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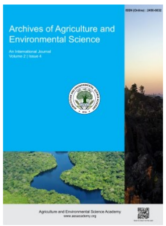

ORIGINAL RESEARCH ARTICLE

Effect of various biochar on selected soil properties and agronomical parameters of okra (*Abelmoschus esculentus* L.) at Rupandehi, Nepal

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ABSTRACT

Biochar is rich in carbon and obtained by carbonization of biomass heated at 300-1000°C under limited oxygen which improves the soil properties and yield of various crops. This study aimed to determine the changes in soil properties and agronomical characteristics of okra by biochar prepared from different feedstock. The research was conducted in randomized blocks and replicated thrice, with treatments; control, wood ash (WA), rice husk biochar (RHB), bamboo biochar (BB), Ashoka leaves biochar (ALB), coconut husk biochar (CHB), and sawdust biochar (SB), applied at 18 t/ha. Biochar-incorporated soil and the biochar were analyzed for pH, electrical conductivity, nitrogen, P_2O_5, K_2O, and organic matter, and the soil for bulk density, particle density, and porosity. Agronomical parameters like plant height, fruit size, and yield were also recorded. The biochar incorporation modified the soil's chemical properties and significantly decreased bulk and particle density. The highest reduction of 10.9% in bulk density (1.22gm/cm^3), and 4.4% in particle density (2.39gm/cm^3) were observed in ALB and SB incorporated soil respectively. ALB (50%) followed by BB (49%) showed a significant increase in soil porosity compared to the control (45.18%). BB (15.7cm) significantly increased the fruit size compared to the control (14.06cm) followed by ALB (15.5cm). ALB (8.16t/ha) significantly increased the yield of okra relative to control (7.82t/ha). The findings suggest the use of ALB and BB to improve soil properties and yield in the long run.

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INTRODUCTION

Okra (*Abelmoschus esculentus* L. Moench) is a member of the Malvaceae family and is one of the most widely cultivated vegetables globally (Raj *et al*., 2020). Okra is primarily known for its edible, immature green fruits (Al-Shawi *et al*., 2021). Okra yielded 110565 Mt overall and 11.54 Mt/ha average production on 9584 hectares of land in Nepal in 2021-2022 (MoALD, 2023). Okra pods are high in nutrients, low in calories, and a good source of dietary fiber (Romdhane *et al*., 2020). These pods contain approximately 90% water, 7% carbohydrates, 2% protein, and 2% fiber (Al-Shawi *et al*., 2021). The dried seeds of okra are a source of oil, protein, vegetable curd, and a coffee additive or substitute, containing about 18–20% oil and 20–23% crude protein (Murovhi *et al*., 2020). Chemical fertilizers are used more extensively to increase yields at present, but they come with several drawbacks, including high costs, unavailability, and environmental issues (Gyanwali *et al*., 2023; Rehman *et al*., 2018a). Consequently, it is necessary to find some other, more affordable, and environmentally friendly sources of nutrients (Rehman *et al*., 2017; Rehman *et al*., 2018b). With fewer environmental risks, higher crop yields, and superior soil properties, biochar offers a lot of potential applications in agriculture (Riaz *et al*., 2018).

Biochar is the solid by-product of the thermochemical conversion of biomass, such as pyrolysis and gasification, in an environment with either very little or no free oxygen (Wang & Wang, 2019). Several thermochemical techniques are employed for biochar production, including pyrolysis, hydrochemical carbonization, gasification, flash carbonization, and torrefaction, with pyrolysis being the most commonly utilized method (Ng *et al*., 2017). The byproducts of pyrolysis are biogases and bio-oils, which can be recycled to provide energy. The amount and quality of biochar can be influenced by several variables, including feedstock, kiln design, processing time, and pyrolysis temperature (Riaz *et al*., 2018). Biochar is typically produced from various organic sources, such as municipal waste, green waste, food waste, agricultural residues, and forestry waste (Beusch, 2021). Biochar contains a lot of refractory carbon, hence it can remain stable in soil for hundreds to thousands of years (Riaz *et al*., 2018). Adding biochar to soil has been suggested as a way to improve agricultural soil fertility and reduce human-caused climate change at the same time (Lehmann *et al*., 2021).

