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A comparative study of fresh and residual biochar effects on wheat growth and yield metrics

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Abstract

Biochar is a highly stable carbon compound produced through pyrolysis, and it has been widely studied for its potential to enhance soil fertility and carbon sequestration. However, the impact of fresh and residual biochar is not thoroughly explored. Therefore, a comparative study on fresh and residual biochar were conducted at filed conditions on wheat cultivation, using a randomized block design. A fresh biochar (S1), residual biochar of previous season crop (S2) and two season old residual biochar (S3) with nine different treatments using varied amounts of rice husk and rice straw biochar along with the fertilizers (recommended doses of N, P, K) were considered in triplicate. Result clearly indicates that biochar application significantly improved plant height, leaf area, fresh and dry biomass of plant, internodal length, node & internode diameter, as well as biological yield, grain and straw yield of wheat crop. S1 had the most significant impact on plant growth and yield-attributing characteristics compared to S2 and S3, even at higher doses. In S1, the most significant results were observed at a biochar application rate of 5 tons/ha, while S2 showed maximum impact at 10 tons/ha. In S3, the highest impact was recorded at the highest biochar dose of 15 tons/ha. The present findings conclusively showed the efficiency of fresh biochar to enhance soil fertility for agricultural production as well as the residual impact of biochar in succeeding crop.

Keywords: Biochar application, Soil amendment, Residual effects, Wheat productivity.

Introduction

Human activities and agricultural residue burning continue to raise atmospheric CO_2 concentrations, this leads to global warming, which poses considerable risks to human health, food security, and biodiversity (Muluneh, 2021). To diminish environmental impacts and enhance the sustainable practices, it is essential to implement climate change mitigation strategies that focus on carbon sequestration and decline in GHG emission (Rao et al., 2024). The most critical soil concerns for agronomic systems are the decrease in soil fertility and production caused by organic matter loss (Fawzy et al., 2020). It is necessary to manage soil by incorporating organic matter to maintain its fertility (Singh et al., 2024). Soil quality is critical for enhanced agricultural output, and testing during drought circumstances might indicate areas of concern for long-term production and soil fertility (Tripathy et al., 2023).

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Soil productivity refers to the optimal setting for plant development, this encompasses an adequate supply of nutrients and a suitable growth medium. Soil quality is also linked to various factors and can be assessed through a range of indicators, such as chemical, biological, and physical properties. Enhancing soil quality can lead to increased crop yields (Nunes et al., 2022). Cation exchange capacity is often utilized to analyze soil texture, while the biochemical properties of the soil also play a crucial role in determining its texture and structure (Zheng et al., 2018). Under this situation, the application of biochar can be a beneficial for long-term to increase soil carbon sequestration, soil fertility, crop productivity and reducing GHG emission (Vijay et al., 2021; Sushkova et al., 2021).

European Biochar Certificate describes biochar as "a charcoal-like material produced from sustainable feedstocks through pyrolysis under controlled conditions, intended for uses other than rapid mineralization to CO_2." Biochar enriches soil by supplying essential nutrients and improving water retention, while its porous structure promotes beneficial microorganisms, enhancing nutrient availability (Brar et al., 2024; Faizan et al., 2024). Biochar also alters the physical and chemical properties in the soil including changed pH, redox, CEC and surface reactivity/sorption (Ismail and Man, 2024). Physical and chemical alterations to the soil environment cause changed biological activity including nutrient destiny and functioning of the microbial population (Birol and Günal, 2024; Devendrapandi et al. 2024).

Currently, the impact of adding biochar on crop productivity are equivocal. These effects can depend on the type and properties of the biochar, as well as experimental conditions such as soil type, crop species, application timing, and environmental factors. Therefore, it is essential to further investigate the influence of biochar on crop yields in specific site conditions (Abhishek et al., 2022; Long and Dung, 2023). It necessary to explore how the addition of biochar affects critical factors that influence crop growth and on availability represents. Wheat (*Triticum aestivum* L.) is considered in current research as it is one of the most cultivated crops globally, yields over 650 million tonnes annually, ranks as the third most produced cereal and known for its excellent nutritional qualities. The goal of this study was to investigate the influence of fresh and residual biochar on durum wheat development and yield matrices.

