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Influence of Biochar and Inorganic Fertilizer on Soil Properties, Growth, Yield and Quality Parameters of French Bean (*Phaseolus vulgaris* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. Author AM conceived the original idea and designed the model methodology, investigation, data curation, formal analysis, and visualization, and wrote the original draft. Author AKS provided scientific supervision, conceptualization, research guidance, methodology, research design, intellectual input, validation of the computational framework, and manuscript refinement. Author OK performed investigation, laboratory analysis, data curation, formal analysis, and visualization, wrote the original draft, and reviewed and edited the manuscript. Author SK provided supervision, conceptualization, guidance in research methodology, interpretation of results, and critical review and revision of the manuscript. All authors read and approved the final manuscript.

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Abstract

French bean (*Phaseolus vulgaris* L.) is an important legume vegetable crop; the integrated use of biochar with inorganic fertilisers may improve soil properties, nutrient availability and nutrient-use efficiency. Therefore, evaluating this approach is important for achieving sustainable and productive French bean cultivation in the Inceptisols of the Kanpur region. A field experiment was conducted at the Student's Instructional Farm, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur, Uttar Pradesh, during the *Rabi* season of 2025-26 to evaluate the effect of graded levels of biochar and fertiliser on the growth, yield-attributing characters and yield of French bean (*Phaseolus vulgaris* L.) cv. Arka Komal grown on a sandy loam Inceptisol. The experiment comprised eight distinct treatment combinations (T_1 to T_8) evaluated in a randomised block design with three replications. The treatments incorporated varying levels of the recommended dose of fertiliser (RDF), namely 100%, 75%, and 50% RDF, together with biochar application rates of 1, 1.5, and 2 t ha-1. Growth, yield-attributing characters and yield were significantly influenced by treatment: T_4 (100% RDF + biochar @ 2.0 t ha^{-1}) recorded the maximum plant height of 14.50 cm at 30 days after sowing (DAS) and 45.12 cm at 60 DAS. Furthermore, the highest pod length (12.34 cm), number of pods plant^{-1} (32.42), seed index (42.12 g), seed yield (16.85 q ha^{-1}), straw yield (27.68 q ha^{-1}) and biological yield (44.53 q ha^{-1}) were recorded under treatment T_4, representing a substantial seed yield increase of approximately 31.03% over the control treatment (T_8: 50% RDF + Biochar @ 2.0 t ha^{-1}). Harvest index (35.42–37.84%) did not differ significantly among treatments. Combining the full recommended fertiliser dose with biochar @ 2.0 t ha^{-1} was an effective option for improving French bean productivity on the alluvial Inceptisols of the Central Plain Zone of Uttar Pradesh.

Keywords: Biochar; French bean; Inceptisol; growth attributes; yield attributes; nutrient use efficiency; sustainable agriculture.

1. Introduction

French bean (*Phaseolus vulgaris* L.) is an important leguminous vegetable and pulse crop of the family Fabaceae, cultivated globally, with production of about 26 million tonnes annually (Food and Agriculture Organization of the United Nations, n.d.), and valued for its protein-rich pods and seeds. In India, the crop is grown on about 137.54 thousand hectares with an annual production of 1370.21 thousand metric tonnes and an average productivity of 9.96 t ha^{-1} (Directorate of Economics and Statistics, n.d.), and it occupies an important place in the diversified cropping systems of Uttar Pradesh.

It contributes to soil fertility through biological nitrogen fixation yet the productivity of French bean remains limited by declining soil fertility and low nutrient utilisation efficiency due to the continued, uneven application of inorganic fertilisers (Bhupenchandra *et al.,* 2022). Integrated nutrient management combining inorganic fertilisers with organic amendments is widely recommended to increase nutrient-use efficiency and productivity while limiting further deterioration of soil quality (Bhupenchandra *et al.,* 2022).

