Received: 12 January 2026 | Accepted: 13 March 2026 | Published online: 29 April 2026
DOI: 10.53550/ijsc.v54.i1.219

ORIGINAL ARTICLE
Indian Journal of Soil Conservation

Evaluation of Different Biochar Sources on Growth, Yield and Soil Fertility of Okra and Brinjal in Inceptisol from Odisha : A Pot Study

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Handling Editor:
Dr Raman Jeet Singh

Key words:
Biochar
Brinjal
Fruit yield
Plant height
Okra
Soil

ABSTRACT

Declining soil organic carbon and nutrient imbalances in Inceptisols of eastern India have reduced productivity of intensive vegetable systems under sole chemical fertilizer use. However, limited information exists on the comparative effectiveness of different biochar sources integrated with farmyard manure (FYM) and recommended dose of fertilizers (RDF) for improving soil fertility and yield of okra and brinjal. In this context, a pot experiment was conducted during 2021–2022 at the ICAR–Indian Institute of Soil Science (IISS), Bhopal, India, to evaluate the effect of different biochar sources and application rates, alone and in combination with FYM and RDF on growth, yield, and soil fertility of okra and brinjal grown in an Inceptisol soil collected from Belpada, Odisha. The experiment was laid out in a Completely Randomized Design (CRD) with eleven treatments replicated four times, involving two biochar sources {crop residue biochar (CRB) of groundnut, mustard, and rice husk and mixed wood biochar (WCB) of *Prosopis juliflora* and coconut husk} applied at 0, 4, and 8 g kg^{-1} soil, with and without FYM (5 g kg^{-1} soil) and (RDF). Results revealed that integrated application of biochar, FYM, and RDF significantly ($p < 0.05$) improved plant height and yield of both the crops over the control (0) and fertilizer-alone treatments. The treatment crop residue biochar @ 8 g kg^{-1} soil + FYM @ 5 g kg^{-1} soil + RDF ($F_1CRB_8M_5$) consistently recorded the highest yields of okra (182.4 g pot^{-1}) and brinjal (262.5 g pot^{-1}), resulting in nearly two-fold higher fruit yield of okra and three- to four-fold higher fruit yield of brinjal compared to the control across both years. This treatment also improved N, P, and K uptake substantially, with N uptake increasing more than four fold in okra and over twofold in brinjal, accompanied by marked increases in P and K uptake across both crops. Biochar application moderated soil reaction, raising soil pH from near-neutral control levels (~7.26) to ~7.64, indicating its liming potential, while soil organic carbon (SOC), available P, and available K increased by 114%, 170%, and 27%, respectively, under integrated treatments. Unlike earlier studies focusing on single biochar sources or short-term responses, this study provides a comparative assessment of crop residue and mixed biomass biochars at graded rates under integrated application with FYM and RDF, highlighting their cumulative effects. The findings offer new insights into optimized biochar-based nutrient management strategies for sustaining vegetable productivity and soil fertility in Inceptisols. Although it is just a pot study but it concludes that biochar alone is insufficient, but its integration with FYM and RDF, particularly crop residue biochar at higher rates, is an effective and sustainable strategy for enhancing vegetable productivity and soil fertility in Inceptisol soils.

1 | INTRODUCTION

Vegetable crops are vital for ensuring nutritional security, income generation, and livelihood diversification in India, particularly for small and marginal farmers. Among them, okra (*Abelmoschus esculentus* L.) and brinjal (*Solanum melongena* L.) are widely cultivated owing to their high market demand, adaptability to diverse agro-climatic conditions, and significant contribution to dietary fiber, vitamins, and antioxidants (Hazra, 2023; Sudhanshu, 2025). Despite their importance, the productivity of okra (12.1 t ha^{-1}) and brinjal (18.8 t ha^{-1}) crop often remains below potential (PJTAU, 2024; Ouedraogo *et al.,* 2024) due to declining soil fertility, low organic carbon content, and suboptimal nutrient management practices, especially in intensively cultivated vegetable-growing regions of India (Meena *et al.,* 2021; Chaudhari *et al.,* 2023).

Soils of eastern India, including Odisha, are predominantly Inceptisols characterized by low to medium

SOC, low available nitrogen, and emerging nutrient imbalances resulting from continuous cropping, removal of crop residues, and limited application of organic amendments (Bhattacharyya *et al.,* 2015). Several Indian studies has reported that long-term reliance on chemical fertilizers without adequate organic inputs has led to deterioration of soil physical structure, reduced nutrient use efficiency, and declining productivity of vegetable-based systems (Titirmare *et al.,* 2023). These concerns underline the need for integrated nutrient management strategies that combine mineral fertilizers with organic amendments to sustain soil health and crop yields.

Biochar, a carbon-rich material produced through pyrolysis of biomass under oxygen-limited conditions, has gained considerable attention as a soil amendment for improving soil quality and crop performance. Due to its porous structure, high surface area, and surface functional groups, biochar can enhance soil water-holding capacity, nutrient retention, microbial activity, and long-term carbon sequestration (Das *et al.,* 2019; Mishra *et al.,* 2023; Subha and Jeyamangalam, 2025). Study conducted in India have demonstrated that biochar application improves SOC, nutrient availability, and crop yields in degraded and low-fertility soils (Jayaraman *et al.,* 2024).

The agronomic effectiveness of biochar is strongly influenced by feedstock source, application rate, soil type, and interactions with fertilizers and organic manures. Crop residue derived biochar generally contains higher ash content and readily available nutrients, whereas woody or coconut-shell biochar is more recalcitrant and contributes primarily to carbon stabilization and soil structural improvement (Siddiqui, 2025). FYM a widely available organic input in Indian farming systems, supplies essential nutrients, improves soil aggregation, and stimulates microbial activity. Indian studies have reported that combined application of biochar and FYM enhances nutrient availability and crop productivity more effectively than their sole application due to synergistic effects on nutrient cycling and soil biological activity (Sharma *et al*., 2025).

While the benefits of biochar have been extensively studied in cereal-based systems, information on its performance in high-value vegetable crops such as okra and brinjal remains limited, particularly under Inceptisol conditions of eastern India. Moreover, comparative evaluations of different biochar sources, such as crop residue and wood/coconut, in conjunction with FYM and recommended fertilizer doses are scarce. It is hypothesized that the integrated application of biochar with FYM and recommended doses of fertilizers would improve soil nutrient availability and result in superior growth and fruit yield of okra and brinjal compared to fertilizer-only treatments. It is further hypothesized that biochar derived from different feedstocks would differ in their effectiveness due to variations in physicochemical properties.

