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# Biochar and Irrigation Strategies for Alleviating Drought Stress in Wheat Production

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**Abstract**

This research was conducted at the Agronomy Field Laboratory, Rajshahi University, from December 2021 to March 2022 to study the impact of biochar and low irrigation on mitigating drought stress in wheat (*Triticum aestivum*), specifically using the BARI Gom 28 variety. The experiment had two main factors: biochar application at rates of 2 t ha $^{-1}$, 4 t ha $^{-1}$, and 6 t ha $^{-1}$ ($B_1$, $B_2$, $B_3$) and irrigation treatments including regular irrigation ($I_1$), skipped irrigation at the booting stage ($I_2$), and skipped irrigation at the heading and flowering stages ($I_3$). The experiment followed a Split Plot Design (SPD) with three replications. Results showed that the highest biochar application rate (6 t ha $^{-1}$) significantly improved growth and yield parameters, such as plant height (96.70 cm), total tillers per plant (5.10), effective tillers per plant (4.55), spike length (16.42 cm), and grain yield (4.34 t ha $^{-1}$). Regular irrigation ($I_1$) also yielded better results compared to the other irrigation treatments, with notable improvements in plant height (96.56 cm), total tillers per plant (4.99), effective tillers per plant (4.29), spike length (16.37 cm), and grain yield (4.34 t ha $^{-1}$). The combination of the highest biochar rate (6 t ha $^{-1}$) and regular irrigation ($B_3I_1$) produced the best overall results, including the tallest plants (98.96 cm), highest total tillers (5.55), highest effective tillers (4.66), longest spikes (16.97 cm), and highest grain yield (4.46 t ha $^{-1}$). This study concludes that using 6 t ha $^{-1}$biochar combined with regular irrigation significantly enhances wheat performance and yield, making it a recommended practice for farmers. Further research is suggested to build on these findings.

**Keywords:** Biochar enhancement, Efficient irrigation, Drought resilience and Water-efficient practices.

## Introduction

Wheat (*Triticum aestivum* L.), a key cereal crop in the Poaceae family, is vital for global food security due to its adaptability to diverse environmental conditions. It provides 327 calories per 100 grams and is rich in essential nutrients, including carbohydrates, protein, fats, minerals, and fiber (Kasahun, 2020). Additionally, wheat contains antioxidants like phenolic compounds that may reduce chronic disease risk (Ma *et al*., 2021). Major wheat producers include China, India, and the United States, among others (Zhang *et al*., 2022). In Bangladesh, wheat is the second most important grain after rice, covering 0.328 million hectares with a production of 1.08 million metric tons in 2021 (BBS, 2021; Tasnim *et al*., 2022). Wheat yields are influenced by both biotic and abiotic factors. Abiotic stresses such as insufficient rainfall, extreme temperatures, and nutrient deficiencies, along with biotic stresses like pests and diseases, significantly impact productivity (Li *et al*., 2022; Hachisuca *et al*., 2022; Deepshikha and Rao, 2022; Singh *et al*., 2022). Biochar, a carbon-rich material from pyrolyzed organic matter, improves soil health by enhancing water and nutrient retention due to its porous structure (Hu and Wei, 2022; Elkhlifi *et al*., 2022; Zhao *et al*., 2022). It can potentially mitigate drought stress in crops by improving soil fertility and structure. Irrigation is crucial for wheat growth, especially in regions with erratic rainfall, as it ensures consistent moisture supply, essential for optimal growth and yield (Marcinska and Mierzwa, 2022). However, excessive irrigation can cause waterlogging, nutrient leaching, and increased disease risk (Sharma and Kumar, 2022). While much research has focused on nutrition management under water stress, the combined effects of biochar and irrigation are less studied. This study aims to evaluate the impact of biochar and optimized irrigation on wheat growth and yield under water stress, using the BARI Gom 28 cultivar.

## Materials and Methods

**Location and Site:** The experiment was conducted at the western side of the Agronomy and Agricultural Extension Department,

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located at 24°22'36'' N latitude and 88°38'36'' E longitude, at an elevation of 20 meters above sea level within the agro-ecological zone (AEZ-11).

**Soil and climate:** The experimental field was a highland area with sandy loam soil, pH 8.1. The soil was well-drained with moderate permeability, semi-loam topsoil, and slightly alkaline. The climate is subtropical, with moderately high temperatures and heavy rainfall during the Kharif season (June to October) and scanty rainfall with moderately low temperatures during the Rabi season (November to March).