Recent evidence indicates that biochar responses are strongly conditioned by soil texture, application rate, and initial soil properties, while improved nutrient retention can contribute to higher crop productivity in coarse-textured soils (Bekchanova et al., 2024). Field studies further show that biochar-based nutrient management can improve nutrient-use efficiency and crop performance by moderating nutrient release and sustaining soil nutrient availability, although the magnitude of response depends on the amendment formulation and cropping context (Mustaffa et al., 2024; Khan et al., 2024). Recent reviews also emphasize that the effects of biochar on soil fertility and crop yield vary with feedstock characteristics, pyrolysis conditions, soil properties, and management practices, supporting site-specific evaluation rather than an assumption of uniform agronomic response (Okine et al., 2026; Singh et al., 2026).

Biochar, a stable carbon-rich material produced by burning biomass under oxygen-limited conditions, has emerged as a promising soil amendment for sustainable crop production (Turyasingura & Chavula, 2022). Due to its porous structure, high specific surface area, and functional surface groups, biochar improves the retention of nutrients in soil, water retention, microbial activity, and the ability to exchange cations, while reducing nutrient losses due to leaching and volatilisation (Lehmann & Joseph, 2024; Agegnehu *et al.,* 2016; Jeffery *et al.*, 2017). When used in combination with inorganic fertilisers, biochar can further improve the efficiency of fertiliser application by increasing nutrient retention and promoting the progressive release of nutrients in the root zone (Uwingabire *et al.*, 2024). As the effectiveness of biochar is strongly influenced by soil characteristics, particularly soil response and structure (Çığ *et al.*, 2026), the response of French bean to graded combinations of biochar and recommended inorganic fertilisers in the neutral to slightly alkaline Inceptisols of the central plain zone of Uttar Pradesh is not well understood.

Therefore, the present study was undertaken to evaluate the influence of graded biochar levels in combination with recommended and reduced doses of inorganic fertiliser on soil properties, growth, yield, and quality of French bean under the agro-climatic conditions of the Central Plain Zone of Uttar Pradesh. The combined application of biochar and the recommended fertiliser dose was expected to improve nutrient retention and availability, thereby enhancing crop growth and yield.