HIGHLIGHTS

- Integrated application of crop residue biochar (8 g kg^{-1} soil or 17 t ha^{-1}) with FYM and RDF nearly doubled okra fruit yield and increased brinjal fruit yield by three- to four-fold compared with the control.
- Biochar-based integrated nutrient management significantly improved soil fertility, increasing SOC by 114%, available P by 170%, and available K by 27% over the control.
- Residual and cumulative effects of biochar were more pronounced in the second season, confirming its long-term role in sustaining vegetable productivity and soil health in Inceptisol.
- Enhanced carbon stabilization and nutrient retention under integrated biochar use provide a practical recommendation of crop residue biochar @ 8 g kg^{-1} soil with FYM and RDF for sustainable vegetable production.

In this context, the present study was undertaken with the objective of evaluating the effect of different biochar sources and application rates, alone and in combination with FYM and recommended fertilizer doses, on growth and fruit yield of okra and brinjal grown in Inceptisol soil collected from the Belpada in Odisha under pot experiment. This study was funded by the GIZ through ICRAF. ICRAF had been taking up their research initiatives in this region with these crops, hence, we designed this study to evaluate biochar application in these soils. The study also aims to assess changes in soil available nutrients following biochar application and to identify suitable biochar-based integrated nutrient management strategies for enhancing vegetable productivity and soil fertility in eastern Indian soils.

2 | MATERIALS AND METHODS

2.1 | Study Location

A pot experiment was conducted during 2021–2022 at the ICAR–Indian Institute of Soil Science**,** Bhopal, Madhya Pradesh. The soil belonged to the Inceptisol soil order (Soil Survey Staff, 2014) and was collected from the Belpada tehsil in Balangir district of Odisha, India. These soils occupy approximately an area of 7.60 million hectare covering 49% area in the state (Mishra *et al,* 2024). The experimental soil had a pH of 6.21, electrical conductivity of 0.11 dS m^{-1}, and SOC content of 0.45%. The soil was classified as low in available nitrogen (220 kg ha^{-1}), medium in available phosphorus (28.3 kg ha^{-1}), and high in available potassium (393 kg ha^{-1}). In the study, biochar was not only intended to treat the pH, but the objective was to assess its effect on vegetable production in conjunction with FYM also.

2.2 | Experimental Design

The experiment was laid out in a Completely Randomized Design comprising eleven treatments with four replications. The treatments included three levels of biochar (0, 4, and 8 g kg^{-1} soil), two levels of FYM (0 and 5 g kg^{-1} soil), one level of the (RDF), and a control. The RDF was applied to each pot based on the recommended rate of $N:P_2O_5:K_2O$ *i.e.*

120:75:50 kg ha^{-1} through urea, single super phosphate, and muriate of potash, respectively to both the crops. Two types of biochar, i.e. crop residue biochar (CRB) of groundnut, mustard, and rice husk and mixed wood biochar (WCB) of *Prosopis juliflora* and coconut husk were used in the study. The biochar was provided by ICRAF, New Delhi through procurement from private suppliers. Wood biochar was prepared from *Prosopis juliflora* and coconut husk and CRB was prepared from mixed residues of groundnut, mustard and rice husk. Basic properties of the biochar and FYM have been mentioned in Table 1. Biochar was applied at the beginning of each crop season, i.e., it was added for every cropping cycle during the experimental period. The detailed treatment combinations are presented in (Table 2). Total nutrient added (mg pot^{-1}) in initial soil nutrient status through different sources have been mentioned in (Table 3).

TABLE 1 Basic properties of different biochar used in this experiment

Biochar	pH	EC (dS m^{-1})	TOC (%)	Total N (%)	Total P (%)	Total K (%)
WCB	8.16-9.20	1.78-5.48	31.9-46.2	0.58	0.09-0.25	0.59- 1.0
CRB	8.12-9.09	1.68-5.36	37.1-49.5	0.38	0.07-0.21	0.53-1.0
FYM	7.2–7.8	1.0–2.0	15–20	0.5–0.8	0.2–0.4	0.5–1.0

TABLE 2 Treatment structure for pot experiment

Treatments	Treatment combination	Biochar (g kg^{-1})	FYM (g kg^{-1})
T_1	$F_0B_0M_0$	0	0
T_2	$F_1B_0M_0$	0	0
T_3	$F_1B_0M_5$	0	5
T_4	$F_1WCB_4M_0$	4	0
T_5	$F_1WCB_4M_5$	4	5
T_6	$F_1WCB_8M_0$	8	0
T_7	$F_1WCB_8M_5$	8	5
T_8	$F_1CRB_4M_0$	4	0
T_9	$F_1CRB_4M_5$	4	5
T_{10}	$F_1CRB_8M_0$	8	0
T_{11}	$F_1CRB_8M_5$	8	5

TABLE 3 Total nutrient added (mg pot^{-1}) in initial soil nutrient status through different sources to each crop

Treatments	Treatment combination	N	P	K
T_1	$F_0B_0M_0$	0	0	0
T_2	$F_1B_0M_0$	600	327	415
T_3	$F_1B_0M_5$	925	477	790
T_4	$F_1WCB_4M_0$	832	395	735
T_5	$F_1WCB_4M_5$	1157	545	1110
T_6	$F_1WCB_8M_0$	1064	463	1055
T_7	$F_1WCB_8M_5$	1389	613	1430
T_8	$F_1CRB_4M_0$	752	383	719
T_9	$F_1CRB_4M_5$	1077	533	1094
T_{10}	$F_1CRB_8M_0$	904	439	1023
T_{11}	$F_1CRB_8M_5$	1229	589	1398

2.3 | Crop Management Practices

Surface soils (0-15 cm) was collected from the Belpada in Balangir district of Odisha, were ground and passed through 2 mm sieve. 10 kg air dry soil was mixed with required dose of WCB and CRB and FYM thoroughly and filled in plastic pots. Okra seeds (var. Supreme) were sown on 24 and 19 July in 2021 and 2022 respectively. Five seeds of okra were sown in each pot (oval shaped with diameter 30 cm and height 22 cm) and later on only two plants were maintained (Plate 1). After harvest of okra in the month of November, soils were mixed thoroughly and refilled in the same pot with same treatment. About 20 days old single seedling of Brinjal (var. Kavya and Ankur hybrid 786) was transplanted (Plate 1) on 01 December and 19 December of 2021 and 2022, respectively. Full dose of P and K fertilizer and 50 per cent of N were applied at the time of sowing/transplanting of okra and brinjal, respectively. Remaining N was applied in two splits after 45 and 60 days after sowing/transplanting of okra and brinjal, respectively. Pots were watered to maintain optimum moisture conditions during plant growth. Crops were raised with standard package of practices. Plants were sprayed with chemicals such as imidachloprid (0.3 ml L^{-1} water) and Abamectin (0.5 ml L^{-1} water) for plant protection at time to time. The pots were kept in a net house of ICAR-IISS, Bhopal and same soil was used again for the next season.

