



RESEARCH ARTICLE

# Biochar and nutrient dynamics: Impact on growth, development and yield of wheat (*Triticum aestivum* L.)

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## Abstract

The Trans-Gangetic Plains are among the most extensively cropped agro-ecological zones of India, with wheat (*Triticum aestivum* L.) being the most widespread rabi season crop. Crop residue and nutrient management are crucial in this system. The experiment was conducted using a split-plot design with 3 replications. The main plot factors consisted of 3 biochar types: paddy straw biochar (B<sub>1</sub>), red gram stover biochar (B<sub>2</sub>) and cotton stover biochar (B<sub>3</sub>) with sub-plot factors included 4 nutrient management strategies: 100 % recommended dose of fertilizers (RDF, N<sub>1</sub>), 70 % RDF + 2 foliar sprays (FS) of liquid compost (N<sub>2</sub>), 70 % RDF + 2 foliar sprays of nano DAP (N<sub>3</sub>) and control (N<sub>4</sub>). Results revealed that, application of cotton stover biochar significantly increased plant height by 3.5 % and 10.06 %, dry matter accumulation (DMA) by 0.51 % and 1.2 %, chlorophyll index by 0.9 % and 1.6 %, grain yield by 3.7 % and 9.4 % and straw yield by 2.9 % and 6.9 %, over red gram and paddy straw biochar respectively. Similarly, application of 100 % RDF increased growth, yield attributes and the yield of wheat, which was statistically similar to N<sub>2</sub>. However, N<sub>2</sub>: 70 % RDF + liquid compost enhanced the grain yield by 3.37 % and the straw yield by 3.13 %. Hence, application of cotton stover biochar with 70 % RDF + FS of liquid compost shows better performance across all growth and yield attributes and the yield of wheat. In the future, biochar has the potential to bioeconomy models, thereby making significant contributions to climate change mitigation, supporting carbon trading initiatives and enhancing circular bioeconomy models.

**Keywords:** biochar; chlorophyll index; grain yield; liquid compost; nano DAP; nutrient management

## Introduction

Wheat plays a key vital role in human diets and also serves as an important feed for livestock. As one of the world's most important food crops, it continues to need genetic and farming advancements to meet the rising food demands of a growing global population (1). Wheat, a nutritionally important cereal crop, is grown extensively across diverse agro-ecological zones worldwide. It ranks 1<sup>st</sup> in global crop acreage, covering about 215.91 M ha with an annual production of 765.77 M t. In India, wheat is cultivated on nearly 30 M ha (around 14 % of the global area), producing a record 99.70 M t (13.64 % of global output) with an average yield of 3371 kg ha<sup>-1</sup>. It is a key component of India's food grain basket, contributing approximately 36 % to the total food grain production (2). These regions experience a variety of climates, ranging from temperate to subtropical, which makes it possible to grow different types of wheat throughout the year (3). Wheat grains are rich in essential nutrients, i.e. carbohydrates 78 %, protein 14 %, fat 2 % and minerals 2.5 % (4). It also contains essential minerals, including copper (Cu), magnesium (Mg), zinc (Zn), iron (Fe) and phosphorus (P), along with significant amounts of vitamins such as riboflavin, thiamine, niacin and alpha-tocopherol (5).

Management of residues has become an essential issue for taking Indian agriculture towards sustainable development and protecting the quality of the environment, especially over the Indo-

Gangetic Plains (IGP). Around 620 M t of crop residues are created each year throughout the nation; out of this, 234 M t are surplus, with the rice and wheat crops alone contributing almost 30 % of the excess biomass (6). To facilitate timely wheat sowing and maintain alignment with optimal crop calendars, farmers often expedite field preparation by rapidly clearing the land. In many cases, this is achieved through the open burning of loose crop residues, particularly straw, a practice that poses significant environmental hazards and has detrimental effects on soil health and quality. Field burning of crop residue (FBCR), even though in the past omitted primarily for its insignificant scope, is increasingly becoming a significant source of agricultural pollution. It is contributing to environmental degradation and climate change through the emission of greenhouse gases (7). The crop residues usually have 40 %–45 % of carbon. Applying crop residues to the soil increases the level of organic carbon in the soil, increases microbial activity and enhances nutrient cycling, so they are important building blocks of sustainable agriculture and soil health (8).

Soil is a major carbon reservoir and integral to the global carbon cycle. Sustaining soil organic carbon (SOC) is crucial for maintaining soil fertility, productivity and quality. Biochar, produced through oxygen-limited pyrolysis of biomass, offers considerable potential for stabilizing and increasing SOC levels (9). The application of biochar to soil is recommended as a sustainable practice to reduce irrigation demands in agricultural fields (10).