**Planting Materials:** The experiment used BARI Gom 28, a modern, heat-tolerant, and high-yielding wheat variety obtained from the Regional Wheat Research Station, Shyampur, Rajshahi. Released in 2012, it is suitable for various planting conditions across Bangladesh.

**Experimental Treatments and Design:** The experiment included two factors. Factor A: Biochar (3 levels) - $B_1$ = 2 t $ha^{-1}$, $B_2$ = 4 t $ha^{-1}$, $B_3$ = 6 t $ha^{-1}$ and Factor B: Irrigation (3 levels)-$I_1$ = Regular irrigation (depending on soil moisture shortage), $I_2$ = Skipped irrigation at booting stage and $I_3$ = Skipped irrigation at heading and flowering stage. The experiment was laid out in a Split Plot Design (SPD) with three replications, totaling 27 plots (3 biochar levels × 3 irrigation levels × 3 replications). Each unit plot measured 5 m² (2 m × 2.5 m), with 1 m distance between subplots and 1.5 m between main plots.

**Crop cultivation and Agronomic practices:** Land preparation began on 25 November with a power tiller, followed by manual spading and clod breaking on 15 November. The field was laid out as per the experimental design, ensuring firm bunds around plots to control water movement. Fertilizers were applied as per requirement viz. TSP @180 kg $ha^{-1}$**,** MoP@50 kg $ha^{-1}$ **and** Gypsum @120 kg $ha^{-1}$**.** Fertilizers were mixed into the soil during final land preparation. Biochar was applied at the crown root initiation (CRI) stage (22 DAS), followed by the second application at 50 DAS, and third at heading and flowering stages. Before sowing, Seeds were treated with Vitavax-200 @ 0.25% to prevent disease. Sowing was done on 8 November at 120 kg $ha^{-1}$, with a 20 cm × 4 cm spacing. Weeding was performed twice, at 20 DAS and 65 DAS, using hand hoes and khurpi. Thinning was done after the first weeding to maintain 3 cm plant-to-plant distance. Irrigation was applied thrice during the growing period: at 22 DAS, 50 DAS, and 75 DAS as per treatment schedules. Drainage was managed as needed using drainage channels. Pests like cutworms and wheat aphids were controlled using Chloropyriphos 20EC @ 5m$L^{-1}$ and Sumithion 100 SCW @ 2m$L^{-1}$, respectively. Rodent pests were managed with Aluminium Phosphide. Three plants from each plot were sampled for data collection before harvesting. The crop was harvested when 90% of the plants were golden yellow. Harvesting was done on 3 March by cutting the crops at ground level. Bundles were tagged and transported to the threshing floor. Crops were sun-dried for two days, then threshed, cleaned, and weighed. Grain and straw yields were recorded separately. Data was collected on several parameters including plant height, tiller number, spike length, spikelet and grain counts, 1000-grain weight, grain yield, straw yield, biological yield, and harvest index. Data were analyzed using "STATVIEW" and "SPSS" software. Mean differences were determined using Duncan's Multiple Range Test (DMRT).