PLATE 1 Some of the photos of the pot study

2.4 | Growth and Fruit Yield

Plant height was measured at periodic growth stages and at final harvest in okra and brinjal. The height of each plant was recorded in centimeters (cm) from the soil surface at the base of the plant to the apical growing point using a graduated measuring scale. Mean plant height per treatment was calculated using observations from all replications. Harvesting of okra fruits was carried out at the tender, marketable stage at regular intervals. Brinjal fruits were harvested at physiological maturity based on varietal characteristics. The fruits were harvested from each plant and their fresh weight was measured using an electronic balance and expressed as g pot^{-1}.

2.5 | Soil Analysis

After maturity of the crops, plants were harvested and the whole soil of pot was drawn out and thoroughly mixed and sampled for analysis. The crop was harvested and the soil of the pot was drawn out and thoroughly mixed and sampled for analysis. SOC was determined by wet oxidation method (Walkley and Black, 1934). Available P was determined by the Olsen's method using 0.5 M sodium bicarbonate ($NaHCO_3$, pH 8.5) as extractant (Olsen *et al.,* 1954). Available K was extracted using neutral normal ammonium acetate (1 **N** NH_4OAc, pH 7.0). The K concentration in the extract was determined using a flame photometer (Jackson, 1973).

2.6 | Statistical Analysis

The study used one-way ANOVA in combination with DMRT (Duncan's Multiple Range Test) method to identify mean differences between various treatments for different parameters (Gomez and Gomez, 1984). Year-wise data analysis was performed separately not as pooled. Software

WASP 2.0 developed by ICAR-ICARI Goa was used to analyze the data statistically. Any p-values that were less than 0.05 were considered significant for deciding the significance of treatments.

3 | RESULTS AND DISCUSSION

3.1 | Effect on Growth of Okra and Brinjal

In both 2021 and 2022, plant height of okra increased progressively with crop age (30, 60, and 90 DAS), but the magnitude of increase varied significantly ($p < 0.05$) among treatments. In 2021, the maximum plant height (114.8 cm) at 90 DAS was recorded under $F_1CRB_8M_5$ (RDF + crop residue biochar @ 8 g kg^{-1} soil + FYM @ 5 g kg^{-1} soil) (Fig. 1a), which resulted in an increase of about 30.7% over the control ($F_0B_0M_0$). The treatments $F_1WCB_8M_5$(112.8 cm) and $F_1CRB_4M_5$ (104.6 cm) followed, recording 19-28% higher plant height than the control, while RDF alone ($F_1B_0M_0$) showed only 1.92% improvement. Sole biochar application did not significantly enhance plant height compared to RDF with or without FYM. A similar and consistent response was observed in 2022, where $F_1CRB_8M_5$ again produced the tallest plants (128.9 cm) at 90 DAS, showing a 54.8% increase over the control (Fig. 1b), confirming the stability of integrated biochar-based nutrient management across seasons. Minor year-to-year variation was observed, but the relative ranking of treatments remained unchanged. The enhanced plant height under crop residue biochar + FYM integration can be attributed to improved soil physical conditions such as higher porosity and water retention, coupled with enhanced nutrient availability during the active vegetative phase. Biochar improves nutrient retention through increased cation exchange capacity, while FYM supplies readily mineralizable nutrients and stimulates microbial activity, together ensuring sustained nutrient availability at later growth stages (Zhang *et al*., 2024). Recent studies under vegetable-based systems have also reported superior vegetative growth when biochar is integrated with organic and inorganic nutrient sources rather than applied alone (Effa *et al.*, 2023). Brinjal exhibited a response pattern similar to okra, with plant height increasing steadily at all growth stages during both 2021 and 2022. In 2021, the treatment $F_1CRB_8M_5$ recorded the significantly ($p < 0.05$) highest plant height (73 cm) at 90 DAS, showing a 56.9% increase over the control, followed by $F_1WCB_8M_5$, which resulted in a 54.8% increase (Fig. 1c). Treatments receiving RDF alone or biochar without FYM produced comparatively shorter plants. In 2022, the superiority of $F_1CRB_8M_5$ was further confirmed, with highest plant height (67.8 cm) remaining 56.8% higher than the control (Fig. 1d), indicating that the beneficial effects of biochar-based integration were more pronounced and sustained in the second year. The response of brinjal to integrated treatments was stronger at later growth stages, reflecting improved root growth and nutrient uptake under improved soil conditions. The improved plant height of brinjal under integrated treatments can be explained by enhanced soil moisture retention and nutrient synchronization with crop demand. Brinjal, being a long-duration and nutrient-exhaustive crop, responds strongly to improved soil structure and continuous nutrient supply, both of which are facilitated by biochar + FYM combinations (Acharya *et al*., 2023; Anusha *et al*., 2025). Recent evidence suggests that biochar derived from crop residues, when co-applied with organic nutrient sources, enhances soil fertility, nutrient availability and vegetative vigor in vegetable systems compared with biochar alone (Acharya *et al.*, 2023; Anusha *et al.*, 2025). Across both years and crops, $F_1CRB_8M_5$ consistently emerged as the most stable and effective treatment, demonstrating that biochar alone is insufficient, but when integrated with FYM and RDF, it significantly enhances yield by improving soil quality, nutrient retention, and nutrient use efficiency. The stronger response observed in brinjal compared to okra highlights the importance of crop-specific nutrient demand and growth duration in determining biochar effectiveness.

