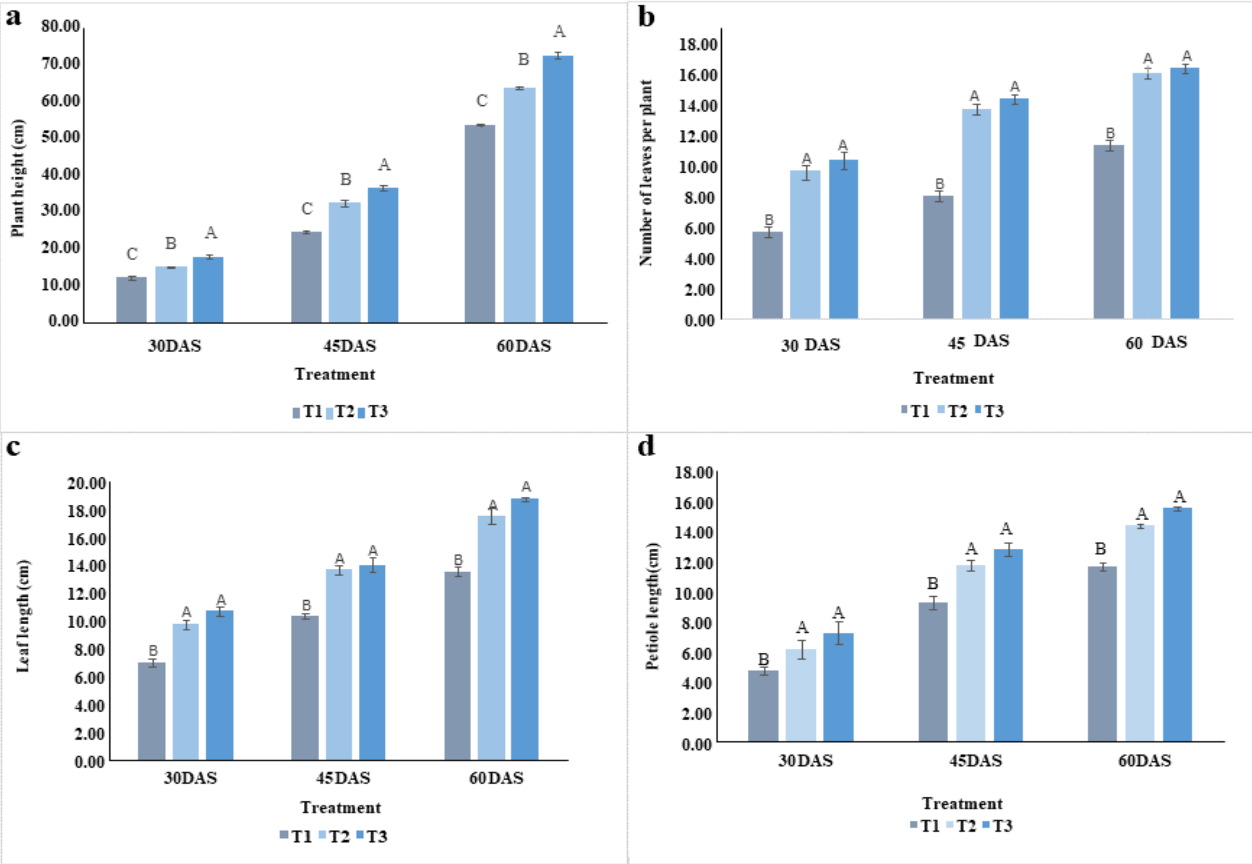

Figure 2: Effect of biochar on (a) plant height, (b) number of leaves per plant, (c) leaf length, and (d) petiole length at 30, 45, and 60 DAS. The vertical bars in the graph indicate the standard error of the mean for each variable. The different alphabets indicate a significant difference in data at the 5% level of significance.