Material and Methods

Experimental site and treatment details

A two-year study was conducted on the PBW 824 variety of wheat at the agricultural research farm of Lovely Professional University in Jalandhar, Punjab, India from 2022 to 2024. The coordinates for the location are latitude 31°14'30.5''N and longitude 75°41'52.1" E. Soil properties were analysed before sowing as shown in Table 1. A total of 9 treatments were executed using a Randomised Block Design (RBD), with three replications, i.e., T1-Absolute control (without fertilizers), T2- 100% Recommended Doses of Fertilizers (RDF) (N:P:K 120:60:60 kg/ha), T3- 100% of recommended doses of N and P without K, T4- T3+ rice husk biochar @5 tons/ha, T5- T3+ rice husk biochar @10 tons/ha, T6- T3+ rice husk biochar @15 tons/ha, T7- T3+ rice straw biochar @5 tons/ha, T8- T3+ rice straw biochar @10 tons/ha and T9- T3+ rice straw biochar @15 tons/ha. The plot size was 5m×5m (25 m^2) with a row to row spacing of 22.5 cm. The drone layout of the research trial is shown in Figure 1. Total four irrigation were applied during Crown root initiation (CRI), tillering stage, flowering stage and milking stage and no additional fertilizers were added except above combination. The first wheat trial was carried out during the Rabi season in 2022, followed by a pigeon pea crop in the Kharif season 2023.To evaluate the residual impacts of biochar, a new plot was built parallel to the previous one, where fresh biochar was applied before seeding pigeon pea in two distinct plots: one with fresh biochar and the other with biochar residual effect. The following wheat trial conducted in Rabi season 2023, using a similar strategy with a new plot constructed alongside the previous two, and fresh biochar was added to the new plot. Wheat was seeded in three plots to conduct a comparative investigation of the impact of biochar on crop performance. The weather data for the experimental site is shown in Figure 2.

Table 1. Different properties of soil, rice husk and straw biochar before application.

Properties	Soil	Rice Husk Biochar	Rice Straw Biochar
pH	7.4	10.4	10.2
EC (dSm^{-1})	0.17	0.16	0.13
Carbon	0.49 %	71.2 %	64.6%
Nitrogen	176 kg/ha	0.9%	1.1%
Phosphorus	8.95 mg/kg	4.7%	5.1%
Potassium	45 mg/kg	1.7 %	2.1%

Figure 1. Drone image of the experimental area

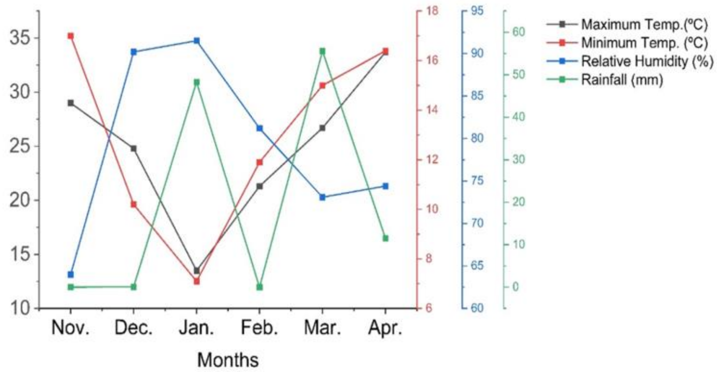

Figure 2. Presents the weather, and monthly average data of temperature, relative humidity and rainfall, collected

Biochar preparation and analysis

Biochar was fabricated by thoroughly dried rice straw and husk,. The rice straw and husk were colonized over an open fire in a stainless-steel container measuring 48 cm tall and 142 cm in circumference to prepare biochar. The open flame is an auto-thermal procedure that burns a portion of the feedstock to heat the remaining material and produce char. The feedstock was placed inside the open-burn tank and fired. Carbonisation of feedstocks happened below the flames, where oxygen is non-existent, as the flames devour all of it, producing a pyrolysis zone. Due to a lack of oxygen, biomass smoulders but does not produce fumes or smoke. Instead, much of it is converted into carbon-rich charcoal, oil, and gas. Rice straw was pyrolysed at 400-600 ºC and recorded using a heat sensor thermometer. Feedstocks were constantly added until the tub until it was not full, after which it was quenched with water. On a dry weight basis, the biochar output ranged between 45 and 50%. Biochar was air-dried and put to the field. The properties of produced biochar are shown in Table 1.

Plant assessment

In this study, major agronomic characteristics of wheat across experimental plots were examined. Plant height was measured from the basal node to the apical meristem of 10 randomly selected plants with a calibrated measuring tape to ensure precision in vertical growth measurement. Wheat plants were harvested at a standardised length of one meter and leaf area was measured in square centimetres using a digital leaf area meter, providing exact foliar surface area measurements for evaluating photosynthetic efficiency. A computerised Vernier calliper was used to measure node and internode diameters, internode distances, and other morphological parameters.

Chlorophyll was extracted from a 100 mg sample using 20 ml of 80% acetone. After centrifugation for 10 minutes at 5000 rpm, the supernatant was transferred to a volumetric flask, and the extraction was repeated until the residue became colourless. The extract's absorbance was measured at 645 and 663 nm wavelength using a spectrophotometer, and the chlorophyll content was calculated using a formula (Arnon, 1949).