3.2 | Effect on Yield of Okra and Brinjal

Fruit yield of okra differed significantly ($p < 0.05$) among treatments during both 2021 and 2022, indicating a strong response to integrated nutrient management involving biochar, FYM, and RDF (Table 4). In 2021, the highest fruit yield (185.4 g pot^{-1}) was obtained under $F_1CRB_8M_5$ (RDF + crop residue biochar @ 8 g kg^{-1} soil + FYM @ 5 g kg^{-1} soil), which resulted in an increase of about 98% over the control (93.5 g pot^{-1}). This treatment was followed by $F_1CRB_8M_0$ (159.2 g pot^{-1}) and $F_1CRB_4M_5$ (153.4 g pot^{-1}), which recorded yield increases of 70% and 64%, respectively. RDF alone ($F_1B_0M_0$) produced only a modest yield improvement (10%), while biochar application without FYM showed inconsistent effects. During 2022, a similar response pattern was observed, confirming treatment stability across years. The maximum fruit yield was again recorded under $F_1CRB_8M_5$ (145.0 g pot^{-1}), which was ~99% higher than the control (72.8 g pot^{-1}) (Table 4). Integrated biochar treatments consistently outperformed RDF alone, suggesting that biochar-mediated improvement in soil conditions plays a key role during reproductive development of okra. The yield enhancement under $F_1CRB_8M_5$ can be attributed to improved nutrient availability and reduced nutrient losses during flowering and fruit development. Biochar improves soil aggregation and nutrient retention, particularly for nitrogen and potassium, while FYM enhances microbial-mediated nutrient mineralization, together improving nutrient synchronization with crop demand (Premalatha *et al.,* 2023). Recent studies in vegetable-based systems have reported that biochar combined with organic amendments significantly improves fruit yield by enhancing nutrient use efficiency and root growth (Kesamreddy *et al.,* 2025).

Fruit yield of brinjal showed a stronger response to biochar-based treatments than okra in both years because the relative increase in plant height was 50% in brinjal compared to 30% in okra. In 2021, the highest fruit yield (96.7 g pot^{-1}) was recorded under $F_1CRB_8M_5$, representing an increase of about 213% over the control (30.9 g pot^{-1}) (Table 4).

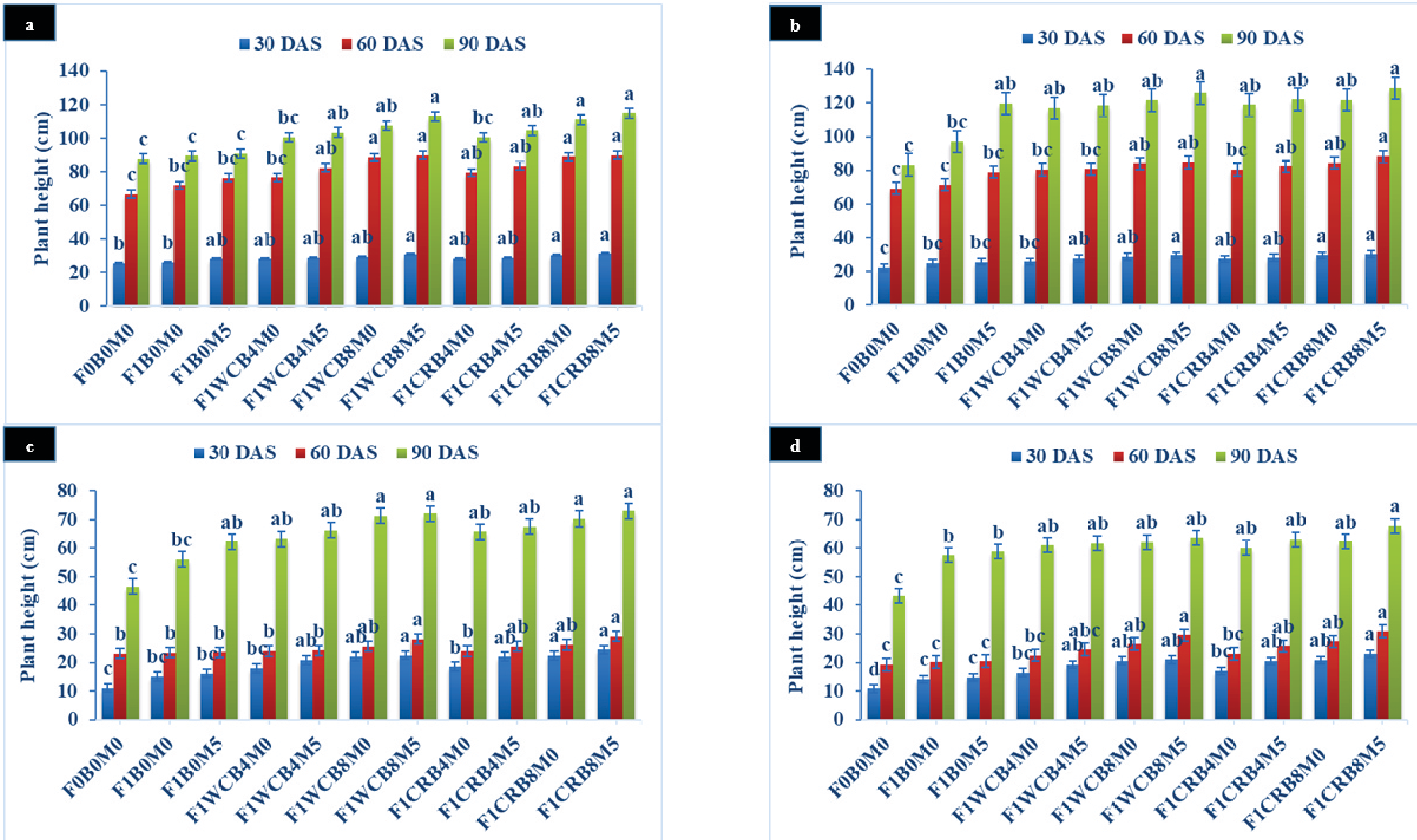

FIGURE 1 Plant height of okra and brinjal as influenced by different treatments at 30, 60 and 90 DAS/DAT during 2021 and 2022. Panels represent: (a) Okra 2021, (b) Okra 2022, (c) Brinjal 2021 and (d) Brinjal 2022. Error bars showing LSD ($p < 0.05$). Treatment means with similar superscripted letters within a column are not significantly different at $P < 0.05$ according to Duncan's Multiple Range Test.