It is widely recognized for its positive effects on soil quality, attributed to its high cation exchange capacity and basic pH. Numerous studies have demonstrated biochar's role in regulating nitrogen dynamics across various climatic conditions. It influences key nitrogen transformation processes, including immobilization, fixation and mineralization, thereby affecting overall nitrogen cycling in the soil-plant system (11). Alongside kitchen waste liquid compost-like derived amendments, recent advancements in nanotechnology are also contributing to sustainable nutrient management by offering more efficient and environmental friendly alternatives to conventional chemical fertilizers. The foliar application of nutrients derived from plant kitchen waste improves nutrient availability and provides bioactive compounds that enhance plant growth, vigor and tolerance to abiotic stress conditions (12). Production and use of nano-fertilizers has the promise of significantly decreasing the use of traditional chemical fertilizers, thus reducing their residual toxic effect on soil and also saving foreign exchange by reducing fertilizer imports (13). In this context, different biochar sources possess varying nutrient compositions, which may influence their suitability for specific crops. Therefore, it is essential to identify which type of biochar is most beneficial for wheat and determine its compatibility with different nutrient sources. Hence, the present study is planned to determine the most suitable biochar source for wheat production and its compatible nutrient management practice.

## Materials and Methods

### Experimental site

The experiment was carried out at the experimental farm of Lovely Professional University, Jalandhar, Punjab. This field has an average elevation of 252 m mean sea level and is located at 31°22'31.81" North latitude and 75°23'03.02" East longitude. The field experiment was conducted using split plot design with 3 main factors (B<sub>1</sub>: Paddy straw biochar, B<sub>2</sub>: Red gram stover biochar, B<sub>3</sub>: Cotton stover biochar) and 4 sub factors (N<sub>1</sub>: 100 % recommended dose of fertilizer (RDF) through inorganic fertilizer, N<sub>2</sub>: 70 % RDF + 2 foliar sprays (FS) of liquid compost, N<sub>3</sub>: 70 % RDF + two foliar sprays of nano DAP (N<sub>3</sub>) and

N<sub>4</sub>: control) with 3 replications. All 3 sources of biochar were purchased from Ekokrishi Solutions, Nandurbar, Maharashtra. The wheat variety DBW222 was sown with 22.5 × 10 cm using a seed drill and the RDF (120:60:40 kg ha<sup>-1</sup> NPK) was applied.

### Statistical analysis

Fisher's analysis of variance technique was employed to analyze and interpret the data following the guidelines (14). A significance level of  $p = 0.05$  was utilized for both F tests and t tests. Critical differences were computed whenever the F tests yielded significant results. OPSTAT online software was used to test the least significant difference (LSD) between the treatment means.

## Results and Discussion

### Effect on growth attributes

#### Biochar effect

The mean values of the growth parameters indicated that various sources of biochar exerted significant effects on wheat (Fig. 1 & 2). At harvest, the significantly greatest plant height was found in cotton stover biochar (114.42 cm), which was statistically on par with red gram stover biochar (110.45 cm). The significantly lowest plant height was recorded in paddy straw biochar (103.96 cm). The application of cotton stover biochar increased plant height by 3.5 % compared to red gram stover biochar and by 10.06 % compared to paddy straw biochar. Cotton stover biochar outperformed others likely due to its favorable physio-chemical properties, such as higher surface area, porosity, nutrient retention capacity and it is dominating with carbon, which enhanced soil fertility and nutrient availability to the plants. The application of biochar and organic manures has been shown to improve soil quality and organic matter content, while also enhancing soil biological properties by creating a better root environment and promoting microbial activity, which supports greater nutrient availability (15).

The dry matter accumulation (DMA) and leaf area index of wheat had a positive correlation with plant height; taller plants had a significantly greater DMA (926.30 g m<sup>-2</sup>) and leaf area index (5.12), which was statistically similar with B<sub>2</sub> (921.54 g m<sup>-2</sup> and 5.04) and the