## Results and Discussion

**Plant Height:** The plant height of wheat was significantly affected by different levels of Biochar application at all observations (21, 42, 63, 84, and 110 DAS) **(Table 1)**. The table indicated that plant height showed an increasing trend with the advancement of time up to 110 DAS. At 21 DAS, the highest plant height of 22.76 cm was measured from $B_3$ showing a statistically identical relationship with $B_2$, and the lowest plant height of 19.60 cm was recorded from $B_1$. The maximum plant height of 44.73 cm was measured at 42 DAS from $B_3$ which had a statistically significant collaboration with $B_2$ and $B_1$, while the lowest plant height of 39.71 cm was recorded from $B_1$. Similarly, at 63 and 84 DAS, Plant heights were the highest (77.61cm and 89.19cm) regarding biochar quantity applied in $B_3$ treatment whereas the lowest plant heights (72.19cm and 84.54cm) were recorded from $B_1$. Considering the data collected on the last observation day, the tallest plant measuring 96.70 cm in length was found from $B_3$, which is statistically similar to $B_2$. The shortest plant of 89.96cm was recorded from $B_1$. Across all observations (21, 42, 63, 84, and 110DAS), there was a significant difference in the plant height of wheat according to the level of irrigation applied. When all treatments were combined, the application of skipped irrigation at the booting stage produced superior results. **(Table 1)**. At 21 days after sowing, $I_2$ reported the maximum plant height of 22.20 cm, indicating a statistically non-identical connection with $I_3$, whereas $I_1$ recorded the lowest plant height of 19.73 cm. By comparing the results from 42DAS, it can be said that the maximum plant height of 43.83cm was recorded from $I_1$ having a statistically equivalent collaboration with $I_2$, while $I_3$ showed the lowest plant height of 40.00 cm. Similar to this, at 63 and 84 DAS, plant heights were maximum (78.32 cm and 90.24 cm) with respect to the irrigation delivered in the $I_1$ treatment, whereas the $I_3$ treatment produced the lowest plant heights (73.41 cm and 85.28 cm). Based on the data gathered on the last observation day, $I_1$ produced the tallest plant, measuring 96.56cm in length and $I_3$ produced the smallest plant, measuring 91.27cm in length which is statistically equal to $I_2$. The cumulative impact of varying biochar and irrigation treatment levels on wheat plant height was significant, and all changes to the data at all observations (21, 42, 63, 84, and 110 DAS) followed an analogous pattern. The data regarding the interactions are presented in **Table 1.** At 21 DAS, the tallest plant (23.50 cm) was found to be from $B_3I_2$, which was statistically equivalent to $B_3I_3$ (23.12 cm). On the other hand, the smallest plant (17.95 cm) was from the combination of $B_1$ with $I_1$. At 42 DAS, the plant height was the highest (46.63 cm) in $B_3I_1$ and the lowest (38.10 cm) was in $B_1I_3$. When biochar at a rate of 6 t $ha^{-1}$ was applied concurrently with regular irrigation, the tallest plant measured 80.20 cm at 63DAS and 91.73 cm at 84DAS. In terms of equivalent treatment, the shortest plants measured 69.70 cm at 63DAS and 82.60 cm at 84DAS. At 110 DAS, the tallest plant was (98.96 cm) recorded from $B_3I_1$ whereas, the shortest (88.10 cm) obtained from $B_1I_3$.

**Number of total tiller plant$^{-1}$:** When comparing three different biochar doses, there were significant variations in all observations regarding the number of total tillers per plant. The highest number of total tiller plant$^{-1}$ (5.10) was obtained in $B_3$ and the lowest (4.56) in $B_1$ **(Table 1)** As a result, $B_3$ was reduced slightly by 6.47% in $B_2$ and significantly by 10.58% in $B_1$, respectively. Significant differences in the number of total tiller plant$^{-1}$ were observed for applying different levels of irrigation, as detailed in **Table 1**. The maximum number of total tiller plant$^{-1}$ (4.99) was recorded in $I_1$, which was reduced slightly by 0.60% in $I_2$, and significantly by 10.42% in $I_3$. Significant interaction in the number of total tiller plant$^{-1}$ was obtained considering irrigation and biochar application **(Table 1).** The maximum number of total tiller plant$^{-1}$ (5.55) was found in $B_3$ when combined with $I_1$ which is statistically similar to all interactions except $B_1I_3$ and the minimum number of total tiller plant$^{-1}$ (3.77) was recorded from $B_1I_3$. In that case, $B_3I_1$ is 47.21% higher than $B_1I_3$.

**Number "of effective tiller plant$^{-1}$:** Significant differences were seen in all data concerning the quantity of effective tiller per plant when considering three distinct biochar dosages. $B_3$ had the most number of effective tiller plant$^{-1}$ (4.55), whereas $B_1$ had the fewest number of effective tiller plant$^{-1}$ (3.70) **(Table 1).** Consequently, $B_3$ had a significant drop of 9.67% and 18.68% in comparison to $B_2$ and $B_1$, respectively. For every single type of irrigation, there were significant variations in the number of effective tiller plant$^{-1}$and the results are shown in **Table 1**. There was a significant decline of