Biochar can decrease the demand for fertilizer while retaining agricultural yield since it can give nutrients that plants can absorb and improve the soil's capacity to hold water and solutes (Liu *et al*., 2021). Biochar can serve as a source of nutrients, including potassium (K), phosphorous (P), nitrogen (N), and other trace elements that were naturally present in the original feedstock (Purakayastha *et al*., 2019). To enhance soil fertility and agronomic qualities of different crops, particularly in harsh environments, biochar is regarded as a safe soil additive (Abbas *et al*., 2017; Ali *et al*., 2017). Biochar application to soil can greatly raise the organic matter content of the soil, improving the quality of the soil because it is a carbon-rich material (Bolan *et al*., 2022). The application of biochar has shown positive effects, including an increase in soil pH, cation exchange capacity, and organic carbon content by 46%, 20%, and 27%, respectively whose effects are more pronounced in coarse and fine-textured soils (Singh *et al*., 2022; Yang *et al*., 2019). Biochar application to soil also has the benefit of reducing very low water pressure, which in turn enhances infiltration rate and percolation (Chen *et al*., 2022). Biochar is effective in increasing soil ventilation and water-holding capacity (Dong *et al*., 2017). In addition, biochar exhibits resilience against microbiological degradation and can provide a sustained release of plant nutrients, therefore improving soil fertility over an extended time (Leng *et al*., 2019). The introduction of biochar into the soil as exogenous carbon not only contributes to the soil carbon pool but also affects soil greenhouse gas emissions (Shi *et al*., 2022). In both acidic and alkaline soils, low-temperature biochar production can enhance crop yields and nutrient availability, while high-temperature biochar production may promote long-term soil carbon sequestration and improve degraded soil (Al-Wabel *et al*., 2018).

The availability of a wide range of biomass allows for the creation of diverse forms of biochar, which results in varying impacts on soil characteristics and agricultural productivity (Ji *et al*., 2022). Based on this, determining which raw material is best to ensure the highest productivity requires first evaluating each form of biochar and its impact on plant and soil health (Farias *et al*., 2020). Biochar related research is very rare in the context of vegetable production in Nepal. The majority of experiments on biochar have been conducted in a greenhouse and not in field conditions. Additionally, not much research has been done on okra plants with the application of biochar from various feedstocks in Nepal. Therefore, we evaluated the effect of biochar prepared from various feedstock on some physical, chemical properties of soil and agronomical parameters of okra in the Terai region of Nepal.

MATERIALS AND METHODS

Plant materials

Okra (*Abelmoschus esculuntus* L.) of the Arka Anamika variety was used for the experiment. Priming of seeds for 24 hours and shade drying for 12 hours was done before sowing.

Experimental site and location

The field experiment was conducted at the horticulture farm of the Institute of Agriculture and Animal Science (IAAS), Paklihawa campus of Rupandehi district from March 2023 to July 2023. The coordinate of this location is 27°29'05.1"N and 83° 27'04.2"E. This site is located in the inner Terai region of the Lumbini province of Nepal.

Experimental design

The experiment was conducted in a Randomized Complete Block Design (RCBD) with three replications and 7 treatments each. The three replications were kept 1 m apart. The area of each plot was maintained at 2m*1.5m (3m^2) and the plots were kept 0.5 m apart in each replication. Plant-to-plant spacing within a plot was maintained at 0.3 m and row-to-row spacing was maintained at 0.4 m. The application of biochar was done 7 days before the sowing of the seed and applied about 0.1 m deep into the soil to avoid the loss of biochar from wind and heavy rainfall.

Treatment details

The experiment includes 7 treatments, out of which 6 are biochar prepared from the different origins of feedstock and 1 is control (without biochar application). The biochar treatments were applied as 18 tons/ha. The substances used for biochar production were focused on six feedstocks and the treatments were:

T1: Wood Ash (WA)
T2: Rice Husk Biochar (RHB)
T3: Bamboo Biochar (BB)
T4: Ashoka Leaf Biochar (ALB)
T5: Coconut Husk Biochar (CHB)
T6: Sawdust Biochar (SB).
T7: Control

The collected feedstocks were dried in the shade to remove excess moisture. Then the biomass was subjected to pyrolysis: the thermochemical decomposition of organic material at elevated temperatures (Around 450 to 500° Celsius) in the absence of oxygen. The biomass was combusted excluding oxygen in a stainless-steel drum, specially designed to prepare biochar.