The plants of wheat were harvested at a standardised length of one metre, and fresh weight was measured with an analytical balance. The samples were then dried in an oven at 55 °C until they reached a constant weight, showing that all moisture had been removed. The dry biomass was determined by weighing the dried samples using an analytical balance. The biological yield was calculated by harvesting a one-meter piece of evenly matured wheat and weighing the whole biomass. The grain yield was then determined by drying the collected biomass and physically threshing it to separate the grains, resulting in precise estimation of the economic output. Finally, straw yield was estimated by subtracting grain yield from biological yield.

Statiscal analysis

The data in this study was analysed using R Studio software (version 4.2.2) using ANOVA at a significance level of $p<0.05$ indicating significant differences between group means. Following the ANOVA, Duncan's Multiple Range Test (DMRT) was used in post-hoc analysis to discover particular group differences. Additionally, Origin Pro software (Origin 2024b) was also used to construct graphical visualisations of the data, allowing for a clear and effective assessment of the results. This thorough strategy ensured a strong statistical analysis and improved the interpretability of our results.

Results and Discussion

A significant ($p<0.05$) improvement in plant height was observed by the application of biochar (Figure 3). In S1, as relative to control (T2), a significant increase in plant height was recorded in T4 (15.8%). In S2, this increase was recorded maximum in T5 (5.3%) while in S3, the maximum increase was recorded in T6 (1.9%). The results clearly indicates that fresh biochar, even at lower doses (5 tons/ha), had a significant impact on plant height compared to the long term residual impact of higher doses of biochar i.e. 10 tons/ha and 15 tons/ha. Fresh biochar can provide immediate nutrient availability due to its inherent nutrient content and the ability to retain moisture and nutrients in the soil. In contrast, residual biochar may not offer the same level of nutrient availability as it ages and loses its initial nutrient content through leaching or microbial consumption that's why residual biochar is less effective (Cong et al., 2023; Premalatha et al., 2023; Muema et al., 2024).

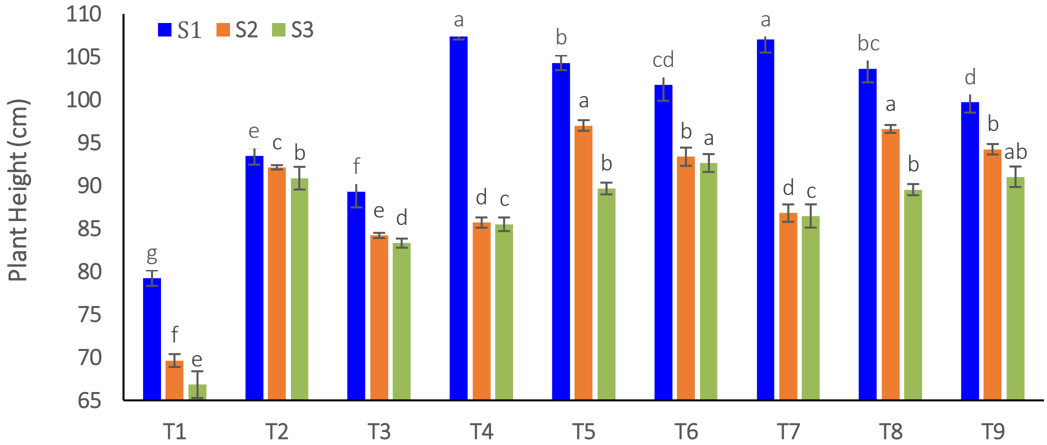

Figure 3. Effect of biochar application on plant height. S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments ($P < 0.05$).

The internodal distance of plant was also influenced by biochar application (Figure 4). The improvement in internodal distance persisted throughout the plant vegetative phase. In S1, compared to the T2, a significant improvement of 36.5% was recorded in T7. In S2, this improvement was recorded maximum in T6 (upto 13.0%) while in S3, the maximum improvement was recorded in T9 (2.6%). Fresh and residual biochar also altered the diameter of node and internode of the plant (Figure 5 and 6). In S1, compared to the T2, a significant increase of node diameter was recorded in T7 i.e. 34.7%, 21 % and 16.4 % at 60, 90 and 120 DAS respectively while in S2, it was recorded maximum in T9 i.e. 14.1%, 7.9% and 9.1% at 60, 90 and 120 DAS respectively. In S3, the maximum increase in node diameter was recorded in T6 (9%, 3.8% and 7.6% at 60, 90 and 120 DAS respectively). Similar trend was observed for internode diameter of plants as well. In S1, the maximum increase of internode diameter was recorded in T7 (42.4%, 27.8% and 19.5% at 60, 90 and 120 DAS respectively). In S2, the maximum increase in internodal diameter was recorded in T9 (16.5%, 12.2% and 6.2% at 60, 90 and 120 DAS respectively) while in S3, treatment T9 (14.4 % at 60 DAS) showed a significant increase at the initial phase but in the later phase, T6 (9.1%, 3.2% at 90 and 120 DAS respectively) had the maximum impact. Overall, the impact of fresh biochar application was more prominent than that of residual biochar on internodal distance, node and internode diameter of the plant. The inclusion of biochar significantly improves the xylem and phloem areas of the main vascular bundle, as well as stem thickness and wall density which allows the co-deposition of silica, hemicellulose, and lignin in the cell walls, that contributes to improved lodging resistance and crop yield (Meng et al. 2021; Miao et al. 2023).