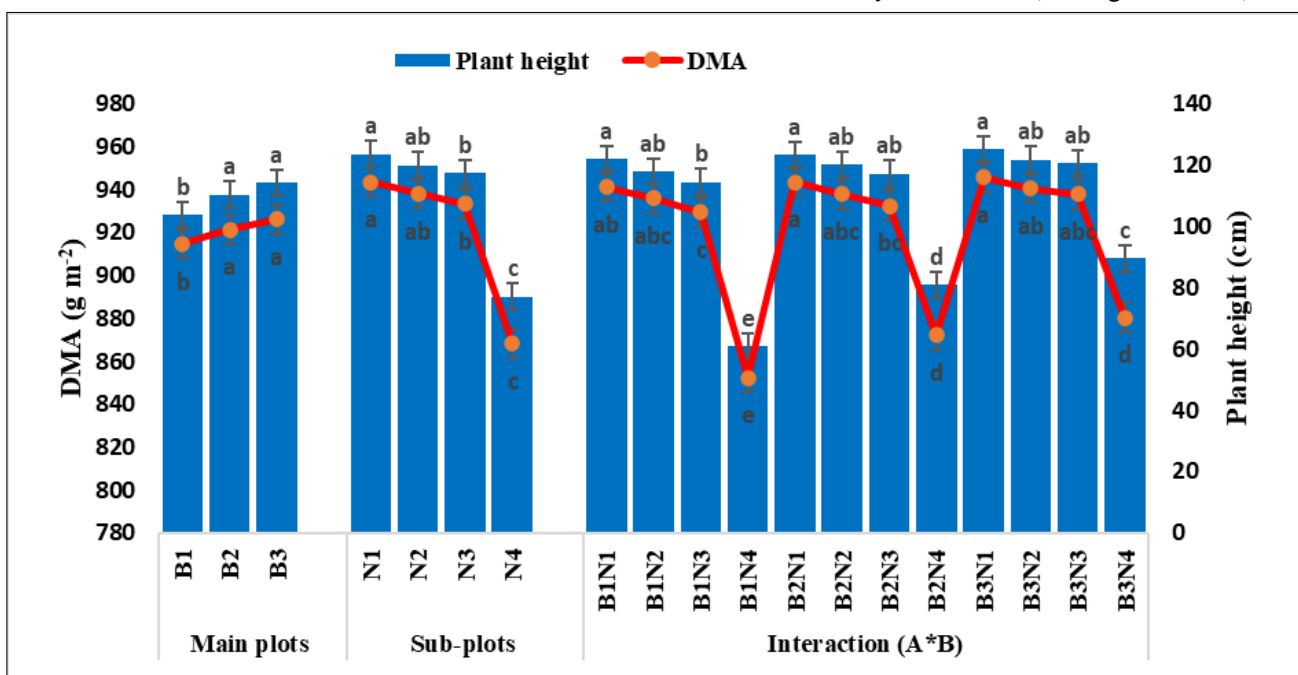
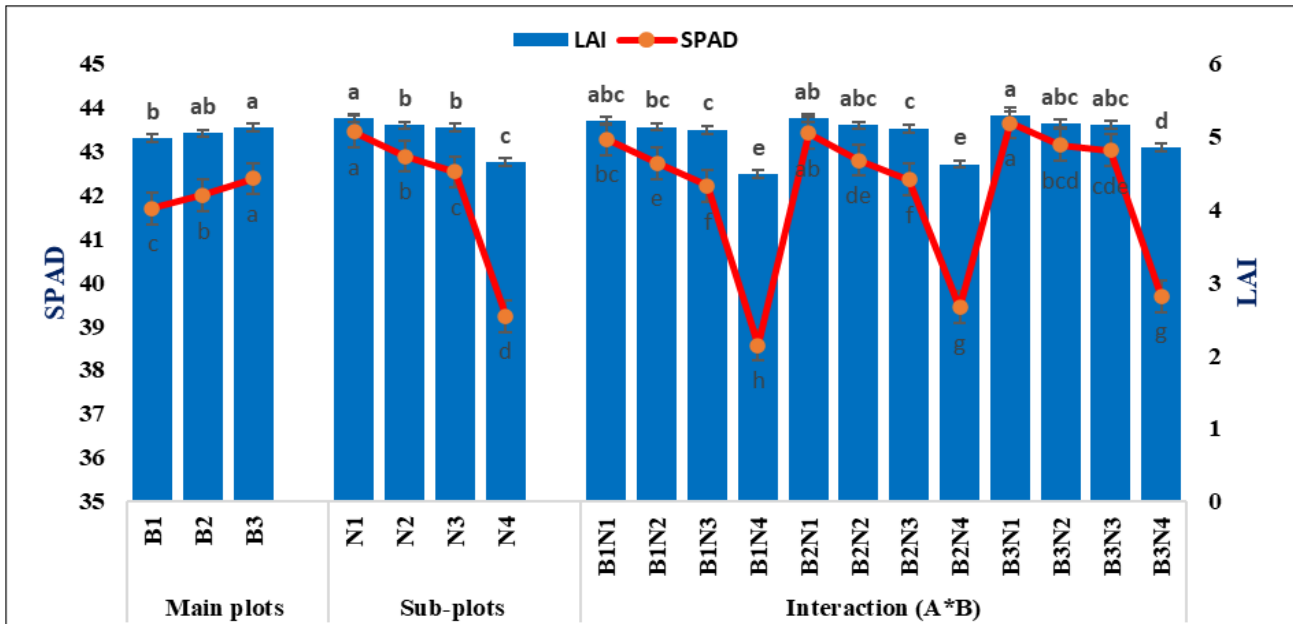


Fig. 1. Effect of biochar sources and nutrient management on height and dry matter accumulation (DMA) of wheat during 2024-25.