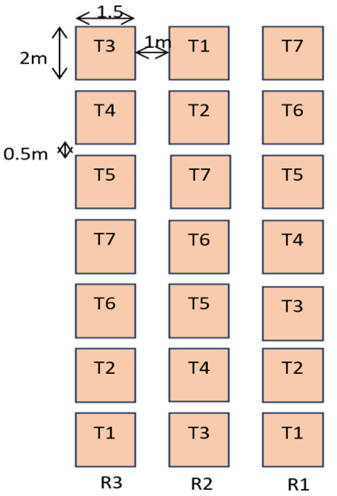

Figure 1. *RCBD experimental layout.*

Table 1. Characterization of biochar (BC) and Experimental soil.

Parameters	pH	EC (µS/ cm)	OC (%)	N (%)	P_2O_5 (%)	K_2O (%)
WA	7.2	1187	24.88	0.11	0.03	0.65
RHB	7.8	1105	31.79	1.12	0.44	2.15
BB	7.6	1129	49.91	0.89	0.24	1.08
ALB	7	1274	27.84	1.77	0.34	3.06
CHB	8	1072	24.71	0.62	0.04	1.35
SB	7.4	1060	52.9	0.96	0.11	0.70
Process used	pH meter	EC Meter	Loss on Ignition (550°C) (Angelova *et al.*, 2019)	Kjeldahl Digestion Distillation Method (Kumar *et al.*, 2017)	Wet Digestion (Vanadomolybdate method) (Novo *et al.*, 2018)	Wet Digestion (Flame Photometric Method) (Kumar *et al.*, 2017)
Experimental soil	7.2	951	3	0.089	27.2 kg/ha	188.16 kg/ha

WA: Wood ash, RHB: Rice husk biochar, BB: Bamboo biochar, ALB: Ashoka leaf biochar, CHB: Coconut husk biochar, SB: Sawdust biochar, EC: Electrical Conductivity, OC: Organic Carbon.

Biochar characterization: The biochar samples of 250g each were sent to Agricultural Technology Centre (ATC), Kupondole-01, Lalitpur, Nepal for their characterization and details of pH, EC, OM, N, P, and K were obtained. The different processes involved during the characterization along with the data obtained are shown (Table 1).

Cultivation practices

Fertilizer application: Chemical fertilizer like Nitrogen, Phosphorus, and potash was used at the ratio of 100:50:50 kg NPK / hectares. Basal dose of nitrogen (Urea) 50kg and a full dose of phosphorus and potash were applied into the field. The remaining 50kg of urea was top-dressed after the 30 days of sowing of okra. Farmyard manure was also applied during field preparation at the rate of 8 tons/hectares.

Intercultural operations: Irrigation was done at regular intervals in the field as necessary. The pipeline was used for irrigation. For the control of weeds manual weeding and hoeing were done at regular intervals.

Harvesting: Multiple harvestings were done at regular intervals of 3 days. A total of 10 harvests were taken within 30 days from the first picking. The maturity for harvest was determined subjectively.

Data observations: Recording of soil pH, EC, nitrogen, phosphorus, potassium, and organic matter content was taken for the experiment. A total of 21 soil samples were taken after harvesting from each plot. Soil samples were collected from a depth of 0.2 m using a tube auger. It was then shade-dried, ground, sieved through a 2 mm sieve, and then subjected to determine their major nutrient status for the experimental site. Chemical and physical characteristics of experimental soil were determined by using different methods. 5 Sample plants from each plot were taken to record the agronomic parameters: plant height, fruit size, and yield (Table 2).

Statistical analysis

All the recorded data was compiled using MS Excel 2010 and analyzed through R-studio version 2023.09.0+463 (Rstudio Team, 2021).