**Table 1.** Efficacy biochar, irrigation and their interactions on growth and yield contributing parameters of wheat

| Biochar | Plant height (cm) | | | | | Number of total tiller plant$^{-1}$ | Number of effective tillers plant$^{-1}$ | Spike Length (cm) | Number of spikelet spike$^{-1}$ | Number of effective spikelet spike$^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | 21 DAS | 42 DAS | 63 DAS | 84 DAS | 110 DAS | | | | | |
| $B_1$ | 19.60±0.82b | 39.71±1.00b | 72.19±1.91b | 84.54±1.71b | 89.96±1.58b | 4.56±0.24b | 3.70±0.21c | 15.04±0.32b | 19.22±0.42b | 16.00±0.39b |
| $B_2$ | 21.32±0.64ab | 41.26±1.56b | 76.00±1.50ab | 87.31±1.67ab | 93.76±1.67ab | 4.77±0.12ab | 4.11±0.08b | 15.50±0.37ab | 19.66±0.35ab | 16.81±0.36ab |
| $B_3$ | 22.76±0.36a | 44.73±0.71a | 77.61±1.16a | 89.19±1.04a | 96.70±1.59a | 5.10±0.13a | 4.55±0.11a | 16.42±0.35a | 20.37±0.34a | 17.15±0.37a |
| **Irrigation** | | | | | | | | | | |
| $I_1$ | 19.73±0.78b | 43.83±0.84a | 78.32±1.43a | 90.24±1.87a | 96.56±1.46a | 4.99±0.14a | 4.29±0.13a | 16.37±0.34a | 20.62±0.40a | 17.48±0.36a |
| $I_2$ | 22.20±0.58a | 41.87±0.64ab | 74.06±1.11ab | 85.51±1.08b | 91.57±1.75b | 4.96±0.09a | 4.22±0.13ab | 15.32±0.34b | 19.40±0.32b | 16.33±0.34b |
| $I_3$ | 21.75±0.67a | 40.00±1.39b | 73.41±2.02b | 85.28±1.22b | 91.27±1.52b | 4.47±0.25b | 3.85±0.25b | 15.26±0.39b | 19.22±0.31b | 16.15±0.35b |
| **Interactions** | | | | | | | | | | |
| $B_1I_1$ | 17.95±1.57d | 41.70±0.92ab | 76.23±3.18sb | 88.03±4.80ab | 93.23±2.82ab | 5.00±0.19a | 4.00±0.19a | 15.82±0.58ab | 20.11±0.97ab | 16.66±0.70abc |
| $B_1I_2$ | 20.76±0.79abcd | 39.33±0.80b | 70.63±1.70b | 82.60±1.52b | 88.56±2.63b | 4.89±0.11a | 4.00±0.19a | 14.70±0.31b | 18.89±0.67b | 15.78±0.48bc |
| $B_1I_3$ | 20.08±1.69bcd | 38.10±2.70b | 69.70±4.27b | 83.00±0.73b | 88.10±2.16ab | 3.77±0.44b | 3.11±0.48b | 14.50±0.58b | 18.66±0.38b | 15.55±0.86c |
| $B_2I_1$ | 19.56±1.06cd | 43.16±0.28ab | 78.53±1.79ab | 90.96±3.32ab | 93.50±1.21ab | 4.77±0.22a | 4.22±0.11a | 16.34±0.64ab | 20.53±0.22ab | 17.77±0.40ab |
| $B_2I_2$ | 22..35±1.12abc | 41.50±4.85ab | 74.80±0.70ab | 86.03±1.38ab | 91.96±3.87ab | 5.00±0.19a | 4.11±0.11a | 15.11±0.58ab | 19.33±0.51ab | 16.44±0.77abc |
| $B_2I_3$ | 22.04±0.38abc | 39.13±1.28b | 74.66±4.28ab | 84.93±3.20ab | 91.80±2.45ab | 5.21±0.22a | 4.00±0.19a | 15.06±0.57ab | 19.11±0.78b | 16.22±0.29abc |
| $B_3I_1$ | 21.66±0.51abc | 46.63±1.07a | 80.20±2.72a | 91.73±2.05a | 98.96±2.71a | 5.55±0.29a | 4.66±0.19a | 16.97±0.55a | 21.22±0.77a | 18.00±0.69a |
| $B_3I_2$ | 23.50±0.56a | 44.80±0.81ab | 76.76±1.32ab | 87.90±1.65ab | 94.20±2.51ab | 5.00±0.19a | 4.55±0.29a | 16.15±0.64ab | 20.00±0.50ab | 16.78±0.58abc |
| $B_3I_3$ | 23.12±0.25ab | 42.76±0.76ab | 76.86±1.29ab | 87.93±1.02ab | 93.93±2.92ab | 5.11±0.29a | 4.44±0.11a | 16.14±0.74ab | 19.89±0.22ab | 16.67±0.57abc |
| **CV%** | 8.23 | 8.32 | 6.15 | 5.01 | 5.01 | 9.24 | 9.94 | 6.54 | 5.37 | 6.47 |