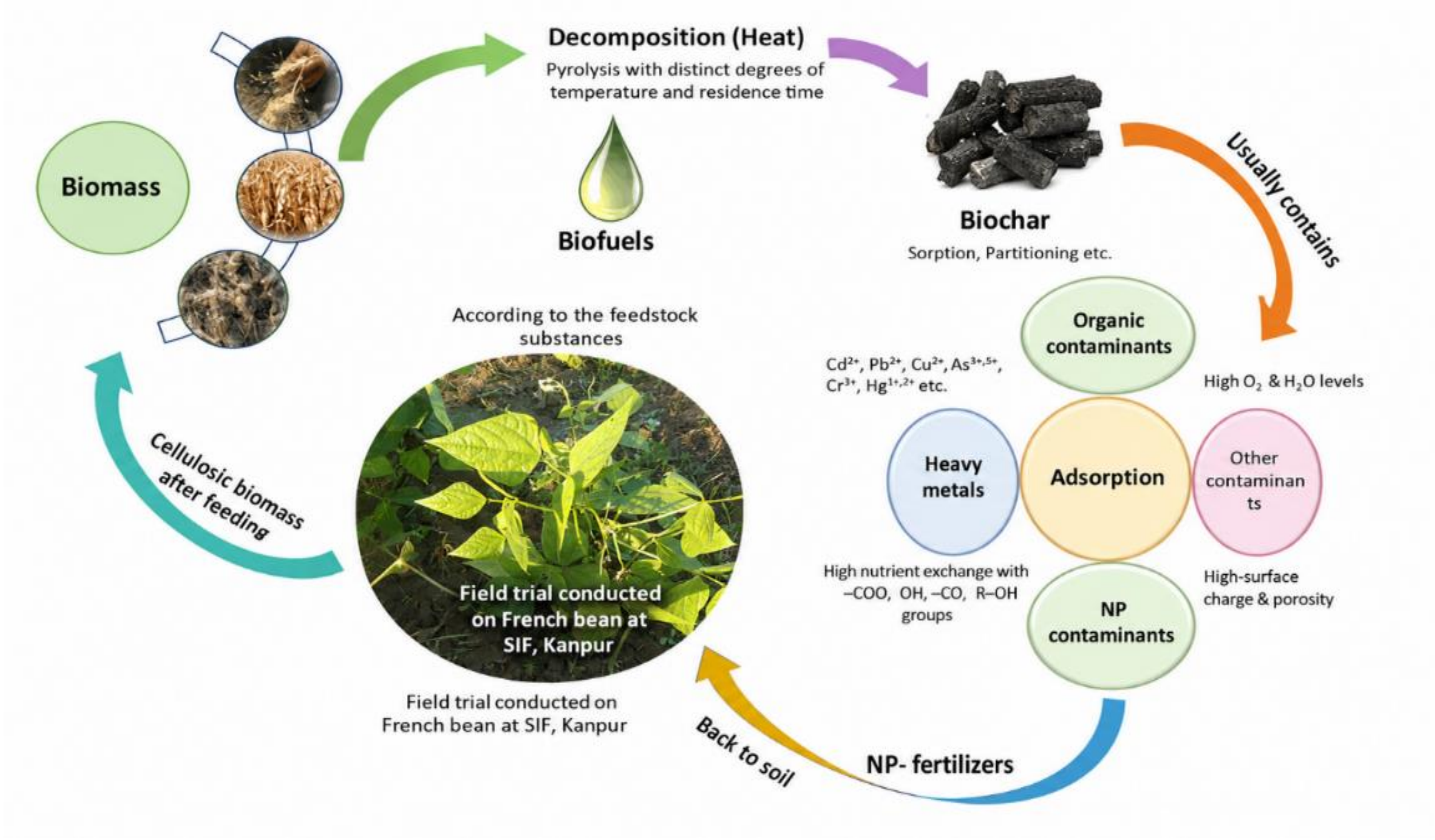

Fig. 1. Schematic representation of the biochar production and soil-plant interaction cycle in the cultivation of French bean

2. Materials and Methods

2.1 Experimental site

The field experiment was conducted during the *Rabi* season of 2025-26 at the Student's Instructional Farm, Chandra Shekhar Azad University of Agriculture and Technology, Kanpur (26.44° N latitude, 80.31° E longitude, 318 m above mean sea level). The site lies on the right bank of the river Ganga within the Central Plain Zone of the Upper Gangetic Plains (Agro-Climatic Zone V) and experiences a subtropical climate with an average annual rainfall of about 880 mm.

2.2 Weather During the Cropping Period

The crop grew between Standard Meteorological Weeks 46 (mid-November 2025) and 6 (February 2026). Maximum temperature during this period ranged from 17.0 to 27.9°C and minimum temperature from 5.6 to 10.8°C. The crop received only 17.5 mm of rainfall, confined to the fourth and fifth weeks of January 2026; morning relative humidity ranged from 84–96% and evening relative humidity from 32–72% (Source: *Meteorological Observatory*, C.S.A.U.A.&T., Kanpur).

2.3 Soil Characteristics

The experimental soil was sandy loam in texture and classified as an Inceptisol. Composite surface samples (0–15 cm), collected from six random spots before land preparation, showed the soil to be neutral to slightly alkaline in reaction (pH 8.12, 1:2.5 soil: water) and low in organic carbon (0.37%) and available nitrogen (168.12 kg ha^{-1}), with moderate available phosphorus (15.25 kg ha^{-1}), high available potassium (215.00 kg ha^{-1}) and an electrical conductivity of 0.35 dSm^{-1}.

2.4 Experimental Design and Treatments

The experiment was laid out in a Randomised Block Design with eight treatments, replicated three times across twenty-four plots of 1 m × 1 m each, separated by a 0.5 m sub-irrigation channel and bund, with a 1 m main irrigation channel: T_1 - 100% RDF; T_2 - RDF + biochar @ 1.0 t ha^{-1}; T_3 - RDF + biochar @ 1.5 t ha^{-1}; T_4 - RDF + biochar @ 2.0 t ha^{-1}; T_5 - 2/3 RDF + biochar @ 1.0 t ha^{-1}; T_6 - 2/3 RDF + biochar @ 1.5 t ha^{-1}; T_7 - 2/3 RDF + biochar @ 2.0 t ha^{-1}; T_8 - 1/2 RDF + biochar @ 2.0 t ha^{-1}. The recommended dose of fertiliser for French bean was 120:60:60 $N:P_2O_5:K_2O$ kg ha^{-1}, supplied through urea, diammonium phosphate and muriate of potash, respectively, and applied as a basal dose at sowing; biochar, where included, was incorporated into the soil at the same time.