RESULTS AND DISCUSSION

Soil chemical properties

pH: There was no significant association between the biochar and soil chemical properties, however, there was a modification in all observed parameters as compared to the control. The highest increment in pH of 6.8% and 5.1% was observed in CHB (7.96) and BB (7.82) in comparison to control (7.45). Previous study has found that there is a direct correlation between pH and the pyrolysis temperature under biochar production thereby increasing soil pH upon application (Hossain *et al.*, 2020). We found the highest pH (8) in CHB compared to other

Table 2. Data observations and methods used.

Observations	Analysis method
pH	pH meter
EC	EC meter
OM	Walkley- Black Method (GLOSAN, 2019)
N	Kjeldahl method (Kumar *et al*., 2017)
P	Modified Olsen's bicarbonate method (Olsen *et al*., 1954)
K	Flame photometer method (Kumar *et al*., 2017)
Bulk Density	Core method: Core sampler (Kannan *et al*., 2021)
Particle density	Pycnometer method (Santos *et al*., 2022)
Porosity	$1 - \frac{\text{Bulk Density}}{\text{Particle density}} \times 100\%$
Plant Height	Average of 5 random samples per plot (Measuring scale)
Fruit Size	Average of 5 random samples per plot (Measuring scale)
Yield	Weighing Balance

EC: Electrical Conductivity, OM: Organic Matter, N: Nitrogen, P: Phosphorus, K: Potassium.

Table 3. Effect of biochar treatments on soil chemical properties.

Treatments	pH	EC	OM (%)	N (%)	P_2O_5 (kg/ha)	K_2O (kg/ha)
Control	7.45±0.174	978.6±58.8	3.02±0.05	0.092±0.006	31.5±1.31	196.5±18.2
WA	7.69±0.062	1107±28.8	3.24±0.12	0.081±0.01	34.7±1.98	204.4±6.63
RHB	7.83±0.07	1040±27.1	3.39±0.12	0.064±0.003	33.5±0.87	198.7±20.3
BB	7.82±0.01	1059±36.9	3.52±0.1	0.092±0.011	35.4±1.49	199.4±3.08
ALB	7.55±0.22	1164±90.9	3.39±0.06	0.089±0.004	34.6±0.14	208.5±24.1
CHB	7.96±0.16	1007±94.1	3.39±0.07	0.099±0.01	33.8±0.29	200.9±1.23
SB	7.7±0.16	995±27	3.41±0.07	0.094±0.012	34.9±1.7	206.8±4.7
CV (%)	3.43	9.3	4.76	17.81	6.9	12.6
LSD	0.471	174.07	0.283	0.027	4.21	45.6
Grand Mean	7.71	1050.23	3.34	0.087	34.1	202.2

WA: Wood ash, RHB: Rice husk biochar, BB: Bamboo biochar, ALB: Ashoka leaf biochar, CHB: Coconut husk biochar, SB: Sawdust biochar, CV: Coefficient of variation, LSD: Least significant difference, EC: Electrical Conductivity; OM: Organic Matter.

feedstuffs biochar. According to (Syuhada *et al*., 2016), the alkaline pH of coconut husk-like biochar (9.73) is due to ash produced during the pyrolysis process. The increased amount of alkaline earth metals and decreased amount of acidic organic moieties is another reason for increasing the pH of biochar (Gezahegn *et al*., 2019). Biochar can quickly release base cations like Ca^{2+}, Mg^{2+}, and K^{+} to the soil solution and lower H^{+} and Al/Ca ratio due to its alkaline nature, which increases soil pH (Al-Sayed *et al*., 2022; Cornelissen *et al*., 2018). Additionally, biochar contains reactive pH-dependent functional groups like phenolic (OH) and carboxylic acid (COOH), which may raise the pH of the soil (Al-Sayed *et al*., 2022). Similar relationship between biochar and soil pH was obtained in previous findings (Dahal *et al*., 2021; Farias *et al*., 2020).

Electrical conductivity (EC): The result revealed that the electrical conductivity of soil increased upon biochar application. The highest increase of 18.9% in electrical conductivity was observed in ALB (1164) in comparison with control (978.6). The manufacturing temperature of biochar has been shown to enhance its pH and electrical conductivity, as a result of the loss of volatile matter and the hydrogen: carbon ratio, which leads to the formation of high ash content (Liu *et al*., 2018). Biochar contains higher amounts of different free elemental ions like Se, Al, K, Ca, Na, and many more. This increases the concentration of free ions in the soil solution resulting in an increase in soil electrical conductivity (Riaz *et al*., 2018). Similarly, previous findings reported that biochar application increased the soil electrical conductivity (Berek *et al*., 2018; Riaz *et al*., 2018).