TABLE 4 Effect of different biochar treatments on fruit yield of okra and brinjal during 2021 and 2022

	Okra (g pot^{-1})		Brinjal (g pot^{-1})	
Treatment	2021	2022	2021	2022
$F_0B_0M_0$	93.5^{f}	72.8^{f}	30.9^{g}	46.0^{c}
$F_1B_0M_0$	103.0^{ef}	87.3^{ef}	54.7^{f}	195.0^{b}
$F_1B_0M_5$	122.8^{cd}	99.6^{de}	76.5$^{cde\backslash}$	229.2^{ab}
F_1WCB4M_0	118.5^{ef}	97.2^{de}	67.3^{e}	188.7^{b}
$F_1WCB_4M_5$	121.6^{c}	106.1^{cd}	83.7^{bcd}	222.6^{ab}
$F_1WCB_8M_0$	89.6^{de}	104.0^{cde}	75.1^{de}	258.3^{a}
$F_1WCB_8M_5$	133.4^{c}	113.8^{bcd}	86.2^{bc}	261.2^{a}
$F_1CRB_4M_0$	123.0^{cd}	102.3^{cde}	76.5^{cde}	189.9^{b}
$F_1CRB_4M_5$	153.4^{b}	123.6^{b}	88.5^{ab}	200.7^{b}
$F_1CRB_8M_0$	159.2^{b}	118.4^{bc}	85.1^{bcd}	218.8^{ab}
$F_1CRB_8M_5$	185.4^{a}	145.0^{a}	96.7^{a}	262.5^{ab}

Treatment means with similar superscripted letters within a column are not significantly different at p <0.05 according to Duncan's Multiple Range Test.

Treatments $F_1CRB_4M_5$ (88.5 g pot^{-1}) and $F_1WCB_8M_5$ (86.2 g pot^{-1}) also produced significantly higher yields, showing 178-186% increases, while RDF alone resulted in only a ~77% increase. In 2022, fruit yield increased substantially across treatments, with $F_1CRB_8M_5$ (261.5 g pot^{-1}) and $F_1WCB_8M_5$ (261.2 g pot^{-1}) (Table 4). Compared to the control (46.0 g pot^{-1}), $F_1CRB_8M_5$ resulted in a 470% increase, highlighting the cumulative and residual benefits of biochar application in the second year. Brinjal, being a long-duration and nutrient-intensive crop, benefits greatly from improved soil structure, moisture retention, and prolonged nutrient supply. Biochar enhances soil aeration and water availability, while FYM supports continuous nutrient release during extended flowering and fruiting phases (Xu *et al.,* 2025). Recent evidence suggests that residual biochar effects can substantially enhance yields of solanaceous crops by improving rhizosphere microbial activity and nutrient uptake efficiency (Zhang *et al.,* 2022). Across both crops and years, $F_1CRB_8M_5$ emerged as the most stable and effective treatment, demonstrating that biochar alone is insufficient, but when integrated with FYM and RDF, it significantly enhances yield through improved soil physical properties, nutrient retention, and nutrient use efficiency. The stronger response in brinjal compared to okra highlights the importance of crop duration and nutrient demand in determining biochar effectiveness.

3.3 | Effect on Nutrient Uptake

Biochar application significantly ($p < 0.05$) influenced N, P, and K uptake by both okra and brinjal during 2021 and 2022. Across treatments, nutrient uptake consistently increased with higher biochar rates and was generally greater under biochar + FYM combinations compared to FYM alone and control. N uptake showed a marked improvement with biochar addition. The lowest N uptake in okra (0.10 and 0.14 g pot^{-1}) was recorded under the control treatment ($F_0B_0M_0$) during both the years, while treatments receiving biochar at higher rates in combination with FYM ($F_1CRB_8M_5$) exhibited the highest N uptake in okra (0.42 and 0.86 g pot^{-1}) during both the years (Fig. 2). Brinjal recorded higher N uptake than okra in both years, with maximum values observed during 2022 (2.82 g pot^{-1}) compared to 2021(1.94 g pot^{-1}) under $F_1CRB_8M_5$ (Fig. 3). A similar trend was observed for P uptake, where biochar-amended treatments significantly enhanced P uptake over the control. $F_1CRB_8M_5$ consistently resulted in maximum P uptake in brinjal (0.13 and 0.20 g pot^{-1}) (Fig. 3) and okra (0.12 and 0.17 g pot^{-1}) (Fig. 2). The increase was more pronounced in the second year, suggesting improved P availability under biochar-amended acidic soil conditions. K uptake also increased significantly with biochar application. The highest K uptake in brinjal (0.93 and 1.64 g pot^{-1}) was recorded with $F_1CRB_8M_5$ during both the years, reflecting the contribution of biochar-derived K and improved soil chemical environment (Fig. 3). Brinjal showed greater K uptake than okra across all treatments and years, with higher uptake during 2022. Enhanced N uptake may be attributed to improved soil pH and nutrient retention, which reduce N losses and promote better synchronization between nutrient supply and crop demand (Agegnehu *et al.,* 2016). The higher uptake observed during the second year supports earlier findings that biochar effects become more pronounced over time. The increase in P uptake under biochar-amended treatments is likely due to reduced P fixation in acidic soils as a result of increased soil pH and the contribution of biochar-derived P, leading to greater P availability (Xu *et al.,* 2013). Similarly, enhanced K uptake reflects the inherent K content of biochar and improved cation exchange capacity, which helps retain K in the root zone and limits leaching losses (Major *et al*., 2010). Brinjal consistently showed higher nutrient uptake than okra, likely due to greater biomass production and nutrient demand. Overall, the improved nutrient uptake aligns with observed changes in soil pH, EC, and nutrient availability, confirming that biochar application, especially when combined with FYM, plays a key role in improving nutrient use efficiency and crop performance in acidic soils.

3.4 | Effect on soil pH and EC

Biochar application significantly ($p < 0.05$) influenced soil pH and electrical conductivity (EC) across treatments (Fig. 4). Soil pH increased progressively with increasing biochar rates and was higher under biochar + FYM combinations compared to the control. The lowest soil pH (7.26) was recorded under the control treatment, while the highest pH values (7.64) were observed under treatments receiving higher biochar doses, particularly $F_1CRB_8M_5$, indicating the liming effect of biochar in acidic soil. Soil EC also showed an increasing trend with biochar addition. Treatments amended with higher biochar rates exhibited greater EC values compared to the control and FYM-alone treatments, reflecting the contribution of soluble salts and ash-derived nutrients from biochar. The maximum EC (0.59 dS m^{-1}) was recorded under $F_1CRB_8M_5$, whereas the lowest EC (0.19 dS m^{-1}) occurred in the control treatment. The increase in soil pH with biochar application observed in this study confirms its effectiveness as an acidity-ameliorating amendment in acidic soils. Recent studies have shown that biochar raises soil pH through the release of base cations and ash components, thereby improving soil chemical conditions and nutrient availability, particularly when applied at higher rates or in combination with organic amendments (Deng *et al.,* 2025). The rise in soil EC with increasing biochar rates reflects the contribution of soluble ions and ash-derived nutrients from biochar. Similar moderate increases in EC without salinity risk have been reported in recent meta-analyses and are associated with improved nutrient pools and ion exchange processes (Asirifi *et al.,* 2025). Overall, the concurrent increase in soil pH and EC indicates an improvement in the soil chemical environment, which likely enhanced nutrient availability and contributed to improved crop performance in the present study.