In a column, figures having similar letters (s) or without letters (s) do not differ significantly, whereas figures dissimilar letters (s) differ significant of probability (as per DMRT).$B_1$ = 2 t ha$^{-1}$, $B_2$ = 4 t ha$^{-1}$, $B_3$ = 6 t ha$^{-1}$, $I_1$ = Regular irrigation (depending on shortage of soil moisture), $I_2$= Skipped irrigation at booting stage and $I_3$ = Skipped irrigation at heading and flowering stage, CV%= Co-efficient of variation

1.63% in $I_2$ and 10.25% in $I_3$ from the highest number of effective tiller plant$^{-1}$ (4.29) that was reported in $I_1$. When biochar and irrigation were applied together, a significant difference in the number of effective tiller plant$^{-1}$ was observed (**Table 1**). The combination of $B_3$ and $I_1$ produced the highest number of effective tiller plant$^{-1}$ (4.66), which is statistically equivalent to all treatments except $B_1I_3$, which had the lowest number of effective tiller plant$^{-1}$ (3.11). In such a scenario, $B_3I_1$ exceeds $B_1I_3$ by 46.62%.

**Spike length (cm):** Significant variations in case spike lengths were observed when comparing three different biochar doses. Considering three treatments, $B_3$ produced the highest spike length (16.42 cm), and the lowest (15.04 cm) was found in $B_1$ (**Table 1**). Among the significant values, $B_3$ was reduced only by 5.60% in $B_2$ and significantly by 8.40% in $B_1$, respectively. Irrigation fertilizer effect differed significantly with respect to the spike length of wheat (**Table 1**). The longest length of spike (16.37 cm) was recorded in $I_1$ and the shortest length of spike (15.26 cm) was measured in $I_3$. $I_1$ is reduced significantly by 6.41% and 6.78% in $I_2$ and $I_3$, respectively. Data considering spike length showed significant interaction due to the combined application of irrigation and biochar (**Table 1**). The tallest spike measuring 16.97 cm in length was found in $B_3$ when combined with $I_1$ whereas, the shortest spike measuring 14.50 cm in length was recorded from $B_1I_3$. Here, $B_3I_1$ is 17.03% higher than $B_1I_3$.

**Number of spikelet spike$^{-1}$:** Significant variations considering the number of spikelet spike$^{-1}$ were observed when comparing three different biochar doses. Considering three treatments, $B_3$ produced the highest number of spikelet spike$^{-1}$ (20.37), and the lowest (19.22) was found in $B_1$ (**Table 1**). Among the significant values, $B_3$ was reduced only by 3.48% in $B_2$ and significantly by 5.65% in $B_1$, respectively. The influence of irrigation differed significantly with respect to the number of spikelet spike$^{-1}$(**Table 1**). The maximum number of spikelet spike$^{-1}$ (20.62) was recorded in $I_1$, which was reduced significantly by 5.925% in $I_2$, and 6.79% in $I_3$, respectively. The number of spikelet spike$^{-1}$ showed significant differences considering the combined application of irrigation and biochar (**Table 1**). The highest number of spikelet spike$^{-1}$ (21.22) was found in $B_3$ when combined with $I_1$ whereas, the lowest number of spikelet spike$^{-1}$ (18.66) was recorded from $B_1I_3$. Considering the interaction data, the lowest value is 13.61% lower than the highest value.

**Number of effective spikelet spike$^{-1}$:** Significant differences were seen in all data concerning the quantity of effective spikelet per spike when considering three distinct biochar dosages. $B_3$ had the highest number of effective spikelet spike$^{-1}$ (17.15), whereas $B_1$ had the fewest number of effective spikelet spike$^{-1}$ (16.00) (**Table 1**). Consequently, $B_3$ had a significant drop of 1.98% and 6.70% in comparison to $B_2$ and $B_1$, respectively. For every single type of irrigation, there were significant variations in the number of effective spikelet spike$^{-1}$ and the results are shown in **Table 1**. There was a significant decline of 6.57% in $I_2$ and 7.60% in $I_3$ from the highest number of effective spikelet spike$^{-1}$ (17.48) that was reported in $I_1$. When biochar and irrigation were applied together, a significant difference in the number of effective spikelet spike$^{-1}$ was observed (**Table 1**). The combination of $B_3$ and $I_1$ produced the