The fresh and residual characteristics of biochar had a considerable influence on plant leaf area (Figure 7). In S1, as relative to T2, the maximum improvement in leaf area was recorded in T4 (40.7%). In S2, the maximum increase was recorded in T9 (16%) while in S3, the maximum increases of 16% was recorded in T9. Improved stomatal conductance and transpiration rates associated with biochar application further support increased leaf area by optimizing photosynthesis and nutrient transport within the plant. Furthermore, biochar reduce oxidative stress in plants by enhancing antioxidant enzyme activities, which help maintain cellular health and promote growth under stress conditions (Blanco-Canqui, 2017). Biochar also enhances root system expansion and plant nutrient uptake, promoting leaf area and production of the crop. However, ageing of biochar may impact on its physical and chemical properties, reducing its ability to retain and release nutrients effectively (Muema et al., 2024).

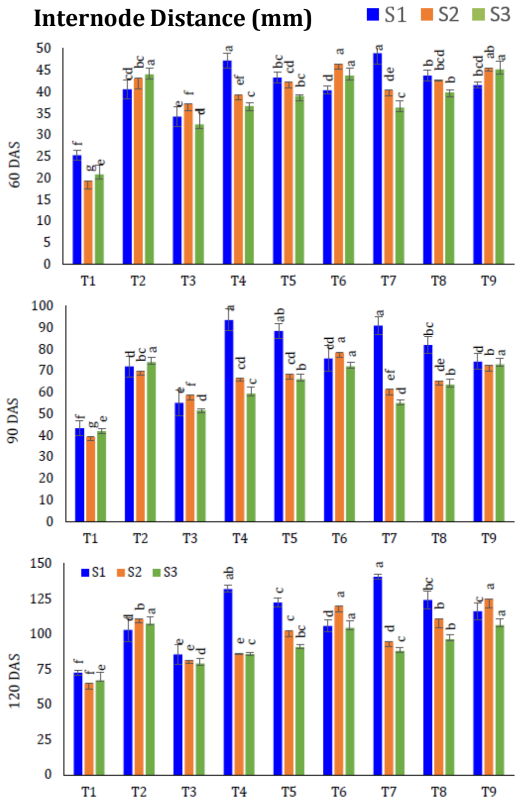

Figure 4. The impact of biochar application on internode distance at 60, 90 and 120 DAS. S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments (P < 0.05).

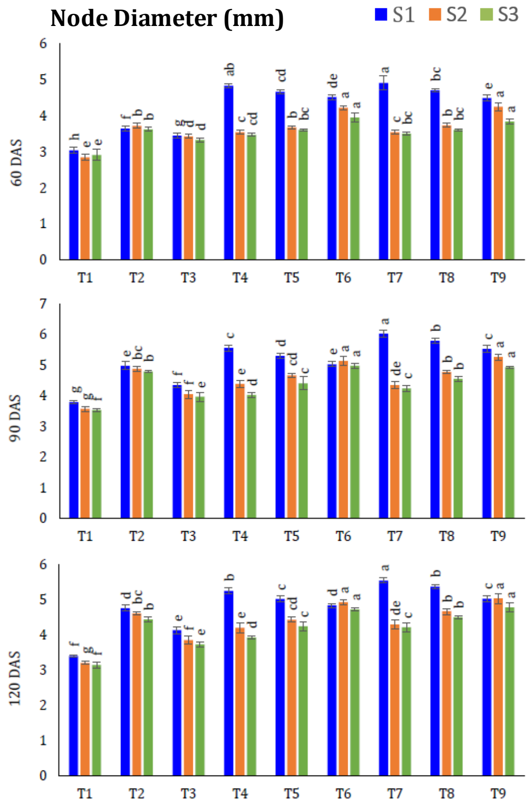

Figure 5. The impact of biochar application on node diameter at 30, 60 and 90 DAS. S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments (P < 0.05).