3.5 | Effect on Soil Fertility

Soil fertility parameters, particularly SOC, P, and K, were significantly ($p < 0.05$) influenced by biochar-based treatments after harvest of okra and brinjal during both years. Across seasons, treatments integrating biochar with FYM and RDF consistently improved soil fertility compared to the control and sole fertilizer treatments. SOC content increased markedly under biochar-amended treatments, with the highest SOC (1.03%) recorded under $F_1CRB_8M_5$ (RDF + crop residue biochar @ 8 g kg^{-1} soil + FYM @ 5 g kg^{-1} soil). Compared to the control ($F_0B_0M_0$), SOC under $F_1CRB_8M_5$ increased by about 114%, followed by $F_1WCB_8M_5$ (0.91%) and $F_1CRB_8M_0$ (0.90%) (Fig. 4). The improvement was consistent in both years, indicating the persistent and cumulative nature of biochar-derived carbon in soil. CRB contributed more effectively to SOC build-up than WCB, likely due to its higher labile carbon fraction and ash content. The increase in SOC under biochar + FYM combinations can be attributed to the high aromatic carbon content and long mean residence time of biochar, which stabilizes soil carbon pools and protects native organic matter from microbial decomposition (Song *et al.*, 2024). FYM further enhances carbon inputs and promotes microbial aggregation, leading to greater physical protection of organic carbon within soil aggregates, while co-application of biochar with organic amendments improves nutrient retention and microbial biomass (Nkrumah *et al.,* 2025). Recent studies have emphasized that integrating biochar with organic manures accelerates carbon sequestration while simultaneously improving soil biological activity and ecosystem multi-functionality in vegetable-based systems (Bi *et al.,* 2024). Available phosphorus also showed a significant ($p < 0.05$) improvement under biochar-amended treatments. The highest available P (70.5 kg ha^{-1}) was observed under $F_1CRB_8M_5$, recording an increase of about 170% over the control, followed by $F_1WCB_8M_5$ (70.1 kg ha^{-1}) (Fig. 5). The increase was more pronounced in the second year, suggesting a residual effect of biochar on P dynamics. Biochar is known to reduce P fixation by Fe and Al oxides in acidic to neutral soils and to enhance P availability through ash-derived P and improved microbial-mediated mineralization (Zhang *et al.,* 2025). The synergistic role of FYM further enhanced P solubilization through organic acid production and phosphatase activity, resulting in improved P availability to crops.

Similarly, soil available K increased significantly ($p < 0.05$) with biochar application, particularly under $F_1CRB_8M_5$ (353 kg ha^{-1}), which showed 27.7% higher available K than the control (Fig. 5). Crop residue biochar was more effective than woody biochar in enhancing soil K due to its higher inherent K content and ash fraction. The increase in available K was sustained across both years, indicating reduced K leaching losses and improved K retention in the soil exchange complex. Recent studies have highlighted biochar ability to act as a slow-release source of potassium while simultaneously enhancing K use efficiency through improved cation retention (Sharma *et al.,* 2025). Overall, the results clearly demonstrate that biochar alone is insufficient to maximize soil fertility, whereas its integration with FYM and RDF, particularly under $F_1CRB_8M_5$, substantially improves SOC sequestration and nutrient availability. The observed improvements in soil fertility provide a mechanistic explanation for the enhanced growth and yield of okra and brinjal under integrated biochar-based nutrient management and underline the importance of combining stable carbon inputs with organic and mineral nutrient sources for sustaining soil productivity in intensive vegetable systems.

4 | Limitations of The Study

The present study provides valuable insights into biochar-based integrated nutrient management. The experiment was conducted under controlled pot conditions, which restrict root proliferation and reduce environmental variability relative to open-field systems. Further the soils of Belpada, Odisha have been studied in Central India, these factors may alter nutrient retention and amplify treatment effects; therefore, the quantitative responses observed may not equally translate to field-scale productivity. Also, biochar is known for its long-term persistence and gradual soil interaction processes that extend over decades; however, this two-year study captures only initial responses and may not fully represent stabilization dynamics, long-term carbon sequestration, or sustained agronomic impacts.