Organic matter (OM): There was a slight increase in the organic matter content of soil upon biochar application. Treatment BB (3.52) showed the highest increase of 16% in organic matter compared to control (3.02). The high organic carbon content of biochar, the abundance of soil microbes, the reduction of leaching, and the slow mineralization rate brought on by enhanced carbon stability could all contribute to an increase in OM content (Liu *et al*., 2022; Ndoung *et al*., 2021; Wu *et al*., 2016). Previous studies have also found that biochar increases the soil organic matter content (Acharya *et al*., 2022; Riaz *et al*., 2018).

Nitrogen (N): A slight increase of 7.6% & 2.1% in soil N was obtained by CHB (0.099) and SB (0.094) respectively in comparison to the control (0.092). The remaining biochar application in the soil decreased the soil Nitrogen content. Biochar reduces leaching and retains more nitrogen because of its extremely porous structure with abundant surface functional groups that adsorb and hold soil N. Biochar increases the available C in soil and its porous structure houses the microorganisms, thus promoting the microbial population. This improves nitrification, mineralization, solubilization, and ultimately the availability of other minerals (Ebrahimi *et al*., 2021; Losacco *et al*., 2022). Biochar application can reduce the nitrate nitrogen and increase the ammonium nitrogen in the soil, thus reducing the loss of nitrogen through denitrification. Promotion of nitrification and reduced denitrification occurs due to increased porosity of soil which creates an aerobic environment in soil, promoting aerobic nitrifying bacteria and inhibiting the growth of anaerobic denitrifying bacteria (Hu *et al.*, 2023). Previous findings support both the increase and decrease of N availability in soil upon biochar application. The increase or decrease differs significantly with biochar feedstock and preparation techniques (Riaz *et al.*, 2018).

Phosphorus (P_2O_5): Biochar application slightly increased the soil phosphorus content. There was an increment of 12.3% & 10.7% in soil phosphorus (P2O5) from treatments, BB (35.4) and SB (34.9) respectively when compared to control (31.5). Biochar application generally increases the soil phosphorus in soil with acidic to neutral pH, with the application of biochar prepared below 600 °C, and with an application rate of above 10 Mg ha^{-1} (Glaser & Lehr, 2019). These conditions were fulfilled during the experiment and although the phosphorus content increased, the result was not significant. This increase may be the result of increased soil P_2O_5 biogeochemical cycles, better soil P_2O_5 retention, and decreased leaching losses (Ebrahimi *et al.*, 2021; Li *et al.*, 2019; Ndoung *et al.*, 2021). The porous structure of biochar can also house microorganisms, especially phosphorus-solubilizing bacteria, which could be one of the reasons for the increment of available soil phosphorus and the prevention of losses from soil (Lu *et al.*, 2023). Similar results were seen with the addition of coconut husk biochar to soil which increased soil phosphorus content by 28.48% in comparison to control (Farias *et al.*, 2020).

Potassium (K_2O): There was an increase of 6.1% in the soil potassium content by ALB (208.5) relative to control (196.5). Biochar contains a high amount of potassium in itself and its ash content. More than 90% of potassium in biochar is present in the form of exchangeable or water-soluble potassium (M. Wang *et al.*, 2023). Depending on the feedstock, pyrolysis temperature, and application quantity, biochar can function as a short-, mid-, or long-term P fertilizer. The P availability was significantly enhanced only by applying biochar at levels more than 10 mg ha^{-1} and by producing biochar at temperatures lower than 600 ° C (Glaser & Lehr, 2019). The porous structure of biochar is conducive to the growth of microorganisms in soil and plant rhizosphere development, which produce organic anions. Organic anions degrade the potassium-bearing mineral source in soil, thus increasing the amount of available potassium (Doulgeris *et al.*, 2023). The low exchangeable acidity caused by the precipitation of Al as hydroxyl discharge cations into the soil may be the cause of the high potassium concentration in soils supplemented with biochar (Rasuli *et al.*, 2022). Previous study showed that there was a significant increase in soil potassium content by 1092.6% upon addition of a combination of coconut husk biochar and sewage sludge biochar to soil (Farias *et al.*, 2020).

