International Journal of Plant & Soil Science

Volume 38, Issue 9, Page 529-536, 2026; Article no.IJPSS.165397
ISSN: 2320-7035

Economic Evaluation of Lantana Derived Biochar for Enhancing Yield, Nutrient Uptake and Quality of Cauliflower in the Subtropics of Himachal Pradesh, India

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/ijpss/2026/v38i96314

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/165397

Original Research Article

Received: 29/06/2026
Accepted: 01/09/2026
Published: 09/09/2026

Abstract

Background: Biochar application in combination with fertiliser may improve crop productivity and nutrient use while providing an avenue for utilising invasive biomass.
Aims: This study evaluated the effects of *Lantana camara*-derived biochar on cauliflower yield, nutrient uptake, quality and economic returns.
Study Design: The experiment was arranged in a randomised block design with nine treatments and three replications.
Place and Duration of Study: The study was conducted at the Experimental Farm of the Department of Soil Science and Water Management, College of Horticulture and Forestry, Neri, Hamirpur, Himachal Pradesh, from October 2023 to March 2024.

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Cite as: *Sepehya, S., Chauhan, D., Kumar, A., Sharma, D., & Shiwani. (2026). Economic Evaluation of Lantana Derived Biochar for Enhancing Yield, Nutrient Uptake and Quality of Cauliflower in the Subtropics of Himachal Pradesh, India. International Journal of Plant & Soil Science, 38(9), 529–536. https://doi.org/10.9734/ijpss/2026/v38i96314*

Results: The results of the present investigation revealed that the application of 100% RDF + 20.0 t ha^{-1} biochar (T_9) was the most effective treatment among those evaluated, consistently outperforming the remaining treatments across the major parameters studied. This treatment recorded the highest head and stalk yields, along with superior quality attributes of cauliflower, including maximum crude protein (14.26 %), total soluble solids (6.55 ˚Brix) and ascorbic acid content (54.02 mg 100 g^{-1}). These results indicate that the sustained and gradual release of nutrients from biochar at this higher application rate created a favourable rhizosphere environment conducive to vigorous crop growth and development. In addition to yield and quality, treatment T_9 recorded the maximum uptake of essential nutrients (nitrogen, phosphorus, potassium, sulphur, calcium, magnesium, iron, copper, zinc and manganese) by the crop, reflecting the combined benefits of enhanced nutrient availability, improved soil physico-chemical properties and greater microbial activity associated with higher rates of biochar application. From an economic perspective, biochar application resulted in a higher benefit:cost ratio than the treatment receiving farmyard manure (FYM), indicating that the additional input costs associated with biochar preparation and application were compensated for by gains in yield and quality, thereby providing greater economic returns. Among all treatments, T_9 (100% RDF + 20.0 t ha^{-1} biochar) registered the highest increase in the benefit:cost ratio, amounting to 15.88 per cent over the FYM-treated control (T_1).

Conclusions: These findings underscore the potential of biochar derived from invasive species such as *Lantana camara* as an eco-friendly soil amendment capable of reducing dependence on chemical fertilisers while simultaneously enhancing nutrient uptake and crop productivity.

Keywords: Lantana camara biochar; cauliflower; recommended dose of fertiliser; curd yield; nutrient uptake; crude protein; total soluble solids; ascorbic acid; benefit-cost ratio; economic returns