2.5 Crop and Cultivation Details

French bean cv. Arka Komal was sown manually at a seed rate of 30 kg ha^{-1} in furrows on 15 November 2025, with row spacing maintained as per the recommended package of practices. The crop was irrigated twice through a tubewell (1 December 2025 and 25 December 2025) and hand-weeded twice, at 30 and 50 days after sowing (DAS). Gap filling was carried out at 20 DAS to maintain a uniform plant stand. The crop was harvested at physiological maturity on 10 February 2026 with a crop duration of about 87 days. The harvested crop was sun-dried for three days, threshing and winnowing were performed manually; observations were recorded from the central, guarded area of each plot to avoid border effects.

2.6 Observations Recorded

Plant height was measured from the base of the plant to the tip of the longest shoot at 30 and 60 DAS. At harvest, pod length was measured on ten randomly tagged pods per plot, and the number of pods per plant was counted on five randomly selected plants. Seed index was recorded as the weight of 1000 cleaned seeds. Seed and straw yield were recorded plot-wise and expressed on a hectare basis (q ha^{-1}); biological yield was computed as the sum of seed and straw yield, and harvest index as the percentage ratio of seed yield to biological yield.

2.7 Statistical Analysis

Data for each character were analysed using the analysis of variance (ANOVA) technique appropriate for a Randomised Block Design, following the standard procedures described by Gomez and Gomez (1984). Treatment means were compared using the critical difference (CD) at $P \leq 0.05$; treatment effects with a calculated F-value below the tabulated value at this probability level are reported as non-significant (NS).

3. Results and Discussion

3.1 Soil Analysis

3.1.1 Soil pH

The post-harvest soil pH values ranged from 7.68 to 8.12, showing an overall variation of 0.44 pH units among treatments. The lowest pH (7.68) was recorded under T_4, whereas the highest pH (8.12) was observed under T_1 (100% RDF) (Fig. 2). The differences among treatments were statistically non-significant. Biochar caused a slight reduction in soil pH due to microbial activity and organic acid production. However, the change was small and non-significant, indicating that biochar maintained a favourable soil environment.

3.1.2 Soil Electrical conductivity (dSm^{-1})

The post-harvest soil EC values ranged from 0.27 to 0.35 dSm^{-1}, with a variation of 0.08 dSm^{-1}. The lowest EC (0.27 dSm^{-1}) was observed under T_4, while the highest EC (0.35 dSm^{-1}) was recorded under T_1 (Fig. 2). However, the treatment differences were statistically non-significant. Biochar slightly reduced EC by adsorbing soluble ions and improving nutrient retention and drainage. The non-significant change indicated that biochar did not cause any salinity problems.

3.1.3 Soil organic carbon (%)

The organic carbon content was significantly influenced by the treatments and ranged from 0.37 to 0.44%, with an overall variation of 0.07%. The highest organic carbon content (0.44%) was recorded under T_4, followed by T_3 (0.43%) and T_2 (0.42%). The lowest value (0.37%) was observed under T_1 (Fig. 2). Treatment T_4 showed an increase of approximately 18.92% over T_1. Biochar significantly increased soil organic carbon because of its high and stable carbon content. This improvement enhanced soil aggregation, water retention, nutrient availability and overall soil fertility.