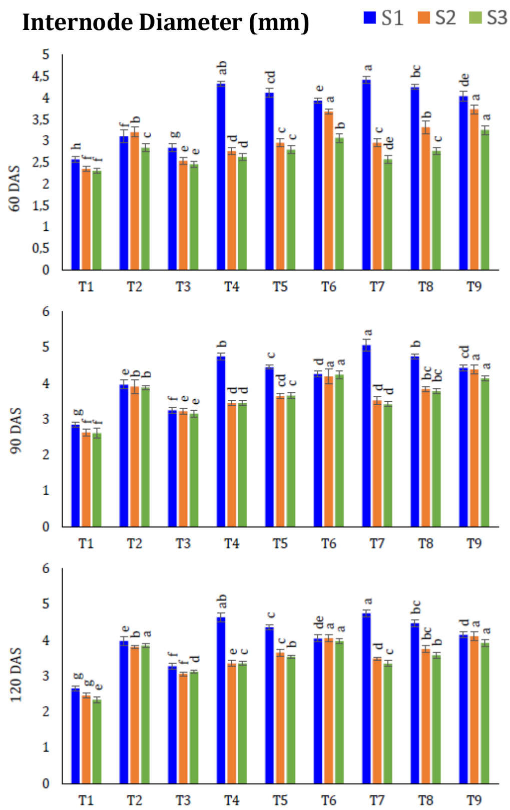

Figure 6. The impact of biochar application on internode diameter at 30, 60 and 90 DAS. S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments (P < 0.05).

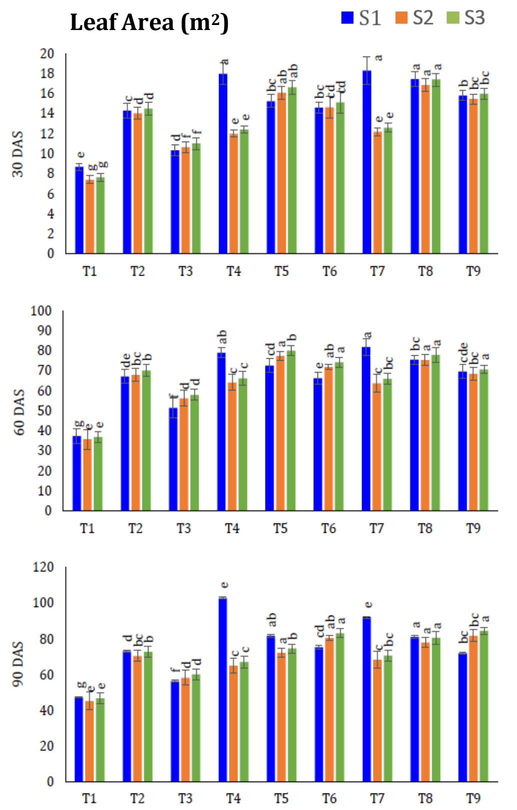

Figure 7. The impact of biochar application on leaf area (m^2) at 30, 60 and 90 DAS. S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments (P < 0.05).

A significant improvement in plant fresh and dry biomass was recorded with the inclusion of biochar (Figure 8). In S1, compared to the T2, a significant increase of fresh biomass was recorded in T7 (54% at 30 DAS) and T4 (30.3%, 17.5 % at 60 and 90 DAS respectively). In S2, during the initial growth stage (30 DAS), the maximum increase was recorded in T9 (34.7 %), while in the later growth stages it was recorded maximum in T6 (33.9%, 19.5% at 60 and 90 DAS respectively). Similarly, in S3, the maximum increase was recorded in T6 (14.7%) during the initial phase (30 DAS). In the mid-growth stage (60 DAS), the maximum increase was observed in T9 (6.3%), while in the later phase (90 DAS), the maximum increase was recorded again in T6 (12.2%). A similar trend was also observed for dry biomass (Figure 9). In S1, as compared to T2, the maximum increase was recorded in T7 (59.1%) at the initial phase (30 DAS). In the mid-growth stage (60 DAS) the maximum increase was observed in T4 (21.2%), while in the later phase (90 DAS) T4 & T7 both have same impact i.e. 21% increase. In S2, the maximum increase was recorded in T5 and T8 (30% at 30 DAS) and 15.7% during the mid-growth stage (60 DAS). In the later phase (90 DAS), the maximum increase was again recorded in T8 (13.1%). In S3, the maximum dry biomass increase was recorded in T6 (43.8%, 29.3% and 19.9% at 30, 60 and 90 DAS respectively). Biochar inclusion increases biomass accumulation due to its high potassium content, which acts as a catalyst, speeding up the process and accumulation of more plant biomass (Guo et al., 2019; Wan et al., 2024; Fachini et al., 2024). Fresh biochar improves soil structure, porosity, and water retention immediately after application, the long-term benefits may not persist as effectively with residual biochar. Soil properties can change over time due to various factors such as compaction or organic matter decomposition, which may limit the residual biochar's ability to enhance crop growth (Alkharabsheh et al., 2021)