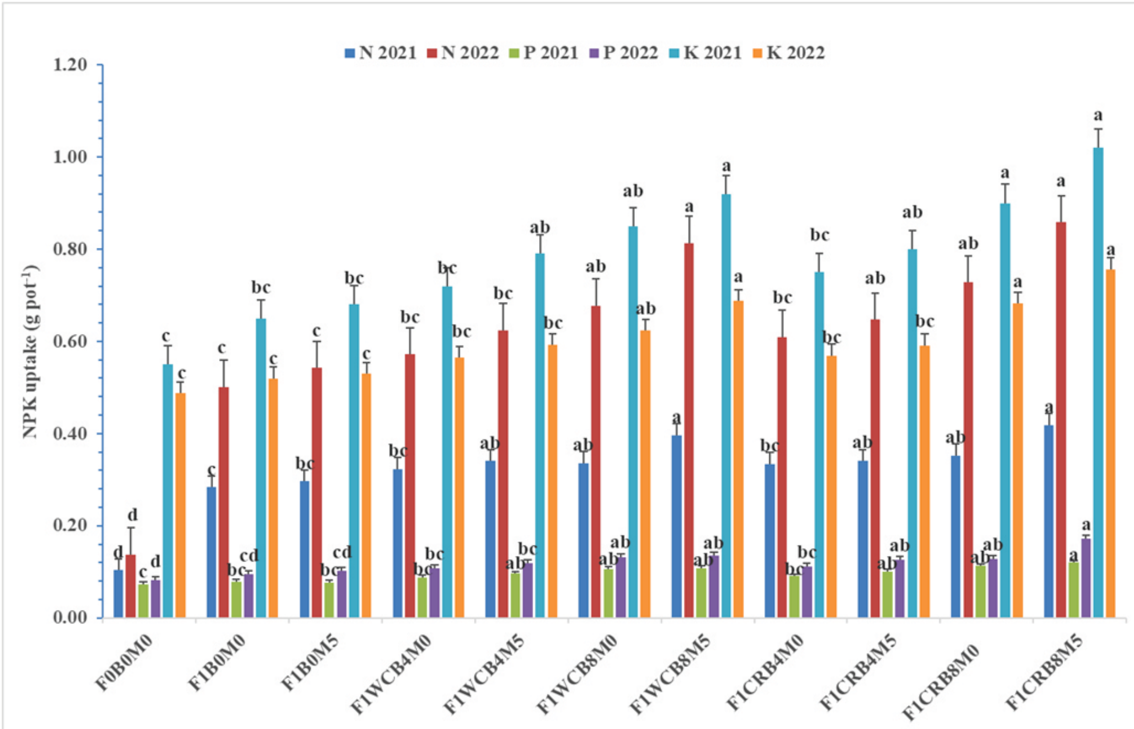

FIGURE 2 Nitrogen (a), phosphorus (b) and potassium (c) uptake (g pot^{-1}) by okra under different treatments during 2021 and 2022. Error bars indicate LSD ($p < 0.05$). Treatment means with similar superscripted letters within a column are not significantly different at $P < 0.05$ according to Duncan's Multiple Range Test.

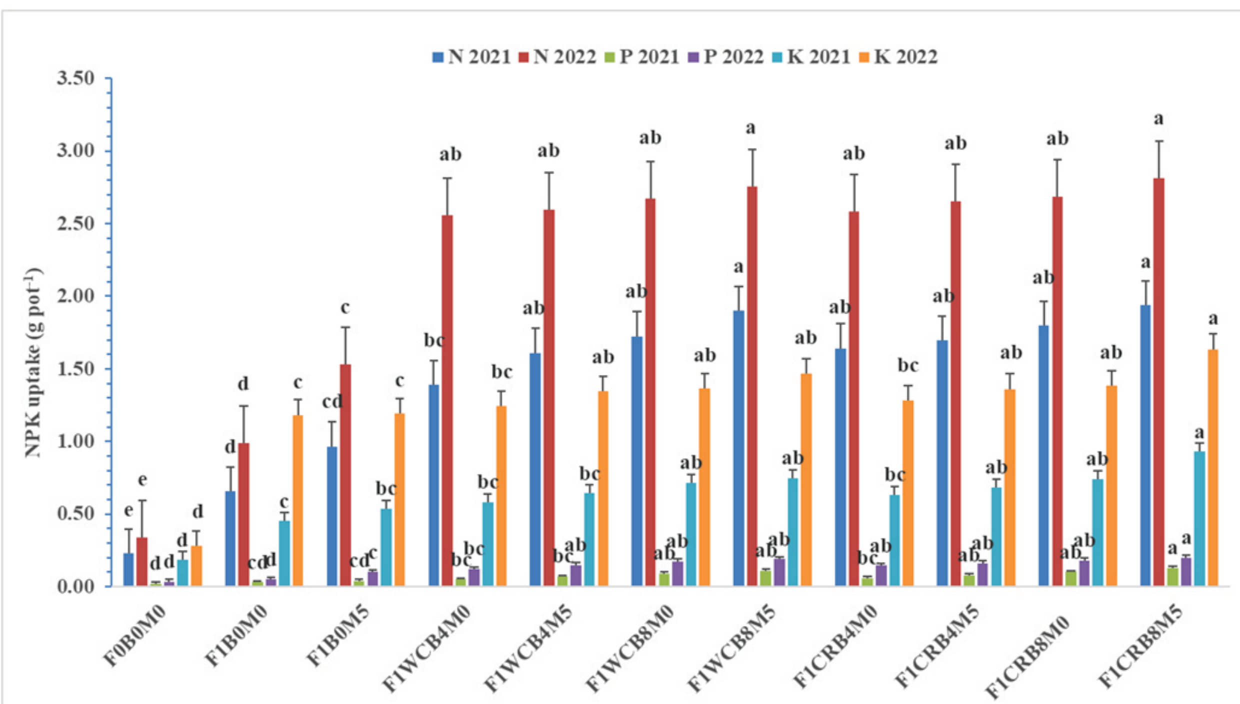

FIGURE 3 Nitrogen (a), phosphorus (b) and potassium (c) uptake (g pot^{-1}) by brinjal under different treatments during 2021 and 2022. Error bars indicate LSD ($p < 0.05$). Treatment means with similar superscripted letters within a column are not significantly different at $P < 0.05$ according to Duncan's Multiple Range Test.