1. Introduction

Modern agricultural production necessitates sustainable fertiliser management through the use of appropriate application rates and sustainable agricultural strategies. In recent years, biochar has become a significant soil amendment. It has been shown to enhance soil fertility and increase crop yield without causing detrimental effects on the soil. Biochar is a carbon-dense product of biomass pyrolysis. This granular, permeable form of charcoal is unique among charcoals because it is used as a soil amendment. Thermal processing of organic biomass to produce biochar increases its surface area and gives it a distinctive capacity to persist in soils with minimal biological degradation (Lehmann et al., 2006). It comprises more than 60 per cent carbon and is rich in numerous nutrients and trace elements vital for crop development. Reintroducing biochar into the soil can rapidly improve carbon sequestration, nitrogen levels and overall soil fertility. Total carbon, organic carbon, total nitrogen, available phosphorus, calcium, magnesium, sodium and potassium can all increase in soil following biochar application (Chan et al., 2007). Additionally, biochar application improves the soil's ability to retain moisture and nutrients, raises soil pH (Yuan et al., 2011) and provides plants with essential nutrients, thereby lessening the need for chemical fertilisers (Bird et al., 2011). Biochar can boost yield by improving the physical, chemical and biological properties of soil. Biochar can be produced from crop residues, forest litter, twigs and animal by-products. Himachal Pradesh has an abundance of biomass, including weeds such as *lantana*. The Kangra, Bilaspur, Hamirpur, Solan, Chamba and Mandi districts are heavily infested with *Lantana*, which is spreading rapidly and has no alternative use. As a noxious invasive plant, *Lantana camara* L., belonging to the family Verbenaceae, has become widely naturalised and often causes allelopathic effects and crop yield loss. Pyrolysis is one of the rapid and effective ways to recycle these organic materials. Therefore, this biomass can be used to produce biochar. Thus, using *Lantana* biomass to produce biochar not only improves soil health sustainably but also enhances farm profitability by reducing fertiliser expenses and increasing productivity.

Recent literature indicates that biochar can influence soil nutrient dynamics and crop productivity, while the magnitude of the response depends on feedstock type, pyrolysis conditions, soil characteristics and application rate (Singh et al., 2026; Okine et al., 2026; Bekchanova et al., 2024). Field studies likewise show that crop yield and nutrient-use efficiency responses to biochar may differ according to the nutrient-management regime and site fertility (Kesamreddy et al., 2025; Sixt et al., 2025).

India is one of the world's leading producers of cauliflower, a crop grown widely across the world. In India, cauliflower covers 473 thousand hectares and produces 9283 thousand metric tonnes annually, with a productivity of 19.6 tonnes per hectare (National Horticulture Board, 2021). Bihar, Uttar Pradesh, Odisha, West Bengal, Assam, Haryana and Maharashtra are among the main cauliflower-producing states. In Himachal Pradesh, the area under cauliflower cultivation, although currently limited, is progressively expanding. The total area and production are estimated at 5,448.09 hectares and 130,233.00 metric tonnes, respectively, with a productivity of 23.9 t ha^{-1} (Directorate of Agriculture, 2021).

However, evidence remains limited on the performance of graded rates of *Lantana*-derived biochar applied with the recommended fertiliser dose for cauliflower under the low-hill subtropical conditions of Himachal Pradesh, particularly with respect to yield, nutrient uptake, quality and economic returns.

Accordingly, the study assessed the effects of graded rates of *Lantana*-derived biochar applied with 100% RDF on cauliflower yield, nutrient uptake and quality.

The present study was undertaken to evaluate the economic viability of biochar utilisation by analysing the benefit-to-cost ratio in cauliflower production.

2. Materials and Methods

The field experiment was carried out at the Experimental Farm of the Department of Soil Science and Water Management, College of Horticulture and Forestry, Neri, Hamirpur, Himachal Pradesh, India (31°41′47.6″ N latitude and 76°28′06.3″ E longitude), at an elevation of 650 metres above mean sea level. The region is classified as sub-montane within the low-hill subtropical zone (Zone I) of Himachal Pradesh. The climate comprises four distinct seasons: winter (December to February), summer (March to June), monsoon (July to September) and autumn (October–November). The region receives an average annual rainfall of 1200 mm, with the monsoon season accounting for 82.0% of the total.

The experiment was arranged in a randomised block design (RBD) with 9 treatments and 3 replications. Treatments included: 100 % RDF + FYM (20t ha^{-1}) (T_1), 100 % RDF + 2.5t ha^{-1} biochar (T_2), 100 % RDF + 5.0t ha^{-1} biochar (T_3), 100 % RDF + 7.5t ha^{-1} biochar (T_4), 100 % RDF + 10.0t ha^{-1} biochar (T_5), 100 % RDF + 12.5 t ha^{-1} biochar (T_6), 100 % RDF + 15.0 t ha^{-1} biochar (T_7), 100 % RDF + 17.5 t ha^{-1} biochar (T_8) and 100 % RDF + 20.0 t ha^{-1} biochar (T_9). During field preparation, biochar and farmyard manure were applied and thoroughly mixed according to the treatments. Urea, single superphosphate and muriate of potash were used as sources of nitrogen, phosphorus and potassium, respectively. According to the treatments, nitrogen supplied through chemical fertiliser was applied in split doses to the respective allocated plots. Full doses of phosphorus and potassium fertilisers were applied at the time of field preparation.