Both fresh biochar and its residual effect had a significant effect on chlorophyll content. Analysis of variance ($p<0.05$) revealed that maximum chlorophyll content denotes during the anthesis stage as compared to grain filling stages. In S1, as relative to T2, the maximum increase of chlorophyll a content was recorded in T7 (23.9%). In S2, it was recorded maximum for T9 (11.9%) while in S3, there were no significant impact on chlorophyll a content (Figure 10). A similar trend was observed for chlorophyll b. In S1, the maximum increase was recorded in T7 (61.7%). In S2, the maximum increase was recorded in T7 (61.9%) while in S3, it was recorded maximum for T6 (4.1%) (Figure 11). Compared to the control, the total chlorophyll content in S1 showed maximum increases of 36.6% for T7. In S2, the maximum increase was recorded in T9 (8.4%) while in S3 there were no significant difference recorded among the treatments (Figure 12). The chlorophyll content is the main aspect that defines plant health and growth. Biochar significantly impacts on physiological attributes of the plant including chlorophyll content (Laird et al., 2010, Agegnehu et al., 2015, Trupiano et al., 2017; Farouk et al., 2023; Murtaza et al., 2024). The use of biochar boosts plant photosynthesis, the quantity of chlorophyll, and transpiration rate. Biochar can help mitigate the effects of environmental stresses, such as drought and salinity, which can negatively impact chlorophyll levels. By improving water use efficiency and reducing oxidative stress in plants, biochar application helps maintain higher chlorophyll content even under stressful conditions. The previous research findings reveals that fresh biochar application significantly increases the chlorophyll content compared to residual biochar application. This enhancement is due to improved nutrient availability, better soil properties, and mitigation of environmental stressors (Khan et al., 2021; Murtaza et al., 2024).

There was a significant impact of biochar application on plant yield attribute viz. biological yield, straw yield and grain yield (Figure 13). When comparing S1, S2 and S3, it was observed that S1 had the greatest impact on yield attributing characters followed by S2 and then S3. As compared to T2, in S1, the maximum increase in biological yield was recorded in T7 (19%). In S2, it was recorded maximum in T8 (9.7%) while in S3, treatment T6 (4.8%) had the most significant impact on improved biological yield. The improved biological yield also influenced the grain yields. S1 showed the highest gain yield followed by S2 and S3. In S1, compared to the T2, the grain yield showed a maximum increases of 30% in T7. In S2, the maximum increase in grain yield was recorded in T8 (15.6%), while in S3, the maximum increase was recorded in T6 (9.4%). A similar trend was observed for straw yield. In S1, the maximum increase was recorded in T7 (11.4%) followed by T4 (10.4%). In S2, it was recorded maximum for T8 (4.9%) followed by T6 (5.4%) while in S3, the maximum increase for straw yield was recorded in T6 and T9 (2.1%). The significant impact of biochar on crop yield attributes is primarily due to its ability to enhance soil fertility by improving nutrient retention and availability, particularly for essential nutrients like nitrogen, phosphorus, and potassium. These nutrients support better spike development and grain filling (Alkharabsheh et al., 2021; Khan et al., 2021). Collectively, these benefits contribute to higher grain yield attributes of crop. Several studies suggested that biochar improves plant growth, increases shoot dry matter, and boosts the yield of various crops (Major et al., 2010; Khan et al., 2022; Wan et al., 2023).

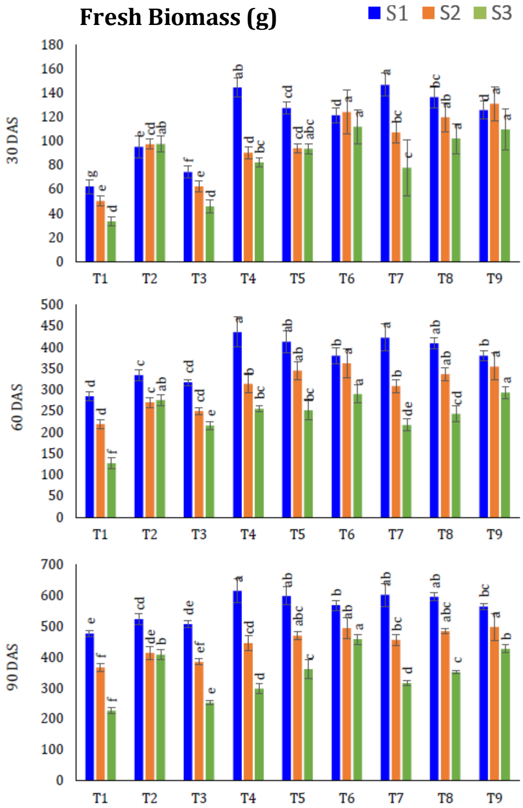

Figure 8. The impact of biochar application on fresh biomass at 30, 60 and 90 DAS, S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments (P < 0.05).