**Table 2**. Efficacy biochar, irrigation and their interactions on growth and yield contributing parameters of wheat

| Biochar | Number of filled grain panicle $^{-1}$ | Number of total grain panicle $^{-1}$ | Thousand grain weight (g) | Grain yield (t ha$^{-1}$) | Straw Yield (t ha$^{-1}$) | Biological Yield (t ha$^{-1}$) | Harvest Index (%) |
|---|---|---|---|---|---|---|---|
| **$B_1$** | 24.01±0.47b | 27.43±0.53b | 39.70±0.88b | 4.00±0.09b | 5.44±0.13b | 9.45±0.22b | 42.38±0.01 |
| **$B_2$** | 24.97±1.04ab | 29.17±1.03b | 40.70±0.74ab | 4.23±0.07ab | 5.79±0.09a | 10.02±0.16a | 42.21±0.18 |
| **$B_3$** | 27.04±0.53a | 31.40±0.38a | 42.26±0.80a | 4.34±0.06a | 5.90±0.09a | 10.24±0.15a | 42.40±0.01 |
| **Irrigation** | | | | | | | |
| **$I_1$** | 26.77±0.64a | 30.79±0.78a | 42.40±0.90a | 4.34±0.07a | 5.94±0.08a | 10.29±0.15a | 42.22±0.18 |
| **$I_2$** | 24.80±0.81ab | 28.81±0.85ab | 40.90±0.75ab | 4.14±0.08ab | 5.62±0.11b | 9.76±0.20b | 42.38±0.01 |
| **$I_3$** | 24.45±0.85b | 28.41±0.85b | 39.83±0.74b | 4.09±0.09b | 5.56±0.12b | 9.65±0.22b | 42.39±0.01 |
| **Interactions** | | | | | | | |
| **$B_1I_1$** | 25.50±0.15ab | 28.80±1.12abcd | 41.46±1.81ab | 4.23±0.12abc | 5.76±0.16abc | 10.00±0.29ab | 42.38±0.01 |
| **$B_1I_2$** | 23.50±0.83b | 26.90±0.75cd | 39.23±1.58ab | 3.94±0.16bc | 5.36±0.21bc | 9.30±0.37bc | 42.38±0.02 |
| **$B_1I_3$** | 23.03±0.52b | 26.60±0.36d | 38.40±1.05b | 3.83±0.15c | 5.21±0.11c | 9.05±0.36c | 42.39±0.02 |
| **$B_2I_1$** | 26.66±1.72ab | 30.93±1.47ab | 42.16±1.67ab | 4.34±0.14ab | 6.02±0.11a | 10.37±0.24a | 42.86±0.53 |
| **$B_2I_2$** | 24.33±1.91ab | 28.66±2.05abcd | 40.20±1.08ab | 4.18±0.14abc | 5.69±0.19abc | 9.87±0.33abc | 42.38±0.00 |
| **$B_2I_3$** | 23.93±2.05ab | 27.93±1.97bcd | 39.73±1.00ab | 4.16±0.10abc | 5.65±0.14abc | 9.81±0.25abc | 42.36±0.00 |
| **$B_3I_1$** | 28.16±0.38a | 32.63±0.42a | 43.56±1.62a | 4.46±0.11a | 6.06±0.15a | 10.52±0.26a | 42.41±0.00 |
| **$B_3I_2$** | 26.56±1.07ab | 30.86±0.17abc | 41.86±1.16ab | 4.29±0.11ab | 5.83±0.14ab | 10.12±0.25ab | 42.39±0.01 |
| **$B_3I_3$** | 26.40±1.10ab | 30.70±0.60abc | 41.36±1.53ab | 4.28±0.13ab | 5.81±0.18ab | 10.10±0.21ab | 42.39±0.01 |
| **CV%** | 8.63 | 7.17 | 6.03 | 5.49 | 5.25 | 5.31 | 0.73 |

In a column, figures having similar letters (s) or without letters (s) do not differ significantly, whereas figures dissimilar letters (s) differ significant of probability (as per DMRT). $B_1$ = 2 t ha$^{-1}$, $B_2$ = 4 t ha$^{-1}$, $B_3$ = 6 t ha$^{-1}$, $I_1$ = Regular irrigation (depending on shortage of soil moisture), $I_2$= Skipped irrigation at booting stage and $I_3$ = Skipped irrigation at heading and flowering stage, CV%= Co-efficient of variation

highest number of effective spikelet spike$^{-1}$ (18.00) and $B_1I_3$ reported the lowest number of effective spikelet spike$^{-1}$ (15.55). In such a scenario, $B_3I_1$ exceeds $B_1I_3$ by 15.76%.