**Fig. 2.** Effect of biochar sources and nutrient management on leaf area index (LAI) and chlorophyll index (SPAD-Soil plant analysis development) of wheat during 2024-25.

lowest DMA ( $914.78 \text{ g m}^{-1}$ ) and leaf area index (4.98) was observed in B<sub>1</sub>. The use of cotton stover biochar led to an increase in DMA by 0.51 % and 1.2 % and in leaf area index (LAI) by 1.5 % and 2.8 % respectively, compared to red gram and paddy straw biochar respectively. Biochar remains in the soil for extended periods, providing long-term benefits. Its lasting presence helps maintain an alkaline pH and improves soil health, making it an effective and durable solution for managing soil acidification (16).

The amount of chlorophyll in the leaf is an indicator of the plant's photosynthetic efficiency, which has a direct impact on crop growth and yield. Chlorophyll not only depends on light exposure but also depends on proper nutrient presence. Significantly higher reading of chlorophyll index was observed in B<sub>3</sub> (42.37), followed by B<sub>2</sub> (41.99). The lowest chlorophyll index was noticed under B<sub>1</sub> (41.69). Incorporation of biochar into the soil improves its aggregation and porosity. As a result, the soil structure becomes more stable, leading to better aeration and water penetration, which in turn reduces the chances of erosion and surface runoff (17). Cotton stover biochar demonstrated superior performance compared to other biochar types in alleviating the adverse effects of salinity on wheat seed germination, early seedling development and improvements in soil properties, including pH regulation, reduced electrical conductivity (EC) and enhanced nutrient availability. Furthermore, the application of cotton stover biochar significantly promoted wheat growth and overall productivity (18).

#### Nutrient management effect

The mean values of the evaluated growth parameters revealed that the application of distinct nutrient sources produced significant effects on wheat growth (Fig. 1 & 2). Significantly, the greatest plant height was recorded in N<sub>1</sub> (123.66 cm), which was on par with N<sub>2</sub> (120.03 cm) and N<sub>3</sub> (117.54 cm) and the lowest plant height was recorded in N<sub>4</sub> (77.20 cm). Applying 100 % RDF resulted in an increase in plant height by 3.02 %, 5.2 % and 60.1 % compared to 70 % RDF with 2 FS of liquid compost, 70 % RDF with 2 FS of nano DAP and the control respectively. This outcome may be attributed to the elevated levels of micronutrients and enhanced microbial activity present in the plant extract and homemade NPK (liquid compost) (19, 20).

A similar trend was observed for DMA and LAI. The greatest DMA ( $943.64 \text{ g m}^{-1}$ ) and LAI (5.25) was recorded under N<sub>1</sub>, which was statistically on par with N<sub>2</sub> ( $938.21 \text{ g m}^{-1}$  and 5.15) and N<sub>3</sub> ( $933.33 \text{ g m}^{-1}$  and 5.12) and significantly lower values were recorded in N<sub>4</sub> ( $868.30 \text{ g m}^{-1}$  and 4.65) respectively. Among the nutrient management methods tested, foliar application of NPK from plant extracts produced the highest yields, followed by nano and homemade NPK sprays (12). These treatments enhance nutrient uptake and provide bioactive compounds that strengthen plant growth and stress resistance. The chlorophyll index observed under the N<sub>1</sub> was 10.73% higher than N<sub>4</sub>. Application of RDF, liquid compost and nano DAP, which allow for rapid and efficient absorption through plant surfaces, stomata, or roots, resulting in improved nutrient use efficiency compared to conventional granular fertilizers. The enhanced growth performance observed in S<sub>5</sub> is likely a result of the synergistic interaction between the bioactive compounds in the plant extract and the inorganic fertilizers (21).

#### Interaction effect

The interaction between biochar and nutrient management had a significant influence on growth attributes (Fig. 1 & 2). The significantly highest plant height was recorded in B<sub>3</sub>N<sub>1</sub> (125.40 cm), which was statistically at par with B<sub>2</sub>N<sub>1</sub> (123.43 cm) and B<sub>1</sub>N<sub>1</sub> (122.15 cm), B<sub>3</sub>N<sub>2</sub> (121.86 cm), B<sub>3</sub>N<sub>3</sub> (120.77 cm), B<sub>2</sub>N<sub>2</sub> (120.16 cm) and B<sub>1</sub>N<sub>2</sub> (118.07 cm) indicating that these combinations promoted superior vegetative growth followed by B<sub>2</sub>N<sub>3</sub> (117.27 cm) and B<sub>1</sub>N<sub>3</sub> (114.57 cm) suggesting a consistent positive response to intermediate nutrient levels across different biochar treatments. On the other hand, the lowest plant height was observed in B<sub>1</sub>N<sub>4</sub> (61.04 cm), which was significantly lower than all other treatment combinations. Biochar, a carbon-dense material derived from the pyrolysis of biomass, improves water retention and enhances the uptake of both water and nitrogen when used in combination with nitrogen fertilizer (22). Consequently, this leads to increased efficiency in water and nitrogen use (23).