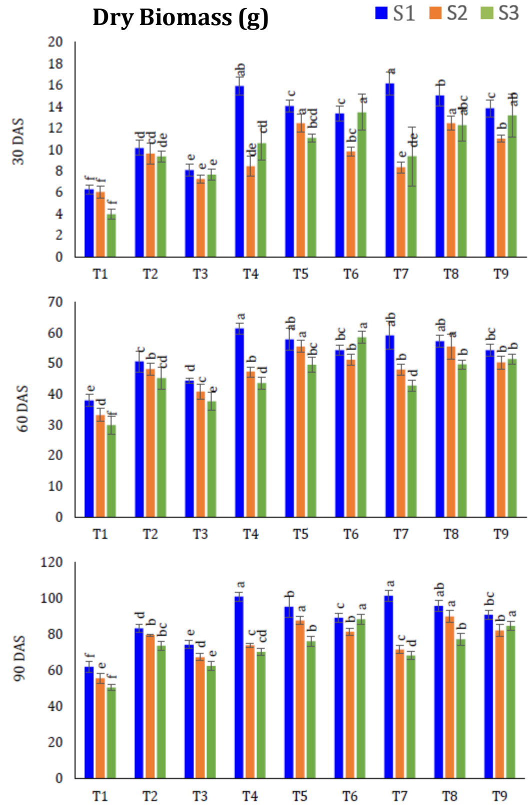

Figure 9. The impact of biochar application on dry biomass at 30, 60 and 90 DAS, S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments (P < 0.05).

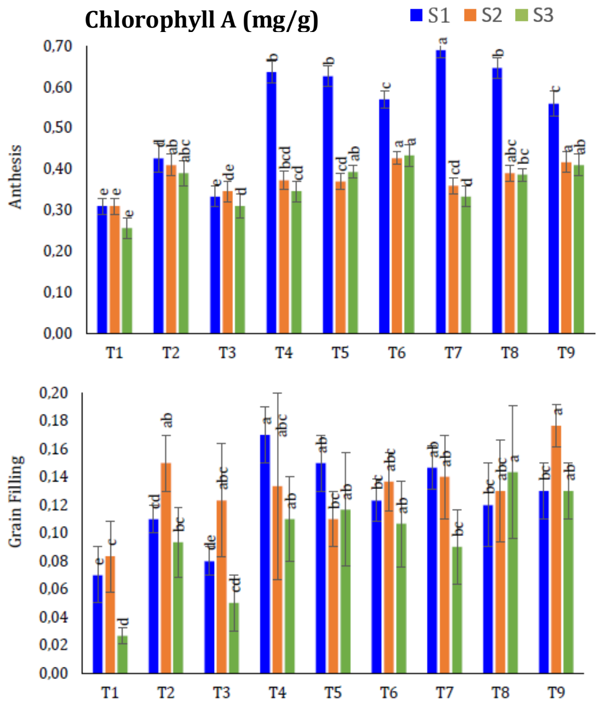

Figure 10. Effect of biochar application on total chlorophyll content (mg/g) at anthesis and grain filling stage. S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments (P < 0.05).

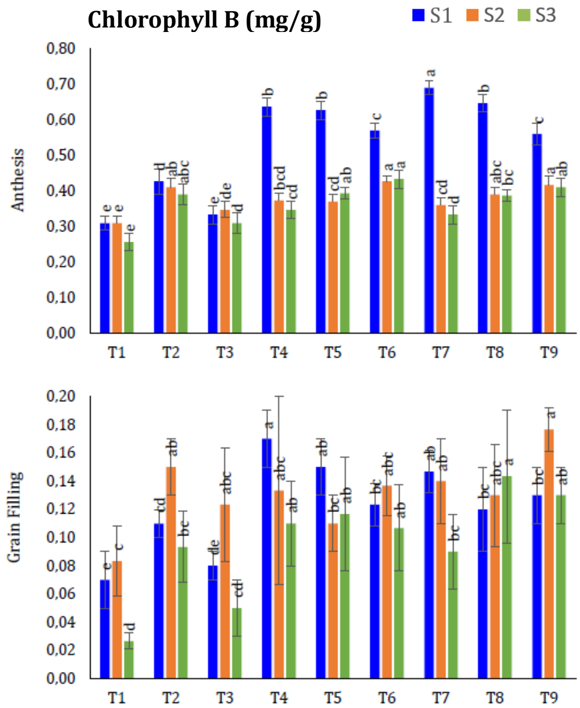

Figure 11. Effect of biochar application on total chlorophyll content (mg/g) at anthesis and grain filling stage. S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments (P < 0.05).