**Number of filled grain Spike$^{-1}$:** When comparing three different biochar doses, significant variations were observed regarding the number of filled grains per Spike. The highest number of filled grain Spike $^{-1}$ (27.04) was obtained in $B_3$ and the lowest (24.01 in $B_1$ **(Table 2)** As a result, $B_3$ was reduced slightly by 7.65% in $B_2$ and significantly by 11.21% in $B_1$, respectively. Significant differences in the number of filled grain Spike $^{-1}$ were observed for applying different levels of irrigation, as detailed in **Table 2**. The maximum number of filled grain Spike $^{-1}$ (26.77) was recorded in $I_{1,}$ which was reduced slightly by 7.35% in $I_2$, and significantly by 8.67% in $I_3$. Significant interaction in the number of filled grain Spike$^{-1}$ was obtained considering the combined application of irrigation and biochar **(Table 2).** The maximum number of filled grain Spike$^{-1}$ (28.16) was found in $B_3$ when combined with $I_1$ and the minimum number of filled grain Spike$^{-1}$ (23.03) was recorded from $B_1I_3$. In that case, $B_3I_1$ was 22.27% higher than $B_1I_3$.

**Number of total grain Spike$^{-1}$**: The number of total grain spike$^{-1}$ differed significantly in comparison to three different biochar doses and the result was presented in **Table 2**. The highest number of total grain spike$^{-1}$ (31.40) was obtained in $B_3$ and the lowest (27.43) in $B_{1.}$ As a result, $B_3$ was reduced both significantly by 7.10% and 12.64% in $B_2$ and $B_1$, respectively. Significant differences in the number of total grain spike$^{-1}$ were observed by applying different levels of irrigation, as detailed in **Table 2**. The maximum number of total grain spike$^{-1}$ (30.79) was recorded in $I_{1,}$ which was reduced slightly by 6.43% in $I_2$, and significantly by 7.73% in $I_3$. A significant interaction effect was found among the number of total grain spike$^{-1}$ due to the application of biochar and irrigation at varying rates. **(Table 2).** The maximum number of total grain spike$^{-1}$ (32.63) was found in $B_3$ when combined with $I_1$ and the minimum number of total grain spike$^{-1}$ (26.60) was recorded from $B_1I_3$. In that case, $B_3I_1$ was 22.67% higher than $B_1I_3$.

**Thousand (1000) grains weight:** Application of various rates of biochar has different effects on 1000 grains weight of wheat variety. The highest 1000-grain weight (42.26 g) was obtained in $B_3$ that is followed by (40.70 g) in $B_2$ and the lowest (39.70 g) was observed in $B_1$ (**Table 2**). This result clearly shows that $B_3$ was reduced by 6.06% from $B_1$. Significant differences in 1000-grain weight were illustrated for different irrigation treatments (**Table 2**). The highest 1000-grain weight was recorded (42.40 g) in $I_1$. This 1000-grain weight was slightly decreased by 3.53% in $I_2$ but significantly by 6.06% in $I_1$. A significant effect was recorded in 1000grain weight due to the interaction between biochar and irrigation treatments (**Table 2**). The maximum 1000 grains weight (43.56g) was found in the combination of $B_3$ with $I_1$ and the minimum (38.40g) was found in $B_1$ with $I_3$. Here, 1000 grains weight in $B_3I_1$ reduced significantly by 11.84% in $B_1I_3$.