A similar trend followed in DMA and LAI. The maximum DMA and LAI were recorded under the treatment combination B<sub>3</sub>N<sub>1</sub> ( $945.87 \text{ g m}^{-1}$ , 5.29) which was statistically at par with B<sub>2</sub>N<sub>1</sub> ( $943.69 \text{ g m}^{-1}$  (5.25), B<sub>1</sub>N<sub>1</sub> ( $941.35 \text{ g m}^{-1}$ ) (5.21), B<sub>3</sub>N<sub>2</sub> ( $940.78 \text{ g m}^{-1}$ ) (5.18), B<sub>3</sub>N<sub>3</sub> ( $938.06$

g m<sup>-1</sup>) (5.16), B<sub>2</sub>N<sub>2</sub> (937.92 g m<sup>-1</sup>) (5.15) and B<sub>1</sub>N<sub>2</sub> (935.93 g m<sup>-1</sup>) (5.13). These treatment combinations demonstrated superior vegetative growth, as evidenced by higher DMA and LAI. This was followed by B<sub>2</sub>N<sub>3</sub> (932.46 g m<sup>-1</sup>) (5.11) and B<sub>1</sub>N<sub>3</sub> (929.48 g m<sup>-1</sup>) (5.09), which also exhibited appreciable performance, suggesting a favorable response to moderate nutrient levels across various biochar treatments. Conversely, the lowest DMA and LAI were recorded in B<sub>1</sub>N<sub>4</sub> (852.35 g m<sup>-1</sup> and 4.48), which was closely related to B<sub>2</sub>N<sub>4</sub> and B<sub>4</sub>N<sub>4</sub> (4.85). These values were significantly lower than those of the other treatment combinations. The superior performance of plots with integrated nutrient application can be attributed to improved water retention, a steady nutrient release from farmyard manure (FYM) and the combined effect of readily available nutrients from chemical fertilizers and nutrient retention by biochar, ensuring better nutrient availability during key growth stages (24, 25).

The highest chlorophyll index was recorded under B<sub>3</sub>N<sub>1</sub> (43.64), which was statistically at par with B<sub>2</sub>N<sub>1</sub> (43.41) and B<sub>1</sub>N<sub>1</sub> (43.27), indicating that these combinations were most effective in enhancing chlorophyll content. Other treatment combinations, such as B<sub>3</sub>N<sub>2</sub> (43.13), B<sub>3</sub>N<sub>3</sub> (43.01), B<sub>2</sub>N<sub>2</sub> (42.79), B<sub>1</sub>N<sub>2</sub> (42.72), B<sub>2</sub>N<sub>3</sub> (42.35) and B<sub>1</sub>N<sub>3</sub> (42.20), also showed relatively higher chlorophyll index values, though slightly lower than the top-performing treatments. These treatments were comparable to each other, reflecting a consistent positive effect of moderate nutrient levels across different biochar applications. This treatment combination also led to the most significant improvement of maize and wheat, compared to the sole application of either mineral fertilizers or biochar (26). In contrast, the lowest chlorophyll index was observed in B<sub>1</sub>N<sub>4</sub> (38.57), which was closely similar to B<sub>2</sub>N<sub>4</sub> (39.43) and B<sub>4</sub>N<sub>4</sub> (39.69). The combined use of biochar and farmyard manure, with or without reduced chemical fertilizers and irrigation, offers an effective strategy to enhance soil quality and crop water productivity in dry tropical agro-ecosystems (27).

### Yield attributes and the yield of wheat

#### Biochar effect

The test weight values observed with cotton and redgram straw biochar were found to be closely related and generally higher compared to those recorded with paddy straw biochar (Fig. 3 & 4). Among the treatments, the significantly highest test weight was recorded in B<sub>3</sub> (41.01 g), followed by B<sub>2</sub> (40.36 g), while the lowest value was observed under B<sub>1</sub>. The application of prosopis and cotton biochar at a rate of 4.0 t ha<sup>-1</sup> significantly enhanced SOC, cation exchange capacity and porosity, while reducing bulk density compared to the maize biochar and control. These findings suggest that biochar, when used as a soil amendment, effectively improves soil fertility and contributes more productivity and also maintains long-term soil sustainability (28).