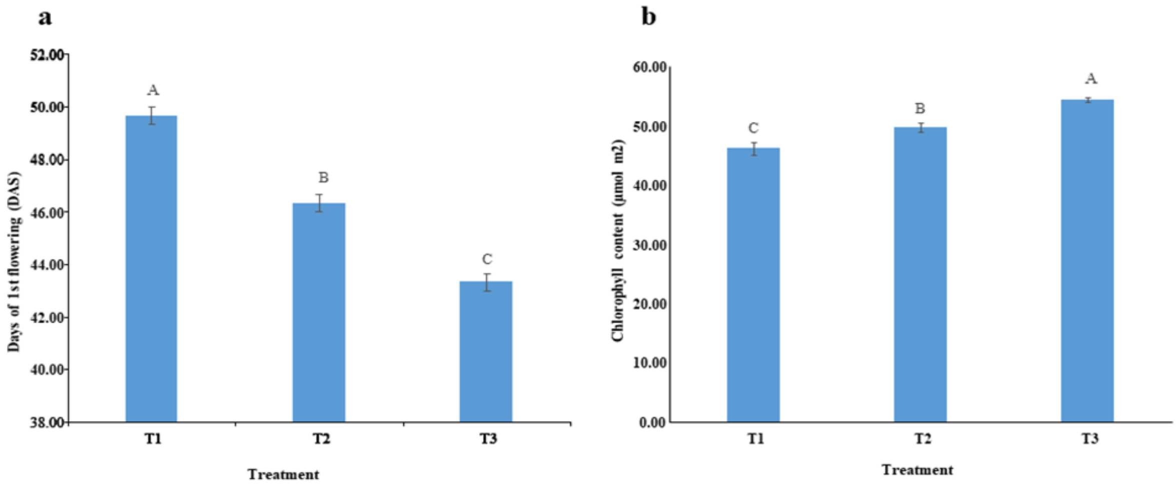

Figure 3: Effect of biochar on (a) days of first flowering, and (b) chlorophyll content. The vertical bars in the graph indicate the standard error of the mean for each variable. The different alphabets indicate a significant difference in data at the 5% level of significance.