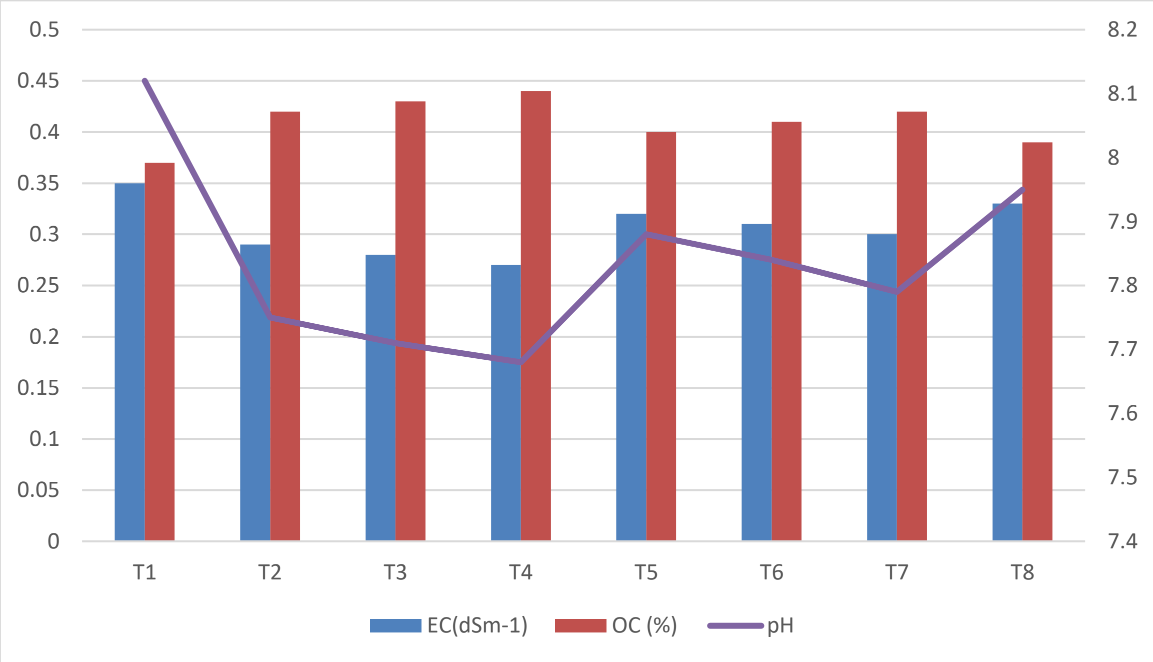

Fig. 2. Effect of biochar and inorganic fertilizers on soil pH, EC (dSm^{-1}) and Organic Carbon (%)

3.1.4 Soil Available Nitrogen (kg ha^{-1})

The soil available nitrogen varied significantly among treatments and ranged from 165.05 to 185.12 kg ha^{-1}, with an overall variation of 20.07 kg ha^{-1}. The highest available nitrogen (185.12 kg ha^{-1}) was recorded under T_4, whereas the lowest value (165.05 kg ha^{-1}) was observed under T_1 (Fig. 3). The increase under T_4 over T_1 was approximately 12.16%. Biochar increased available nitrogen by reducing nitrogen losses and providing a favourable environment for soil microorganisms. This improved nitrogen availability and contributed to better crop growth and yield.

3.1.5 Soil Available Phosphorus (kg ha^{-1})

The available phosphorus content ranged from 15.21 to 18.85 kg ha^{-1}, with an overall variation of 3.64 kg ha^{-1}. The highest available phosphorus (18.85 kg ha^{-1}) was recorded under T_4, while the lowest value (15.21 kg ha^{-1}) was observed under T_1 (Fig. 3). Treatment T_4 increased available phosphorus by approximately 23.93% over T_1. Biochar improved phosphorus availability by reducing phosphorus fixation and enhancing nutrient retention and microbial activity. The increased phosphorus availability supported better root growth and crop performance.