The mean values of the yield parameters demonstrated that different biochar sources had significant impacts on wheat. The significantly highest grain yield was recorded in B<sub>3</sub> (53.68 q ha<sup>-1</sup>), which was statistically on par with B<sub>2</sub> (51.75 q ha<sup>-1</sup>). The significantly lowest grain yield was recorded in B<sub>1</sub> (49.03 q ha<sup>-1</sup>). The use of cotton stover biochar resulted in a 3.7 % and 9.4 % increase in grain yield compared to red gram and paddy straw biochar, respectively. The cotton stover biochar demonstrated superior performance, which improves soil aggregation, tilth and water retention, supporting better root development and its indirect effect on grain yield. Biochar helps soil resist acidification by improving its structure, creating a stable environment that supports plant growth and microbial

activity. Its long-lasting presence in the soil further adds to these benefits (29). Similarly, the significantly highest straw yield is recorded in B<sub>3</sub> (69.46 q ha<sup>-1</sup>), followed by B<sub>2</sub> (67.46 q ha<sup>-1</sup>) and the lowest straw yield was observed in B<sub>1</sub> (64.43 q ha<sup>-1</sup>), which was at par with B<sub>2</sub>. The beneficial impact of biochar on maize yield can be linked to several factors: (i) it improves soil texture, structure and boosts microbial activity (30); (ii) it provides essential minerals and organic carbon that support plant development (31); and (iii) it enhances the soil's capacity to store, transform and absorb nutrients (32). The significantly highest number of grains per spike was recorded under B<sub>3</sub> (45.25 no.), which was on par with B<sub>2</sub> (44 no.). The lowest no. of grains per spike was recorded in B<sub>1</sub>.

#### Nutrient management effect

The mean values of the evaluated yield parameters indicated that the application of different nutrient sources had a significant impact on wheat growth (Fig. 3 & 4). The effect of nutrient combinations on the number of grains per spike was recorded significantly highest under N<sub>1</sub> (48.44 no.) due to the balanced supply of macronutrients through NPK promoted optimal vegetative and reproductive growth, resulting in improved spike development and grain setting. But the use of liquid compost and Nano DAP, due to its higher nutrient use efficiency and rapid absorption, contributed to enhanced N and P uptake during critical stages of spike formation so result was found under N<sub>2</sub> (44.89 no.), N<sub>3</sub> (44.11 no.) were closely relate to each other and the lowest values for number of grains per spike of wheat crop was recorded in N<sub>4</sub> (39.11 no.).

Among the nutrient management approaches evaluated, foliar application of plant-based NPK extracts led to the highest yields, with nano-NPK and homemade NPK sprays performing slightly lower. These fertilizers improve nutrient availability and contain bioactive substances that boost plant health and stress tolerance (12). Under different nutrient management practices, all nutrient combinations resulted in nearly similar test weight compared to those of the control (N<sub>4</sub>). The test weight observed under the N<sub>1</sub> treatment (100 % RDF) was 8.5 % higher compared to the N<sub>4</sub> treatment (control). The plant extract may contain higher levels of micronutrients, which boost nutrient efficiency within the plant's metabolic processes. A similar result was found previously (20, 33, 34). Significantly, the highest grain and straw yield was recorded in N<sub>1</sub> (58.42 q ha<sup>-1</sup> and 74.30 q ha<sup>-1</sup>), which was statistically on par with N<sub>2</sub> (56.45 q ha<sup>-1</sup> and 71.97 q ha<sup>-1</sup>) and N<sub>3</sub> (54.25 q ha<sup>-1</sup> and 70.67 q ha<sup>-1</sup>) and the lowest grain and straw yield was recorded in N<sub>4</sub>. The integrated application of mineral and organic NPK inputs enhances soil nitrogen availability and stimulates the activity of soil enzymes involved in organic matter formation. This, in turn, improves soil fertility, promotes aggregate formation and positively influences wheat yield (26).

#### Interaction effect

The interaction effect between biochar and nutrient management had a significant influence on yield attributes and yield of wheat (Fig. 3 & 4). In contrast, a progressive decline in grain number was observed with reduced nitrogen levels (under N<sub>2</sub> to N<sub>3</sub>) within each biochar level, along with liquid compost and nano DAP application. And the lowest value recorded under B<sub>1</sub>N<sub>4</sub> (37.33). The highest test weight was recorded in the B<sub>3</sub>N<sub>1</sub> (42.43 g) treatment, which was significantly superior to all other combinations. It was followed by B<sub>2</sub>N<sub>1</sub> and B<sub>1</sub>N<sub>1</sub>, which also showed relatively higher values and fell within a comparable range, though statistically different and the lowest value was recorded under B<sub>1</sub>N<sub>4</sub>. Research findings showed