Lantana camara residue was used as the feedstock for biochar production and was collected from the area surrounding the Experimental Farm. The residue was sun-dried, chopped and loaded into a kiln constructed from a cylindrical metal drum with a capacity of 212 litres and a square-shaped opening measuring 16×16cm at the top for loading the residues. The opening could be securely closed using a metal lid (26 x 26 cm) equipped with a 110 cm handle. The loaded kiln was placed on a hearth of three bricks (20 cm high) to ensure proper airflow. Dry twigs were used to ignite the residues through the base vents, initiating partial combustion and generating heat for thermal bio-carbonisation. The process continued until thin blue hot gases and a puff of flame appeared, signalling completion. The kiln was then sealed with soil paste and covered with the metal lid to restrict airflow, thereby enhancing biochar yield. After cooling, the charred material was crushed and sieved into uniform particles for field application, and a sample was collected for further analysis.

Curd yield per plot was calculated by summing the weight of curds from all harvests and was expressed in kg. Curd yield per hectare was calculated from the curd yield per plot and expressed in q ha^{-1}. Stalk yield per plot was calculated by summing the weight of stalks from all harvests and was expressed in kg. Stalk yield per hectare was calculated from the stalk yield per plot and expressed in q ha^{-1}.

The dry-weight nutrient uptake of cauliflower plants was computed by multiplying the nutrient percentage by the curd and stalk dry-matter yield (q ha^{-1}). The curd and stalk nutrient values were averaged to calculate nutrient uptake in cauliflower.

$$\text{Nutrient uptake (kg ha}^{-1}\text{)} = \text{Nutrient content (\%) x Yield (q ha}^{-1}\text{)}$$

$$\text{Total uptake (kg ha}^{-1}\text{)} = \text{Uptake by curd + Uptake by stalk}$$

Using the 2,6-dichlorophenol indophenol visual titration method, the ascorbic acid content of cauliflower curds from each plot was determined. A pink appearance indicated the endpoint of the titration. The following formula was used to calculate the ascorbic acid content, and the result was expressed in mg of ascorbic acid per 100 g of sample (AOAC, 1990).

The total nitrogen content of the curd sample was evaluated using the Micro-Kjeldahl method. Crude protein was computed by multiplying the total nitrogen content of the curd sample by a factor of 6.25, as suggested by Jones (1941), and was expressed as a percentage (%). Total soluble solids were estimated using a hand refractometer. The curd was crushed, and a few drops were placed on the refractometer plate; the result was expressed in degrees Brix (Ranganna, 1986).

The benefit-cost ratio (BCR) is a metric employed in cost-benefit analysis to represent the overall relationship between cultivation costs and total marketable output (yield multiplied by price). The BCR can be interpreted qualitatively. If the BCR is greater than 1, it indicates a positive net return, whereas if it is less than 1, the cost of cultivation is high relative to the returns. The ratio of gross returns per rupee invested was calculated.

3. Results

3.1 Effect of Biochar on Yield

The curd and stalk yields under the various treatments ranged from 157.10 to 265.36q ha^{-1} and 10.08 to 13.93q ha^{-1}, respectively, according to the data shown in Figs. 1 and 2. Curd and stalk yields were highest when 100% RDF + 20t ha^{-1} biochar was applied (T_9) and lowest when 100% RDF + 2.5t ha^{-1} biochar was applied (T_2). According to the statistical analysis, treatment T_9 outperformed all other treatments. The results further indicated that curd and stalk yields increased progressively with increasing biochar application rates from T_2 to T_9. Lower biochar application rates (2.5, 5.0, 7.5, 10.0 and 12.5 t ha^{-1}) recorded lower yields than treatment T_1 (100% RDF + 20 t ha^{-1} FYM), whereas higher biochar rates (15.0, 17.5 and 20.0t ha^{-1}) produced higher yields than T_1. In comparison with FYM, treatments T_2, T_3, T_4 and T_5 were statistically inferior, treatments T_6 and T_7 were statistically at par, and treatments T_8 and T_9 were statistically superior.