3.1.6 Soil Available Potassium (kg ha^{-1})

The available potassium differed significantly among treatments and ranged from 212.34 to 235.42 kg ha^{-1}, with an overall variation of 23.08 kg ha^{-1}. The highest available potassium (235.42 kg ha^{-1}) was recorded under T_4, followed by T_3 (232.56 kg ha^{-1}) and T_2 (229.61 kg ha^{-1}). The lowest value (212.34 kg ha^{-1}) was observed under T_1 (Fig. 3). Treatment T_4 recorded an increase of approximately 10.87% over T_4. Biochar increased available potassium through the release and retention of potassium in the soil. Higher potassium availability improved nutrient uptake, growth, yield attributes and overall productivity of French bean.

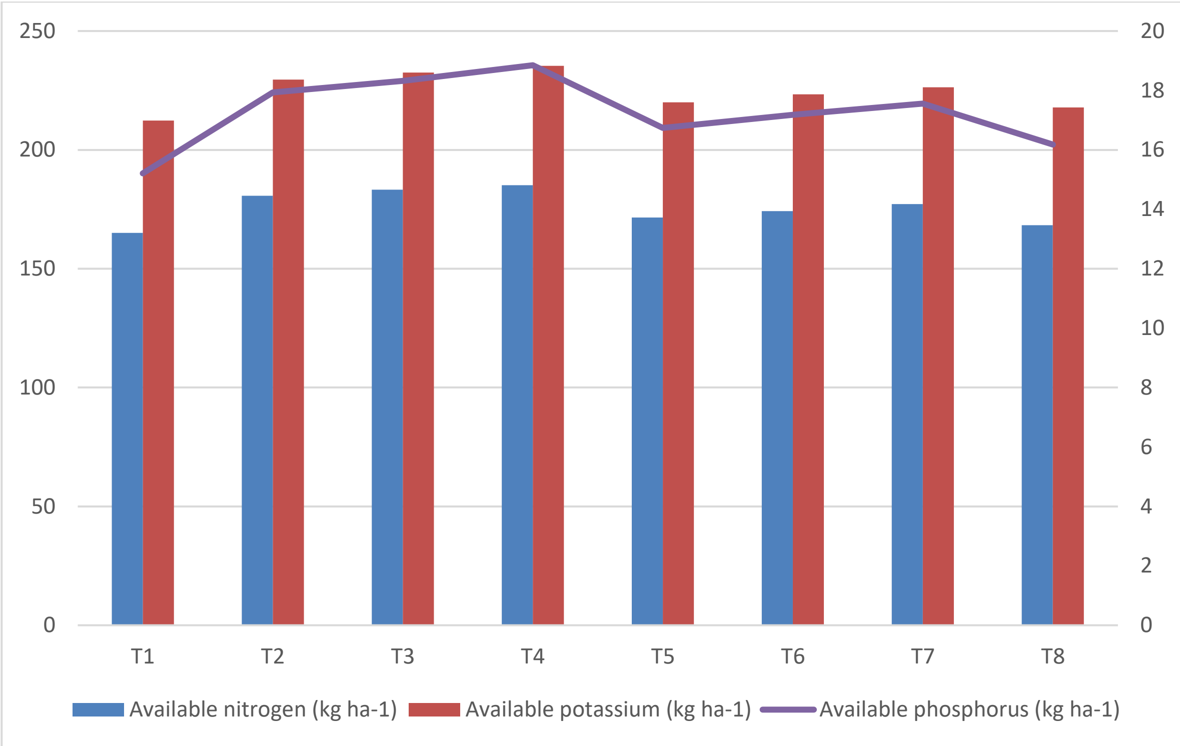

Fig. 3. Effect of biochar and inorganic fertilizers on soil available nitrogen, phosphorus and potassium (kg ha^{-1})

3.2 Plant Analysis

3.2.1 Plant Height

Plant height differed significantly among treatments at both 30 and 60 DAS (Table 1). The tallest plants were recorded under T_4 (100% RDF + biochar @ 2.0 t ha^{-1}) at both stages, exceeding the shortest treatment, T_8, by 29.0% at 30 DAS and 24.9% at 60 DAS. Plants receiving a reduced fertiliser dose (T_5-T_7) remained shorter than the corresponding full-RDF treatments (T_2-T_4) despite receiving biochar, indicating that biochar alone could not substitute for an adequate nutrient supply. The taller growth under T_4 is consistent with biochar's reported role in improving nutrient retention and moisture availability within the root zone, which may have supported greater cell elongation and chlorophyll synthesis (Kumari *et al.*, 2022; Gudade *et al.*, 2023). The results indicate that biochar effectively enhanced the efficiency of applied fertilisers and sustained crop growth throughout the vegetative phase. Therefore, the integrated application of RDF and biochar at 2.0 t ha^{-1} was most effective in improving plant growth and biomass accumulation in French bean.