Soil physical properties

Bulk density: Results showed that there was a significant decrease in soil bulk density upon biochar application in comparison to control. There was a decrease of 10.9% & 8.7% in soil bulk density from ALB (1.22 gm cm^{-3}) and BB (1.25 gm cm^{-3}) respectively relative to control (1.37 gm cm^{-3}). The degree to which soil particles are tightly packed together is measured by bulk density (Riaz *et al.*, 2018). The observed decrease in BD could be caused by a number of factors, including characteristics of the biochar such as particle size, active surface area, porosity, and soil characteristics. Additionally, biochar combines with the soil particles to produce aggregates that lower the bulk density (Toková *et al.*, 2020). This decrease in soil bulk density increases aeration, water water-absorbing capacity and decreases penetration resistance improving crop performance (Riaz *et al.*, 2018). Previous studies also found that there was a significant decrease in soil bulk density upon application of biochar (Guo *et al.*, 2022; Riaz *et al.*, 2018; Toková *et al.*, 2020).

Particle density: There was a significant decrease of 4.4% in particle density upon SB incorporation while other treatments showed minimal modification. There is a lack of studies precisely assessing the impact of biochar on soil particle density, however, they show that applying biochar can lower particle density. This decrease in soil particle density in soil may be attributed to the lower particle density of biochar (Blanco-Canqui, 2017).

Soil porosity: Biochar treatments significantly increased soil porosity with the highest increase of 10.6% & 8.4% in ALB and BB respectively in comparison to the control. The highest and lowest soil porosity was observed in ALB (50%) and control (45.18%) respectively. Biochar application results in an increment of porosity (Walters & White, 2018). This can be attributed to the highly longitudinal pores in biochar varying in size from micro- to macro-pores (Tomczyk *et al.*, 2020). This increases the surface area of biochar thus improving the soil's physical properties and improving the yield of crops (Toková *et al.*, 2020). However, the porosity of biochar is dependent on multiple factors including pyrolysis temperature, feedstock used, and time of pyrolysis (Leng *et al.*, 2021). Biochar with higher ash content has less effect on porosity in comparison to biochar with higher lignin content (Leng *et al.*, 2021; Tomczyk *et al.*, 2020). Previous findings also have found that there was a significant increase in soil porosity upon biochar application in comparison to non-biochar applied soils (Chang *et al.*, 2021; Singh *et al.*, 2022).

Agronomical parameters of okra

Plant height: There was no significant relationship between various treatments of biochar and plant height however, there was an increase in plant height upon biochar application. Plant height increased by 4.3% upon wood ash incorporation compared to control. The increase in plant height may be attributed to biochar's ability to hold water and nutrients due to its high water-holding capacity and low bulk density (Rahayu *et al.*, 2022). In addition, the mineralized elements in biochar, particularly nitrogen, may have helped the okra plants grow taller (Riaz *et al.*, 2018). However, previous findings found that plant height was significantly increased upon biochar application in comparison to control (Farias *et al.*, 2020; Riaz *et al.*, 2018).

Table 4. Effect of biochar treatments on soil physical properties.

Treatments	Bulk density (g cm^{-3})	Particle density (g cm^{-3})	Porosity (%)
Control	1.37±0.007a	2.5±0.04a	45.18±1c
WA	1.32±0.006ab	2.46±0.02a	46.3±0.6c
RHB	1.3±0.02b	2.45±0.02a	47±0.76bc
BB	1.25±0.02bc	2.48±0.01a	49±1ab
ALB	1.22±0.03c	2.47±0.02a	50±1.1a
CHB	1.29±0.05bc	2.48±0.06a	47.98±1.9abc
SB	1.26±0.01bc	2.39±0.02b	46.99±0.6bc
CV (%)	3.19	1.4	0.2
LSD	0.07	0.06	0.16
Grand Mean	1.28	2.46	47.3

Means of treatment values are significantly different at 5% level of significance determined through LSD test. Means with same letters show no significant difference. WA: Wood ash; RHB: Rice husk biochar; BB: Bamboo biochar; ALB: Ashoka leaf biochar; CHB: Coconut husk biochar; SB: Sawdust biochar; CV: Coefficient of variation; LSD: Least significant difference.