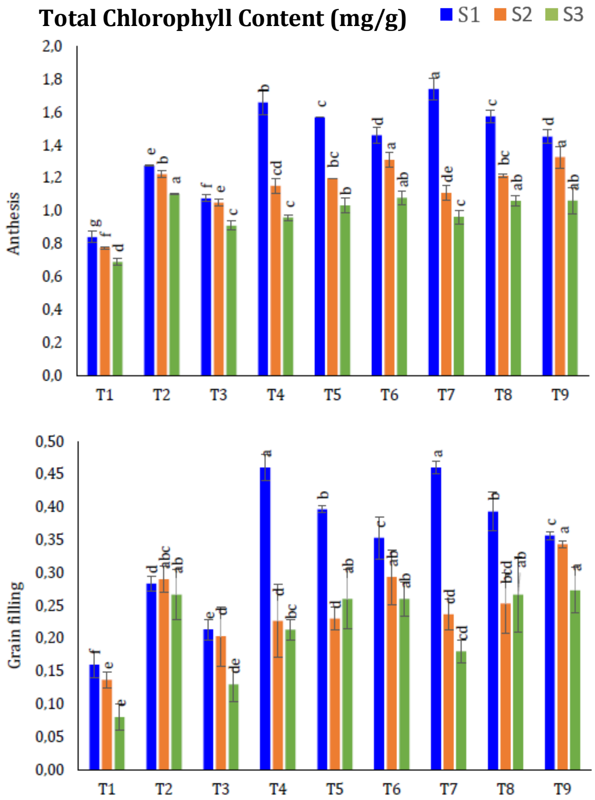

Figure 12. Effect of biochar application on total chlorophyll content (mg/g) at anthesis and grain filling stage. S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments (P < 0.05).

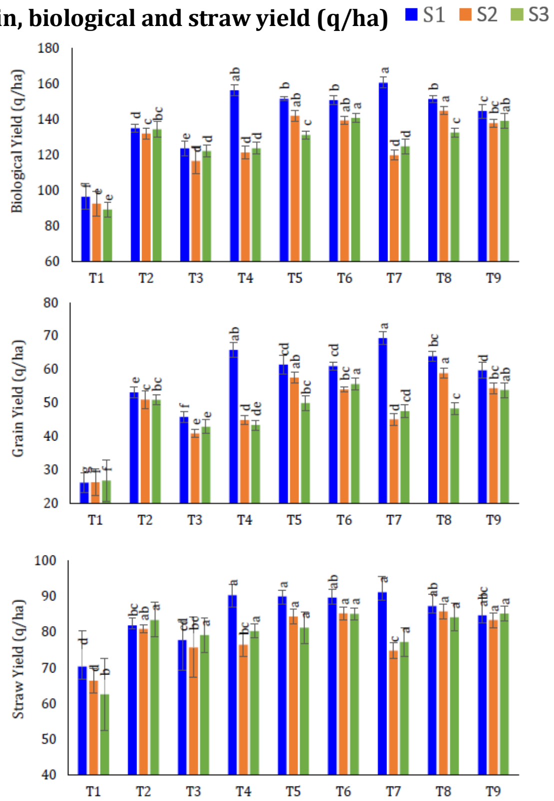

Figure 13. Effect of biochar application on grain yield, biological yield and straw yield (q/ha). S1 (Fresh biochar), S2 (Previous season residual biochar) and S3 (two seasons old residual biochar). Different lower cases indicate significant differences between treatments (P < 0.05).

Conclusion

Biochar is rich in nutrients and facilitates the transport of essential nutrients that improves growth and yield attributing characters of the wheat crop. In the present study, the most significant results were observed with a fresh biochar application at a dose of 5 tons/ha. Meanwhile, a 10 tons/ha biochar application significantly enhanced growth in one-season-old biochar, whereas the optimum result for two-season-old biochar was achieved at a dose of 15 tons/ha. When comparing fresh biochar application with residual biochar, fresh biochar had the greatest impact on plant growth and yield attributes. These findings highlight that the fresh application of biochar at an optimal dose has the greatest potential to improve plant health and productivity of wheat.

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