Table 1. Effect of biochar and inorganic fertilizers on plant height (cm) of French bean at 30 and 60 DAS

Treatment	Treatment description	Plant height (cm) 30 DAS	Plant height (cm) 60 DAS
T_1	100% RDF	11.78	37.42
T_2	RDF + Biochar @ 1.0 t ha^{-1}	13.41	43.83
T_3	RDF + Biochar @ 1.5 t ha^{-1}	14.06	44.58
T_4	RDF + Biochar @ 2.0 t ha^{-1}	14.50	45.12
T_5	2/3 RDF + Biochar @ 1.0 t ha^{-1}	12.23	38.54
T_6	2/3 RDF + Biochar @ 1.5 t ha^{-1}	12.65	40.98
T_7	2/3 RDF + Biochar @ 2.0 t ha^{-1}	13.02	42.36
T_8	1/2 RDF + Biochar @ 2.0 t ha^{-1}	11.24	36.11
	CD at 5%	0.62	1.91
	SE(m)±	0.20	0.62

3.2.2 Pod Length and Number of Pods Per Plant

Pod length and the number of pods per plant were also highest under T_4 and lowest under T_8 (Table 2), a difference of 48.3% for pod length and 23.2% for pods per plant. Biochar improved soil moisture retention and nutrient availability, thereby supporting reproductive growth and pod elongation. Adequate availability of nitrogen, phosphorus and potassium during flowering and pod development enhanced cellular expansion and carbohydrate accumulation within pods. Because pod length is closely tied to marketable yield, this response is agronomically important; it may reflect improved translocation of assimilates to developing pods under adequate, steadily available nutrition, a mechanism also proposed for French bean (Gudade *et al.,* 2023; Patel *et al.,* 2025).

Since pod number depends on flower retention as much as on vegetative vigour, the higher pod count under T_4 may be attributed to increased photosynthetic activity and assimilate production under biochar-amended treatments, which may have promoted greater flower retention and reduced flower drop. Kumari et al. (2022) similarly linked biochar-mediated improvement in pod and seed traits of French bean to enhanced potassium retention in the root zone rather than nitrogen supply alone. Comparable gains in pod number under combined nutrient and biochar management were also reported (Uwingabire *et al.,* 2024; Kadam *et al.,* 2020).

Seed index was 13.7% higher under T_4 than under T_8. Larger, better-filled seeds under T_4 are consistent with improved nutrient availability during grain filling. Biochar also enhanced root growth and nutrient-use efficiency, ensuring a continuous nutrient supply during reproductive stages. This is in line with the improvement in seed weight reported for French bean under integrated biochar and nutrient management (Singh *et al.,* 2023; Changkiri *et al.,* 2024).

Table 2. Effect of biochar and inorganic fertilizers on pod length, pods plant^{-1} and seed index of French bean

Treatment	Treatment description	Pod length (cm)	Pods plant^{-1}	Seed index (g)
T_1	100% RDF	9.02	27.62	38.02
T_2	RDF + Biochar @ 1.0 t ha^{-1}	11.05	30.32	41.24
T_3	RDF + Biochar @ 1.5 t ha^{-1}	11.92	31.87	41.78
T_4	RDF + Biochar @ 2.0 t ha^{-1}	12.34	32.42	42.12
T_5	2/3 RDF + Biochar @ 1.0 t ha^{-1}	9.89	28.57	38.87
T_6	2/3 RDF + Biochar @ 1.5 t ha^{-1}	10.32	29.26	39.62
T_7	2/3 RDF + Biochar @ 2.0 t ha^{-1}	10.85	29.87	40.56
T_8	1/2 RDF + Biochar @ 2.0 t ha^{-1}	8.32	26.31	37.05
	CD at 5%	0.38	1.49	2.01
	SE(m)±	0.12	0.49	0.66