**Grain yield (t ha$^{-1}$):** Significant variations were seen in wheat grain yield when biochar was applied. As indicated by **Table 2**, $B_3$ produced the highest amount of grain yield (4.34 t ha$^{-1}$), followed by $B_2$ (4.23 t ha$^{-1}$) and $B_1$ (4.00 t ha$^{-1}$). It is evident from this data that $B_3$ was decreased by 7.83% in $B_1$. Regarding wheat grain yield, the effects of irrigation treatment varied considerably (**Table 2**). The largest amount of grain yield (4.34 t ha$^{-1}$) was seen in $I_1$, and it was considerably lower in $I_2$ and $I_3$ by 4.61% and 5.76%, respectively. The effect of a combination of biochar and irrigation treatments showed statistically significant differences in the wheat grain yield. The highest grain yield (4.46 t ha$^{-1}$) was measured in the combination of $B_3$ with $I_1$ and the lowest (3.83 t ha$^{-1}$) in the combination of $B_1$ with $I_3$ (**Table 9**). The highest grain yield considering $B_3I_1$ combination was decreased by 14.13% in $B_1I_3$.

**Straw yield (t ha$^{-1}$):** The straw yield of wheat showed significant differences regarding biochar treatment **(Table 2).** The highest straw yield (5.90 t ha$^{-1}$) was obtained in $B_3$ that was followed by 5.79 t ha$^{-1}$ in $B_2$ and the lowest (5.44 t ha$^{-1}$) was observed in $B_1$. This result clearly shows that $B_3$ was reduced by 7.79% in $B_1$. The efficacy of irrigations differed significantly with respect to the straw yield of wheat **(Table 2).** The highest quantity of straw yield (5.94 t $ha^{-1}$) was recorded in $I_1$, which was reduced significantly by 5.39% in $I_2$, and 6.38% in $I_3$, respectively. Variation was obtained when comparing the result of the straw yield of wheat due to the interaction between biochar and irrigation treatments. The highest straw yield (6.06 t $ha^{-1}$) was calculated in the combination of $B_3$ with $I_1$ and the lowest (5.21t $ha^{-1}$) in the combination of $B_1$ with $I_3$ (**Table 2**). The highest straw yield following the $B_3I_1$ combination was decreased by 14.03% in $B_1I_3$.

**Biological yield (t $ha^{-1}$):** The wheat's biological yield was significantly impacted by the application of biochar and the result is presented in **Table 2.** The biological yield of $B_3$ was the highest (10.24 t $ha^{-1}$), followed by $B_2$ and $B_1$ (10.02 t $ha^{-1}$ and 9.45 t $ha^{-1}$), respectively. In this instance, $B_3$ is higher than $B_2$ and $B_1$ by 2.19% and 8.36%, respectively. There were significant variations found in the biological yield of wheat based on the time of irrigation supplied **(Table 2).** A considerable reduction of 5.15% in $I_2$ and 6.21% in $I_3$ was seen from the highest biological yield of 10.29 t $ha^{-1}$ which was found in $I_1$. When it came to the biological yield of the experimental variety, the combined application of biochar and irrigation was shown to have a statistically significant difference **(Table 2)**. The combination of $B_3$ and $I_1$ produced the highest biological yield (10.52 t $ha^{-1}$), whereas the combination of $B_1$ and $I_3$ produced the lowest biological yield (9.05 t $ha^{-1}$). Taking these interactions into account, the $B_3I_1$ combination is 16.24% higher than the $B_1I_3$ combination.

**Harvest index (%):** Harvest index differed non-significantly under the effect of biochar application and the result is presented in **Table 2**. From the table, it can be said that the highest harvest index (42.40%) value was calculated in $B_3$, which was 0.05% higher than the lowest value (42.21%) in $B_2$ and these differences were statistically non-significant. The harvest index did not differ considerably when irrigation treatments were applied **(Table 2).** According to the table, $I_3$ had the highest harvest index value (42.39%) and $I_1$ had the lowest value (42.22%). The combined effect of biochar and irrigation was shown to have a statistically non-significant interaction concerning the harvest index of wheat **(Table 2).** The highest harvest index (42.86%) value was calculated from the combination of $B_2$ with $I_1$ and the lowest value (42.36%) was recorded from the combination of $B_2$ with $I_3$.

## Conclusion

The study found that applying biochar and optimized irrigation significantly improves wheat growth and yield. The best results were achieved with the highest biochar dose (6 t $ha^{-1}$) and regular irrigation, showing substantial increases in plant height, tiller number, spike length, grain count, and overall yields. The combination of biochar and efficient irrigation, especially B3 with I1, effectively mitigated water stress and enhanced wheat productivity, suggesting a viable approach for improving wheat cultivation under water-limited conditions.

## Conflict of interest

The authos declare there is no conflict of interest.

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