3.2 Nutrient Uptake

Data on nutrient uptake by cauliflower under the different treatments are displayed in Figs. 3, 4 and 5. The results indicated that the uptake of N, P, K, S, Ca, Mg, Fe, Cu, Zn and Mn ranged from 48.09 to 85.85 kg ha^{-1}, 9.54 to 19.55kg ha^{-1}, 34.51 to 58.44kg ha^{-1}, 10.60 to 21.68kg ha^{-1}, 7.70 to 16.75kg ha^{-1}, 5.07 to 11.68kg ha^{-1}, 317.88 to 491.96 g ha^{-1}, 70.29 to 122.11 g ha^{-1}, 61.60 to 106.48g ha^{-1} and 53.72 to 94.54g ha^{-1}, respectively. Biochar significantly affected nutrient uptake by cauliflower, with treatment T_9 (100% RDF + 20.0t ha^{-1} biochar) recording the highest nutrient uptake and treatment T_2 the lowest. Nutrient uptake increased with increasing biochar application rates from T_2 to T_9. Lower biochar application rates (2.5-12.5t ha^{-1}) resulted in lower nutrient uptake, whereas higher rates (15.0-20.0t ha^{-1}) led to greater nutrient uptake than treatment T_1 (100% RDF + FYM).

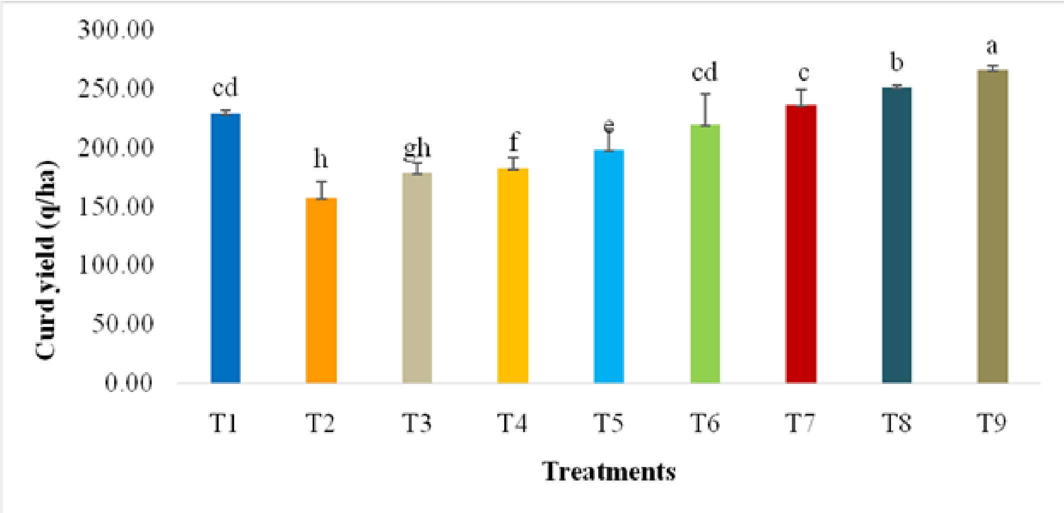

Fig. 1. Effect of biochar on curd yield of cauliflower. [Bars with different letters within each panel are significantly different (P<0.05). Error bar represent standard deviation of the mean]