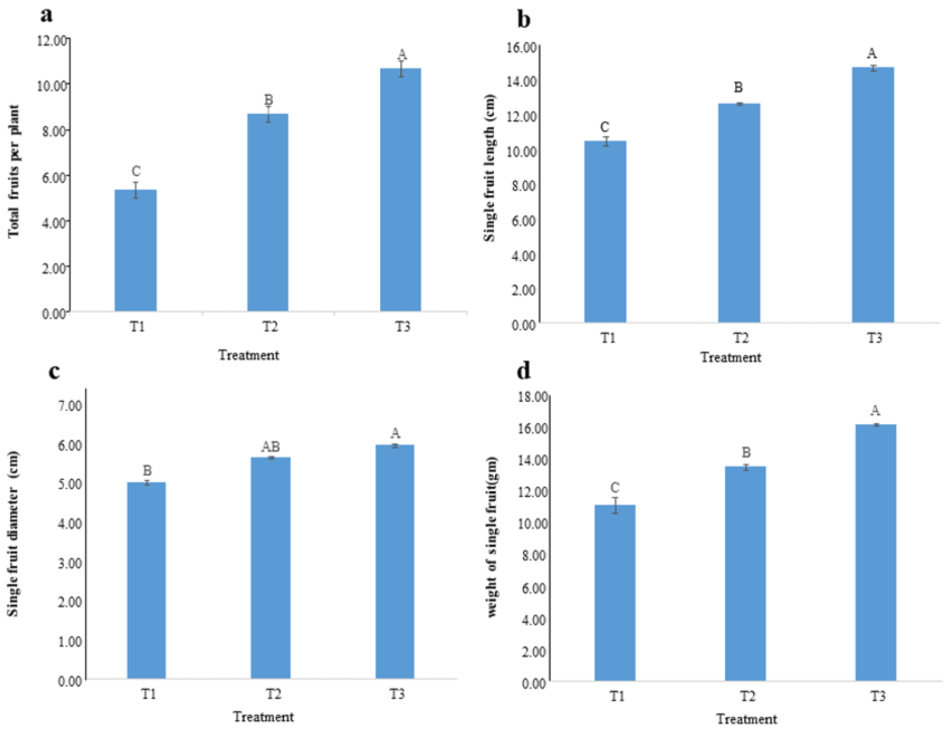

Figure 4: Effect of biochar on (a) total fruit per plant, (b) single fruit length, (c) single fruit diameter, and (d) weight of single fruit. The vertical bars in the graph indicate the standard error of the mean for each variable. The different alphabets indicate a significant difference in data at the 5% level of significance.

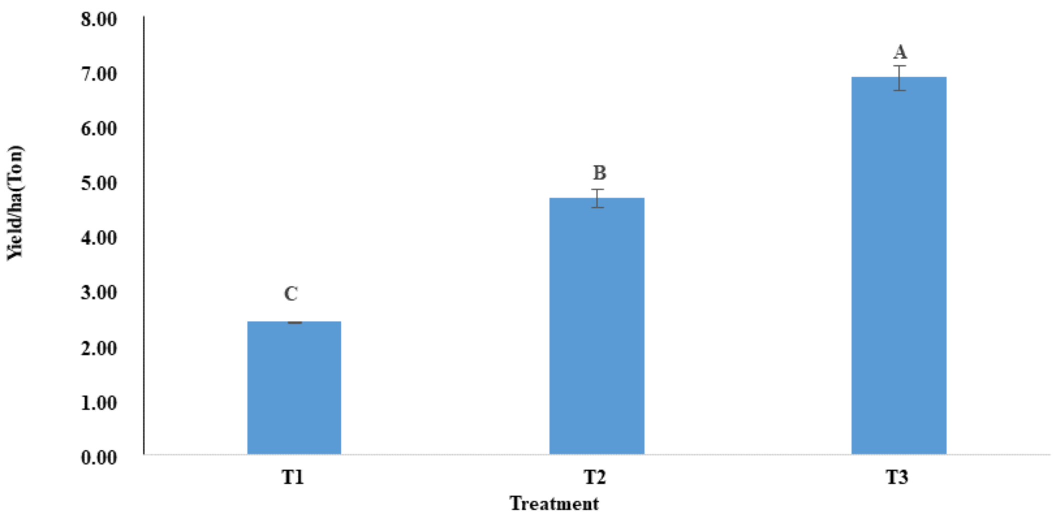

Figure 5: Effect of biochar on yield per ha. The vertical bars in the graph indicate the standard error of the mean for each variable. The different alphabets indicate a significant difference in data at the 5% level of significance.

	CC	SFL	SFD	WSF	FN	DF	Y	PH	LN	LL
SFL	0.92									
SFD	0.876	0.973								
WSF	0.891	0.986	0.965							
FN	0.827	0.912	0.948	0.885						
DF	-0.932	-0.987	-0.975	-0.987	-0.884					
Y	0.934	0.979	0.958	0.968	0.925	-0.971				
PH	0.918	0.966	0.966	0.957	0.951	-0.963	0.984			
LN	0.816	0.878	0.942	0.842	0.916	-0.881	0.854	0.863		
LL	0.909	0.921	0.944	0.886	0.904	-0.929	0.912	0.924	0.933	
PL	0.89	0.864	0.87	0.79	0.897	-0.841	0.895	0.89	0.884	0.888

PH: Plant Height (cm), **LN**: Number of Leaves Per Plant, **LL**: Leaf Length (cm), **PL**: Petiole Length (cm), **DF**: Days of 1^{st} Flowering (DAS), **CC**: Chlorophyll Content (µmol m^2), **FN**: Number of Fruits Per Plant, **SFL**: Single Fruit Length (cm), **SFD**: Single Fruit Diameter (cm), **WSF**: Weight of a Single Fruit (gm), **Y**: Yield (ton/ha)

Figure 6: Correlation among growth and yield contributing parameters at P<0.05.