3.2.3 Seed, Straw, Biological Yield, and Harvest Index

Seed, straw and biological yield were all highest under T_4 and lowest under T_8 (Table 3), with T_4 exceeding T_8 by 31.0%, 18.0% and 22.6%, respectively. The consistently larger margin in seed yield than in straw yield suggests that the treatment improved reproductive efficiency, that is, the conversion of vegetative growth into seed, rather than simply increasing total biomass; biochar improved soil physical conditions and supported efficient nutrient uptake, resulting in greater biomass accumulation and assimilate translocation to seeds. This is broadly consistent with the yield gains reported under integrated biochar–fertiliser management (Uwingabire *et al.,* 2024; Prashanth *et al.,* 2020).

Harvest index ranged narrowly from 35.4 to 37.8% and did not differ significantly among treatments (Table 3). Because seed and straw yield both increased under T_4 relative to T_8 in similar proportion, the stable harvest index indicates that biochar and fertiliser combinations promoted vegetative and reproductive growth together rather than shifting assimilate partitioning towards either; the yield advantage of T_4 is therefore better interpreted as an increase in total productive biomass than as an improvement in partitioning efficiency.

Table 3. Effect of biochar and inorganic fertilizers on seed yield, straw yield, biological yield and harvest index of French bean

Treatment	Treatment description	Seed yield (q ha^{-1})	Straw yield (q ha^{-1})	Biological yield (q ha^{-1})	Harvest index (%)
T_1	100% RDF	14.31	24.98	39.29	36.42
T_2	RDF + Biochar @ 1.0 t ha^{-1}	16.04	26.88	42.92	37.37
T_3	RDF + Biochar @ 1.5 t ha^{-1}	16.45	27.51	43.96	37.42
T_4	RDF + Biochar @ 2.0 t ha^{-1}	16.85	27.68	44.53	37.84
T_5	2/3 RDF + Biochar @ 1.0 t ha^{-1}	14.78	25.67	40.45	36.54
T_6	2/3 RDF + Biochar @ 1.5 t ha^{-1}	15.24	25.97	41.21	36.98
T_7	2/3 RDF + Biochar @ 2.0 t ha^{-1}	15.64	26.48	42.12	37.14
T_8	1/2 RDF + Biochar @ 2.0 t ha^{-1}	12.86	23.45	36.31	35.42
	CD at 5%	2.35	1.273	2.37	NS
	SE(m)±	0.77	0.416	0.76	1.307

4. Conclusion

The study showed that French bean growth, yield attributes, yield, and selected post-harvest soil fertility indicators responded favourably to the combined application of biochar and inorganic fertiliser. Among the eight treatments, T_4 (100% RDF + biochar at 2.0 t ha^{-1}) consistently recorded the highest plant height, pod length, pods per plant, seed index, seed yield, straw yield, biological yield, soil organic carbon, and available nitrogen, phosphorus, and potassium. Seed yield under T_4 reached 16.85 q ha^{-1} and was approximately 31.03% higher than under T_8. In contrast, harvest index did not differ significantly among treatments, and post-harvest soil pH and electrical conductivity also showed non-significant treatment effects. The reduced-fertiliser treatments did not match the performance of the full-RDF treatment combined with biochar, indicating that biochar did not substitute for an adequate fertiliser supply under the conditions of this experiment. The results therefore support 100% RDF combined with biochar at 2.0 t ha^{-1} as the most effective treatment evaluated for French bean under the studied Inceptisol conditions.

5. Limitation

The findings are based on a single field experiment conducted during one Rabi season at one site in Kanpur under sandy loam Inceptisol conditions. The observed treatment responses may therefore vary across seasons, locations, soil types, and contrasting weather conditions. Multi-season and multi-location validation, together with assessment of production economics and longer-term changes in soil properties, would be required before broader recommendations are made.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing 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 manuscript.

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