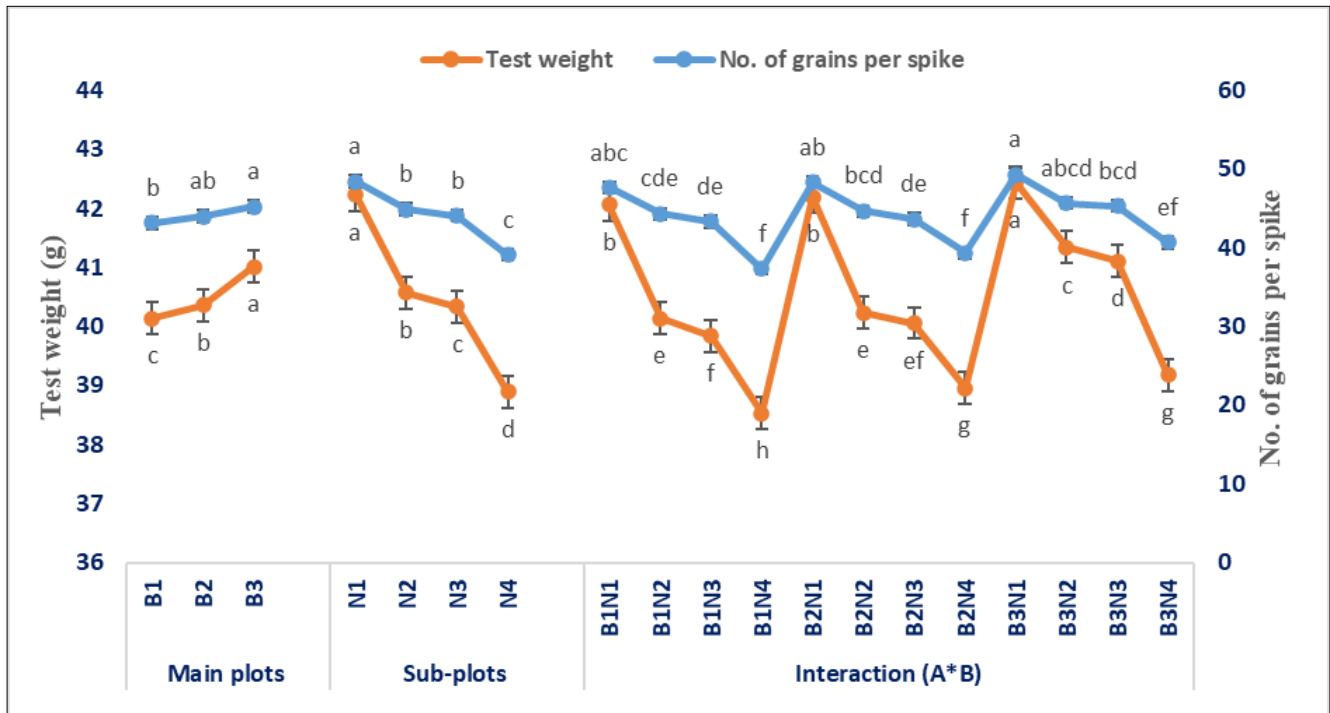


Fig. 3. Effect of biochar sources and nutrient management on test weight and no. of grains per spike of wheat during 2024-25.