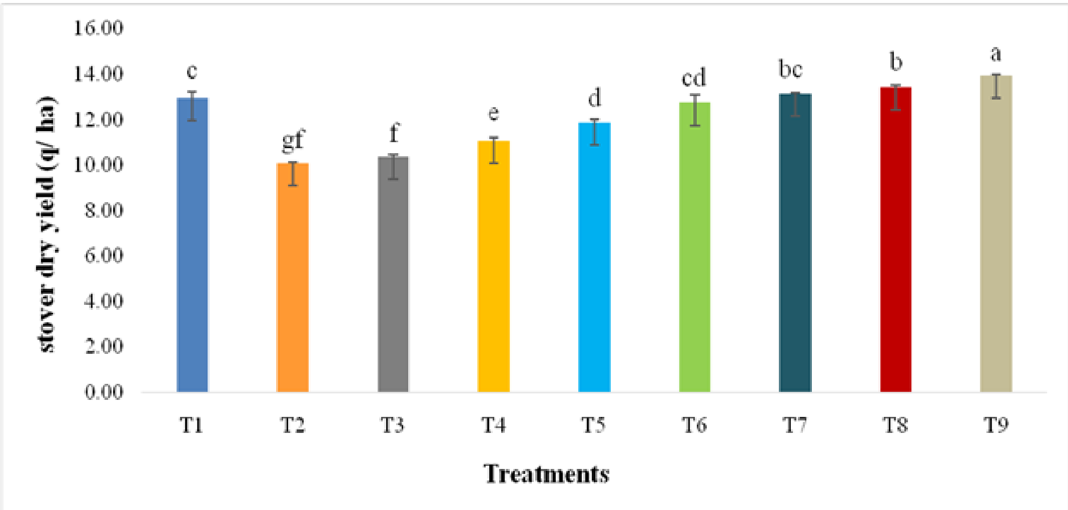

Fig. 2. Effect of biochar on stalk dry yield (q ha^{-1}) of cauliflower. [Bars with different letters within each panel are significantly different (P<0.05). Error bar represent standard deviation of the mean]

3.3 Quality Parameters

The quality parameters of cauliflower were significantly influenced by the different treatments applied (Table 1). Crude protein, total soluble solids (TSS) and ascorbic acid ranged from 13.08 to 14.26 per cent, 6.08 to 6.55 ˚Brix and 52.60 to 54.02 mg 100 g^{-1}, respectively. The highest crude protein, total soluble solids and ascorbic acid values were recorded under treatment T_9 (100% RDF + 20.0 t ha^{-1} biochar), whereas the lowest values were recorded under treatment T_2 (100% RDF + 2.5t ha^{-1} biochar). A progressive improvement in quality parameters was noted as the rate of biochar application increased from T_2 to T_9. In comparison with the FYM treatment, treatments T_2, T_3, T_4 and T_5 were statistically inferior, treatments T_6 and T_7 were statistically at par, and treatments T_8 and T_9 were statistically superior.

3.4 Economic Analysis

The benefit-cost ratio (BCR) of cauliflower production was significantly affected by biochar (Table 2). The highest BCR (3.72) was recorded under treatment T_9 (100% RDF + 20.0 t ha^{-1} biochar), which was statistically at par with treatment T_8 (100% RDF + 17.5t ha^{-1} biochar) and treatment T_7 (100% RDF + 15.0 t ha^{-1} biochar), with BCR values of 3.70 and 3.69, respectively. However, the lowest BCR (3.21) was observed under treatment T_1 (100% RDF + FYM), indicating that the use of FYM resulted in lower economic returns than the treatments that incorporated biochar.