Table 5. Effect of biochar treatments on agronomical parameters of okra.

Treatments	Plant height (cm)	Fruit size (cm)	Yield (t ha^{-1})
Control	138.6±2.6	14.1±0.16d	7.82±0.07c
WA	144.6±0.88	14.9±0.08abcd	7.95±0.05bc
RHB	141±1.73	14.5±0.51cd	7.98±0.04bc
BB	143.6±1.76	15.7±0.14a	7.96±0.07bc
ALB	139.6±1.76	15.5±0.23ab	8.16±0.05a
CHB	142.6±1.45	15.1±0.06abc	8.04±0.04ab
SB	144.3±1.76	14.6±0.56bcd	7.86±0.05c
CV (%)	2.2	3.7	1.19
LSD	5.62	0.99	0.16
Grand Mean	142	14.9	7.9

Fruit size: There was a significant increase ($p \leq 0.05$) in the fruit size of okra upon biochar application in the soil. The largest fruit size (15.7cm) was observed in BB followed by ALB (15.5) while the smallest was observed in control (14.1cm). There was an increment of 11.3% & 9.9% in fruit size by BB and ALB respectively. Improved plant nutrition during the okra growth season is the cause of the larger fruit in biochar-applied soils. This resulted in the production of chlorophyll, proteins, and growth-regulating hormones, all of which directly contribute to increased fruit size (Ali *et al*., 2017). Similarly, there was a significant increase in the fruit size of okra under biochar application, where sugarcane waste straw biochar gave the largest fruit size (15.45cm) (Riaz *et al*., 2018).

Yield: Results further revealed that biochar significantly ($p \leq 0.05$) increased the yield of okra. The highest yield was observed in ALB (8.16 t ha^{-1}) followed by CHB (8.04 t ha^{-1}) and the lowest in control (7.82 t ha^{-1}). Greater okra yields brought on by biochar may be the result of a combination of factors, including enhanced plant nutrients, decreased nitrogen leaching, enhanced water holding capacity, greater electrical conductivity, and higher organic matter content (Riaz *et al*., 2018). In addition, biochar-based fertilizers may have produced higher yields due to improved nutrient uptake and photosynthetic activities, which could have boosted carbohydrate synthesis, dry matter, and eventual fruit development (Zhang *et al*., 2020; Zhao *et al*., 2022). Previous findings also support that the yield increases significantly upon biochar application (Acharya *et al*., 2022; Farias *et al*., 2020; Ibrahim, 2022; Riaz *et al*., 2018).

Conclusion

The incorporation of biochar in soil significantly improved the soil physical properties (bulk density, particle density, soil porosity), and fruit size and yield of okra. Similarly, non-significant changes were observed in soil chemical parameters (pH, OM, EC, N, P, K), and plant height of okra. Ashoka leaf biochar resulted in the highest reduction of bulk density by 10.9%, increment of soil porosity by 10.6%, the highest fruit yield of 8.16 t ha^{-1}, and the second largest fruit size of 15.5 cm. Similarly, sawdust biochar resulted in the highest reduction of 4.4% in soil particle density, and bamboo biochar resulted in the largest fruit size among all the treatments with length of 15.7 cm. It is recommended that Ashoka leaf biochar be used for okra cultivation in the study area for improving soil properties as well as to obtain a higher fruit yield. However, multiyear studies are required for further verification of the results.

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Authors' contribution

Conceptualization, Methodology, J.J.G.; Software, Validation, Data curation, Formal analysis, P.B. and P.G.; Investigation, J.J.G., P.B., P.G., R.K., R.M., S.P., M.P. and P.K.S.; Writing—Original draft preparation, J.J.G., P.B., P.G., R.K., R.M., S.P., M.P. and P.K.S; Review and editing, P.B and P.G.; Visualization, P.G. and P.B. All authors have read and agreed to the published version of the manuscript.

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