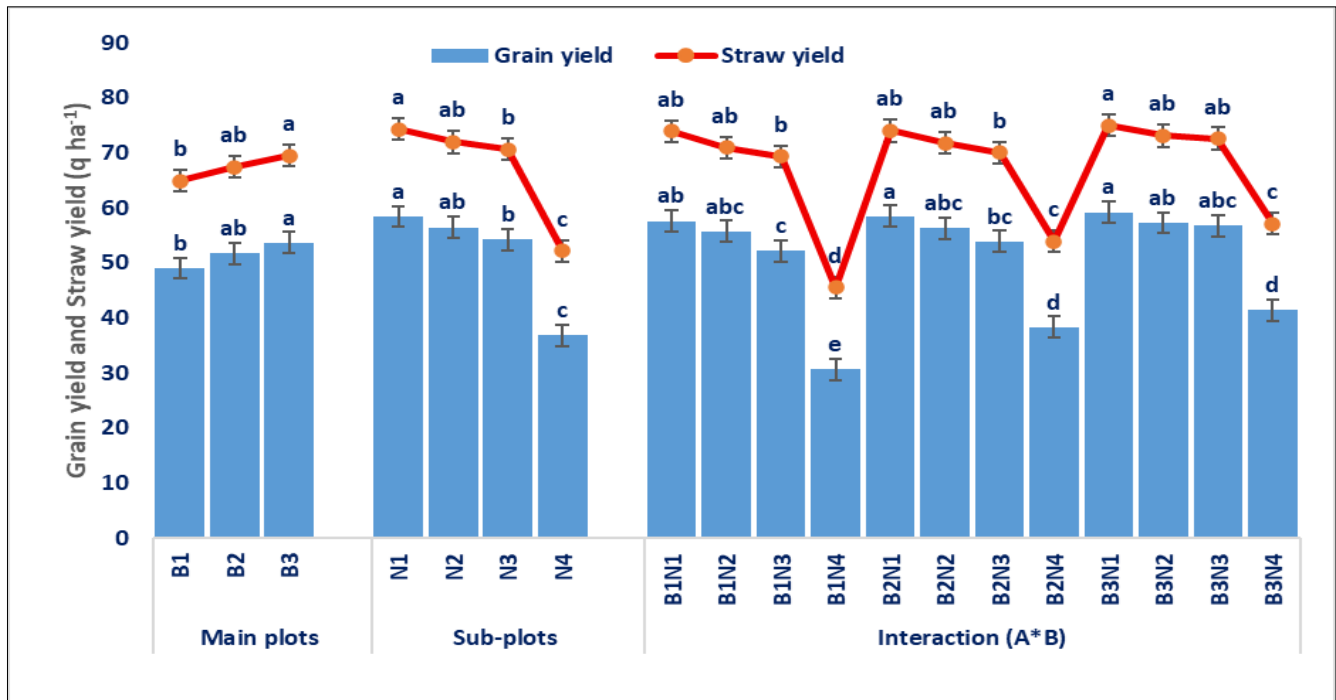


Fig. 4. Effect of biochar sources and nutrient management on grain and straw yield of wheat during 2024-25.

that applying biochar alongside nitrogen fertilizer boosts nitrogen uptake in plants and can serve as a slow-release nitrogen source, effectively providing the necessary nutrients for optimal plant growth and development (35).

Among the treatment combinations, the highest grain and straw yield were recorded in  $B_3N_1$  ( $59.19 \text{ q ha}^{-1}$  and  $74.96 \text{ q ha}^{-1}$ ), which was statistically at par with and  $B_1N_1$ ,  $B_3N_2$ ,  $B_3N_3$ ,  $B_2N_2$  and  $B_1N_2$ , indicating that these combinations promoted superior reproductive growth followed by  $B_2N_3$  and  $B_1N_3$  suggesting a consistent positive response to intermediate nutrient levels across different biochar treatments. On the other hand, the lowest yield was observed in  $B_1N_4$ . These treatment combinations demonstrated superior vegetative growth, as evidenced by higher straw yield and also exhibited appreciable performance, suggesting a favorable response

to moderate nutrient levels across various biochar treatments. Applying nutrient-enriched biochar alongside chemical fertilizers in intensively managed soils is a more effective approach for increasing grain yield, nitrogen uptake and soil carbon levels compared to using biochar alone or no treatment (36). The maximum number of grains per spike was recorded under the  $B_3N_1$  ( $49.33$ ) treatment combination, which was statistically at par with  $B_2N_1$  ( $48.33$ ) and  $B_1N_1$  ( $47.67$ ). This indicates that application of the full dose of RDF ( $N_1$ ) in combination with optimized levels of biochar (particularly  $B_3$ ,  $B_2$  and  $B_1$ ) is highly effective in improving grain formation in wheat. The combination of biochar with farmyard manure, either alone or with reduced chemical inputs and irrigation, can effectively improve soil health and water use efficiency in dry tropical regions (27).

## Conclusion

The application of cotton stover biochar led to an increase in the chlorophyll index by 0.9% and 1.6% and in test weight by 1.6% and 2.1%, compared to red gram stover biochar and paddy straw biochar respectively. Among nutrient treatments, 100% RDF, using inorganic sources led to the highest growth and yield, followed closely by liquid compost and nano DAP spray, which act as bio-stimulants and promote sustainable agriculture. However, 70% RDF + liquid compost enhanced the grain yield by 3.37% and straw yield by 3.13%. The combined use of cotton stover biochar and 100% RDF was the most effective strategy, but the reduced dose of inorganic fertilizer application and this gap of nutrient recommendation can be replaced by the organic liquid compost and nano DAP spray practice. It is choice towards the sustainability of agriculture, enhancing the soil fertility and the yield of crops and utilizing agricultural residues effectively as biochar.

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## Authors' contributions

VDJ carried out conceptualization, methodology, investigation, data curation and writing-original draft. SK carried out supervision, visualization, validation, writing the original draft and editing. VDJ and SK participated in the formal analysis, writing review and editing. All authors read and approved the final manuscript.

## Compliance with ethical standards

**Conflict of interest:** The authors do not have any conflicts of interest to declare.

**Ethical issues:** None

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