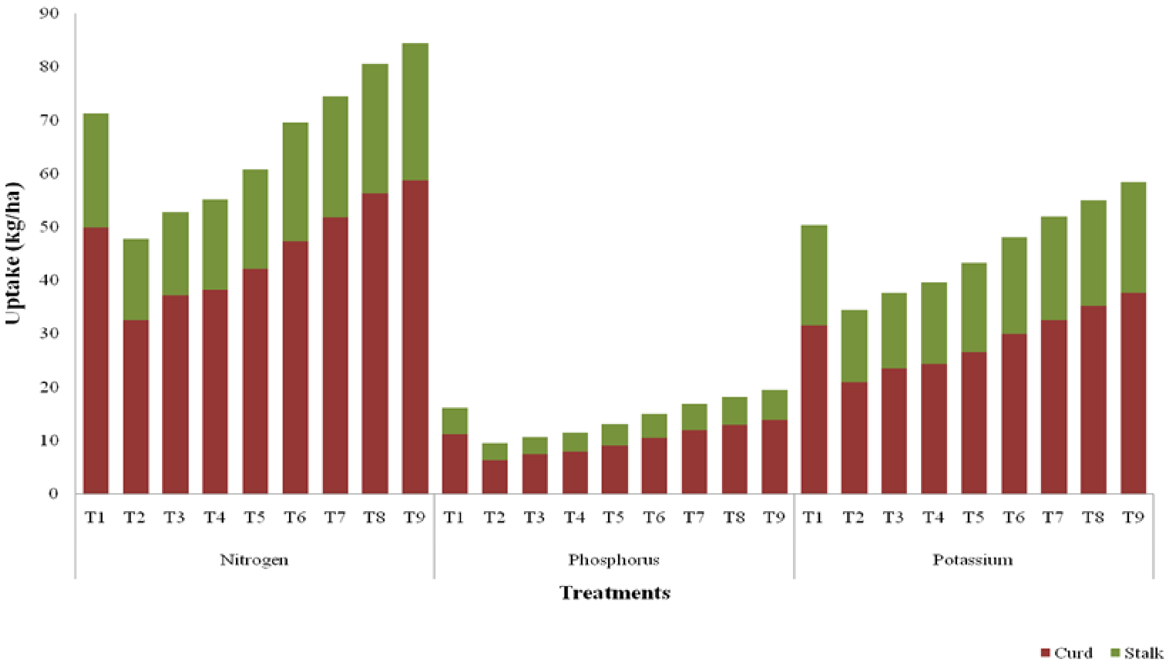

Fig. 3. Effect of biochar on nitrogen, phosphorus and potassium uptake (kg ha^{-1})

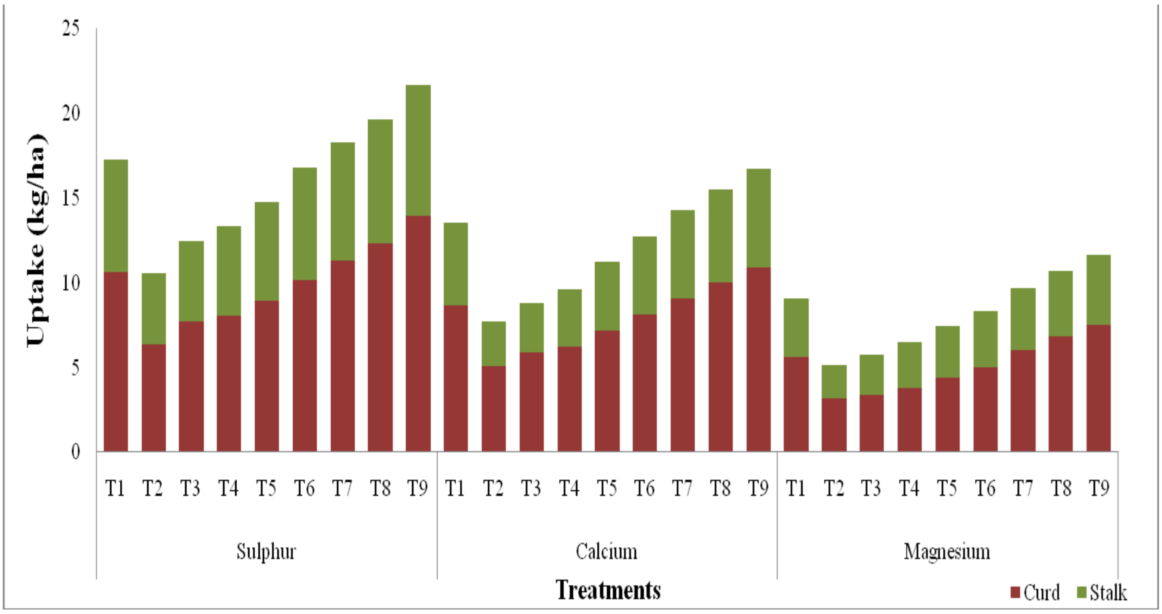

Fig. 4. Effect of biochar on sulphur, calcium and magnesium uptake (kg ha^{-1})

The data show that treatment T_9 registered a 15.88 per cent increase in the BCR over the recommended practice of 100% RDF + FYM (T_1). This improvement indicates the economic benefit of applying 20.0t ha^{-1} biochar with RDF. As biochar application increased from 2.5 to 20.0t ha^{-1} (T_2 to T_9), the B:C ratio increased, suggesting a positive association between biochar levels and profitability.