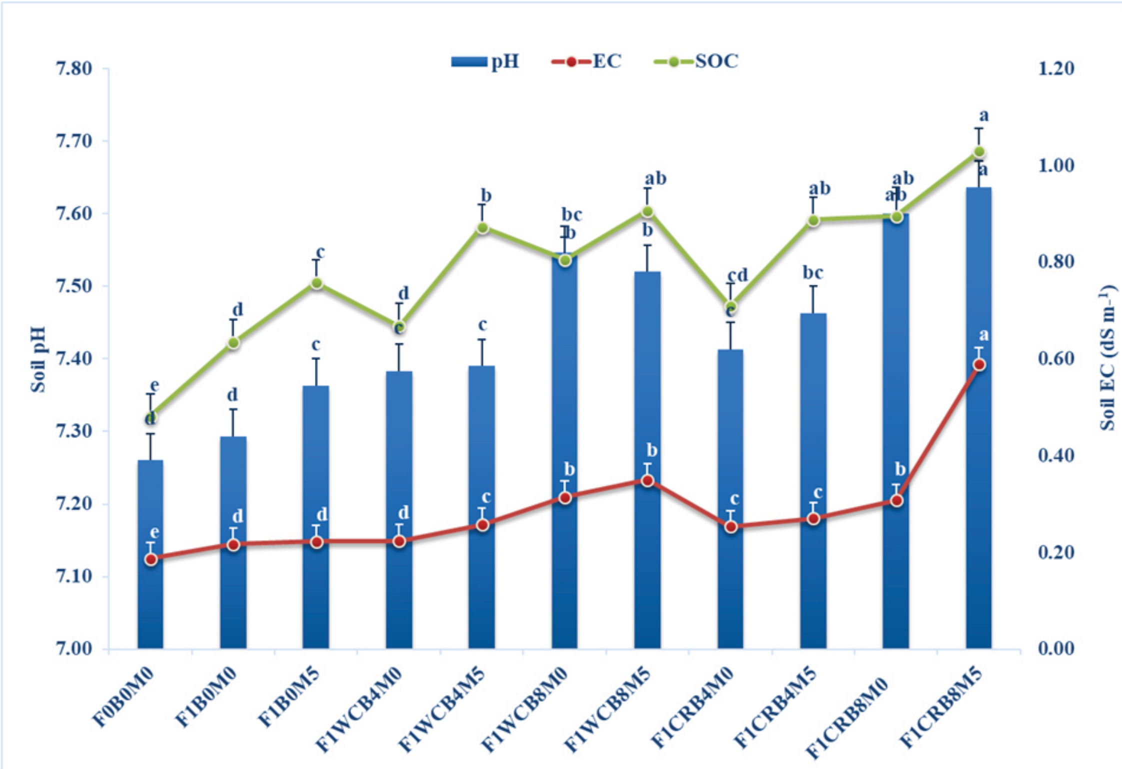

FIGURE 4 Effect of different biochar treatments on soil pH, EC, and SOC measured after two-years period (post-harvest). Error bars indicate LSD ($p < 0.05$). Treatment means with similar superscripted letters within a column are not significantly different at P <0.05 according to Duncan's Multiple Range Test.

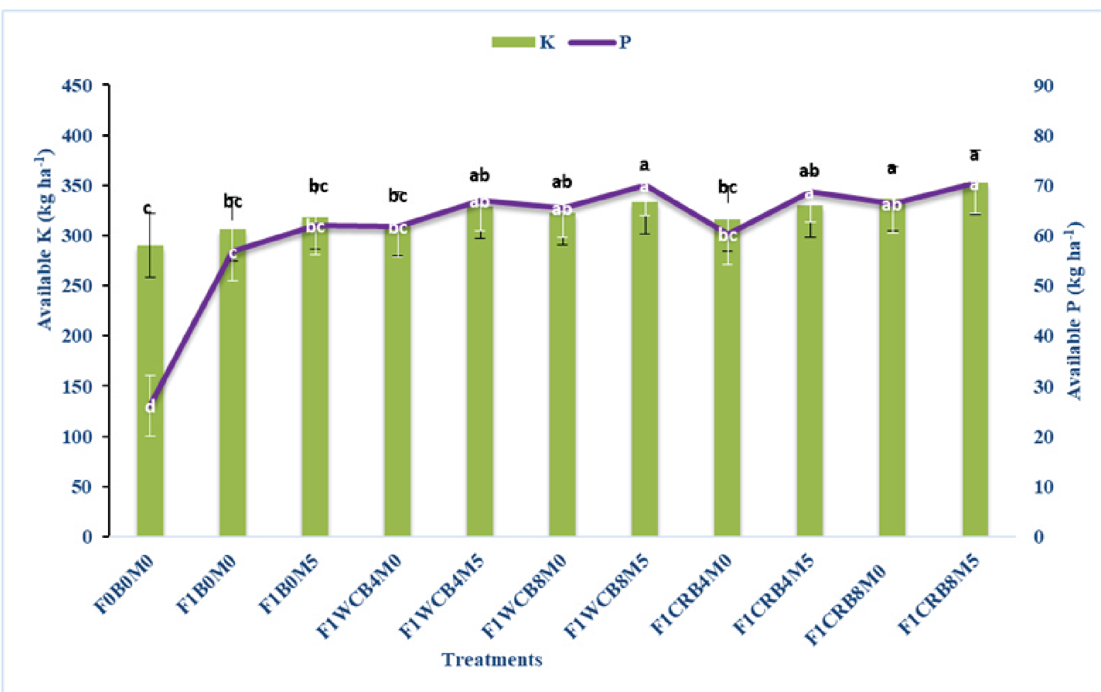

FIGURE 5 Effect of different biochar treatments on soil available P and K measured after two-years period (post-harvest). Error bars indicate LSD ($p < 0.05$). Treatment means with similar superscripted letters within a column are not significantly different at P <0.05 according to Duncan's Multiple Range Test.

5 | CONCLUSIONS

The present pot study demonstrated that integrated application of biochar, FYM and RDF significantly enhanced growth, fruit yield, nutrient uptake and soil fertility of okra and brinjal grown in an Inceptisol. Among the treatments, CRB @ 8 g kg^{-1} soil combined with FYM @ 5 g kg^{-1} soil and RDF consistently produced the best results. Improvements in crop productivity were closely associated with enhanced SOC, nutrient availability, and improved soil chemical environment, confirming synergistic interactions between stable carbon inputs and nutrient amendments. The biochar rate used in the best treatment (8 g kg^{-1} soil) corresponds to approximately 17 t ha^{-1} under field conditions. Considering a typical biochar production efficiency of about 25–35% from dry biomass, producing 17 t ha^{-1} of biochar would require roughly 50–70 t of crop residues such as groundnut shells, mustard residues, or rice husk. While this requirement is substantial, biochar production can be feasible in regions with surplus agricultural residues where alternative uses are limited. Although the findings are derived from controlled pot conditions and therefore require validation under field environments, the results clearly indicate that biochar alone is insufficient, whereas its integration with FYM and mineral fertilizers provides synergistic benefits for nutrient availability, carbon stabilization and vegetable productivity. Therefore, crop residue biochar @ 8 g kg^{-1} soil integrated with FYM and RDF can be considered a promising component of sustainable nutrient management strategies for vegetable-based systems in Inceptisols, Future research should focus on long-term field trials, uniform varietal testing, expanded treatment structures, and multi-location validation to refine agronomic recommendations and quantify ecosystem-scale impacts.

ACKNOWLEDGMENTS

The authors sincerely acknowledge the financial and technical support provided by the GIZ, ICRAF, New Delhi, India.

CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

Data will be made available on request.

AUTHOR'S CONTRIBUTION

Brij Lal Lakaria, Pramod Jha, BP Meena, Vassanda Coumar, AK Vishwakarma: Conceptualization, conducting pot study, methodology, writing original manuscript; Brij Lal Lakaria: Lab analysis, data collection; Statistical analysis; Brij Lal Lakaria, Aqeel Hasan Rizvi, S.K. Dhyani, Javed Rizvi, Monitoring and supervision; Brij Lal Lakaria, Pramod Jha, Dinesh Jinger: Interpretations, writing and reviewing.

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How to cite this article: Lakaria, B.L., Jha, P., Meena, B.P., Coumar, V., Vishwakarma, A.K., Rizvi, A.H., Dhyani, S.K., Jinger, D., 2026. Evaluation of Different Biochar Sources on Growth, Yield and Soil Fertility of Okra and Brinjal in Inceptisol from Odisha: A Pot Study. *Indian J. Soil Cons*., **54(1): 62-73**