4. Discussion

Higher yields obtained at increased biochar application rates might be attributed to its potential to improve soil physico-chemical properties, stimulate microbial activity, and enhance nutrient retention and use efficiency, thereby promoting better plant growth, curd development and biomass production. At lower biochar application rates, the benefits of biochar may not have been fully realised, resulting in comparatively lower nutrient availability than in FYM-treated plots, where nutrients become readily available through mineralisation. Similar increases in crop yield with higher biochar application have also been reported by Timilsina et al. (2021), Ty et al. (2013), Woldetsadik et al. (2017), Širić et al. (2022) and Singh et al. (2024).

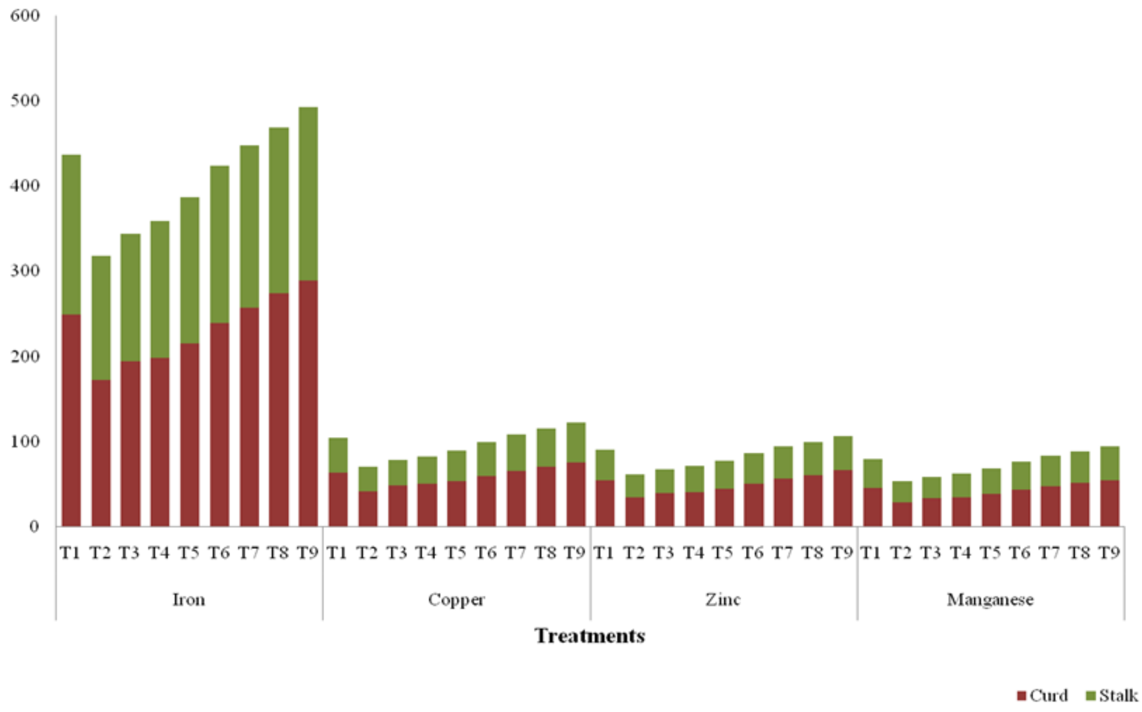

Fig. 5. Effect of biochar on micronutrient uptake (g ha^{-1})

Table 1. Effect of biochar on quality parameters

Treatment		Crude protein (%)	TSS (^{O}Brix)	Ascorbic acid (mg 100 g^{-1})
T_1	100 % RDF + FYM (20 t ha^{-1})	13.74	6.40	53.42
T_2	100 % RDF + 2.5 t ha^{-1} biochar	13.08	6.08	52.60
T_3	100 % RDF + 5.0 t ha^{-1} biochar	13.11	6.16	52.76
T_4	100 % RDF +7.5 t ha^{-1} biochar	13.19	6.23	52.91
T_5	100 % RDF +10.0 t ha^{-1} biochar	13.41	6.30	53.04
T_6	100 % RDF +12.5 t ha^{-1} biochar	13.58	6.38	53.28
T_7	100 % RDF +15.0 t ha^{-1} biochar	13.83	6.42	53.50
T_8	100 % RDF +17.5 t ha^{-1} biochar	14.09	6.50	53.76
T_9	100 % RDF +20.0 t ha^{-1} biochar	14.26	6.55	54.02
	C.D.	*0.09*	*0.21*	*0.23*
	S.E.	0.03	0.08	*0.08*

Table 2. Economics analysis

Treatment		Value of marketable produce (₹ kg^{-1})	Total cost of inputs (₹ kg^{-1})	Gross returns (₹ kg^{-1})	B: C
T_1	100 % RDF + FYM (20 t ha^{-1})	457620	142500	315120	3.21
T_2	100 % RDF + 2.5 t ha^{-1} biochar	314200	95000	219200	3.30
T_3	100 % RDF + 5.0 t ha^{-1} biochar	347100	103000	244100	3.36
T_4	100 % RDF +7.5 t ha^{-1} biochar	364860	105000	259860	3.47
T_5	100 % RDF +10.0 t ha^{-1} biochar	395040	112500	282540	3.51
T_6	100 % RDF +12.5 t ha^{-1} biochar	438440	120000	318440	3.65
T_7	100 % RDF +15.0 t ha^{-1} biochar	471420	127500	343920	3.69
T_8	100 % RDF +17.5 t ha^{-1} biochar	500620	135000	365620	3.70
T_9	100 % RDF +20.0 t ha^{-1} biochar	530720	142500	388220	3.72
	C.D.				*0.06*
	S.E.				0.02

At lower rates of biochar application (2.5, 5.0, 7.5, 10.0 and 12.5 t ha^{-1}), nutrient uptake was lower than in the treatment where FYM was applied because of the lower yields obtained in these plots. The increased nutrient uptake at higher biochar rates (15.0, 17.5 and 20.0 t ha^{-1}) can be attributed to a slow and sustained release of nutrients. This slow release may help prevent nutrient losses, ensuring nutrient availability to plants throughout the growing period and leading to higher uptake. Previous studies, such as those by Woldetsadik et al. (2017) and Xue et al. (2023), have also reported increases in yield and nutrient uptake with increased biochar application, supporting the findings of the current study.

Increased biochar application improves crude protein, TSS and ascorbic acid content through improvements in soil fertility, structure and nutrient availability, particularly nitrogen and potassium, which are essential for protein synthesis and carbohydrate metabolism. Moreover, biochar improves soil microbial activity, nutrient retention and gradual nutrient release, leading to improved plant growth and metabolic processes that enhance crop nutritional quality. These results are consistent with the outcomes reported by Ty et al. (2013), Širić et al. (2022), Xue et al. (2023) and Kayes et al. (2024), who also observed improvements in crop quality parameters with increasing biochar application.

The increased B:C ratio in the biochar treatments reflects its positive role in enhancing both yield and economic returns, making biochar a viable option for improving profitability in cauliflower production. Similar findings were reported by Singh et al. (2024), who observed that biochar application resulted in high B:C ratios.

5. Conclusion

This study showed that biochar increased cauliflower yield, nutrient uptake, quality and economic returns. Among the treatments, 100% RDF + 20 t ha^{-1} biochar (T_9) was the most effective, recording the highest curd and stalk yields, nutrient uptake, quality parameters and benefit-cost ratio. Higher rates of biochar were more effective for increasing yield, nutrient uptake and quality, as well as economic returns. Therefore, the application of biochar, particularly at higher rates in combination with RDF, may be considered a sustainable and economically viable practice for improving cauliflower production in the low-hill region of Himachal Pradesh.

6. Limitations

This study was conducted during a single cauliflower season at one experimental location with three replications, limiting direct extrapolation across contrasting soils, climates and seasons. All biochar treatments received 100% RDF; therefore, the experiment does not directly establish whether biochar can reduce the required fertiliser dose. The findings are also specific to Lantana camara biochar produced using the described kiln method and application rates. Economic results reflect the input and produce values used for this experiment and may vary with local prices. Longer-term field evaluation would be needed to assess the persistence of the observed responses.

Acknowledgement

The authors are thankful to the Department of Soil Science and Water Management, College of Horticulture and Forestry (YSPUHF), Neri, Hamirpur, Himachal Pradesh, India for providing facility to perform the experiment.

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 Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/165397