PERFORMANCE OF WHEAT PROGENY UNDER DEFICIT IRRIGATION: EFFECTS ON GERMINATION AND SEED RESERVE UTILIZATION

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Abstract

This study explores the impact of biochar amendments under deficit irrigation on seed germination performance, mineral content, and early growth in wheat (*Triticum aestivum*). A controlled experiment was conducted using three wheat varieties (Dilkhsh-2020, Akbar-2019, and Faisalabad-08) under two irrigation levels (100% and 50% field capacity) and three levels of soil applied biochar (0, 1.25, and 2.50 g/pot). The seeds used were the yield of previously conducted field trial and observed for their germination viability. Results showed that biochar significantly ($p \leq 0.05$) enhanced seed germination percentage and rate, particularly under water-limited conditions, where the Dilkash-2020 outperformed other varieties. Mineral analysis revealed increased nutrient contents in seeds from biochar-amended soils i.e. 82% higher nitrogen and 77% higher potassium in 2/5 g/pot biochar as compared to control under deficit irrigation. Biochar at 2.5 g/pot under deficit irrigation increased germination index (9%), seedling length (9%), seedling vigor (27%), water uptake (23%), stress tolerance (13%), root to shoot ratio (12%), and uniformity index (4-5%) as compared to normal irrigation. Multivariate analysis identified strong correlations between germination performance, nutrient content, and soil applied biochar, particularly under deficit irrigation. The findings emphasize potential of biochar in mitigating water stress, enhancing seed germination, and improving seed's nutrient use efficiency, offering insights for sustainable crop establishment in water scarce environments.

Keywords

Biochar, seed germination, drought, soil amendment, mineral content.

INTRODUCTION

One of the important stages in the development of plants is the germination of seeds, which depends on the success of the establishment of crops and productivity. There is a role of certain factors such as soil compaction, availability of moisture, and nutrients in the soil, among others. When it comes to growing crops in arid and semi-arid areas of the world where access to water is a challenge, methods to boost the germination and emergence rates of crops are critical to the effective establishment and growth of productive agricultural systems (Tian *et al.,* 2021). Besides, the methods like the soil amendments such as biochar have received a special attention as it may have the rural of enhancing the physical properties of the soils as well as water retention capacity and nutrient status (Adhikari *et al.,* 2022).

The negative charge of the biochar, derived from the pyrolysis of biomass, is known to dramatically alter the soil properties. This characteristic allows it to hold water; such problematic factors as water stress on plants can be combatted more effectively. It also improves cation exchange capacity that works in favor of nutrient availability necessary for seed emergence and seedlings growth and development (Hailegnaw *et al.,* 2019).

The literature survey showed that the use of biochar could enhance the germination percentage and germination rate due to the enhancement of moisture content and decrease in nutrient runoff specifically under restricted water supply (Faloye *et al.,* 2019).Current study aims to mitigate the negative impacts of deficit irrigation on seed germination using biochar as soil amendment. Seed germination is a crucial stage to be observed for understanding plant establishment which is mediated by well-irrigated condition, ensuring moisture availability for metabolic activities, enzyme activation, nutrient mobilization and cell elongation (Ali and Elozeiri, 2017). However, under water-deficit conditions, these processes are limited, restraining the germination rates and percentages. Nevertheless, these issues can be addressed by using biochar for enhancing the soil moisture retention and reducing the risk of drought stress as stated by Haider *et al.* (2020).

Additionally, seed mineral content, which is influenced by soil nutrient availability, plays a vital role in seed germination and early seedling growth. Essential nutrients such as nitrogen, phosphorus, potassium, and micronutrients are critical for metabolic activities during germination (Finch-Savage and Bassel, 2016; Martínez-Ballesta *et al.,* 2020). Biochar-amended soils have been reported to enhance mineral availability, thus improving seed mineral content and subsequent germination performance (Zhang *et al.,* 2022). These effects are particularly pronounced in nutrient-poor soils or under water-limited conditions.

This study investigates the effects of biochar amendment and varying irrigation regimes on seed germination percentage, seed germination rate, and seed mineral content. No study have reported how the progeny of biochar cultivated wheat performs under deficit irrigation. Therefor it is crucial to observe the seed germination related attributes to understand the role of biochar in sustainable wheat production over the growing seasons. Hence, it is hypothesized that biochar amendment enhances seed germination and reserve utilization efficiency under water-limited conditions, particularly in drought-tolerant wheat varieties.

MATERIALS AND METHODS

EXPERIMENTAL SITE AND DESIGN

The study was conducted at Plant physiology lab, Institute of Botany, University of the Punjab, Lahore, Pakistan. Seeds were produced from a field experiment during the year 2023-2024 comprising split-split-plot arrangement with RCBD having three replicates with three biochar levels (0T, 5T, and 10T, T= tons per hectare), three wheat cultivars (V1= Dilkash-2020, V2= Akbar-2019, and V3= Faisalabad-08) receiving varying irrigations. Seed yielded from this field work was utilized in current study and a completely randomized design (CRD) was employed in petri plates to check the germination parameters of seeds.

Using CRD in lab experiments was based on homogeneous experimental units as compared to RCBD that maintains variability among experimental units in field condition. The germinated seeds were transplanted to pots with two irrigation regimes (100% and 50% of field capacity) and three soil treatments (Control, 1.25 g/pot, and 2.50 g/pot biochar). The quantity of biochar per pot was calculated in accordance with per pot soil weight and estimated amount of soil per hectares. Each treatment was replicated three times, and the experiment was conducted over a two-week period (Figure 1).

Figure 1. Pictorial diagram presenting petri plate experiment with subsequent pot experiment for each treatment.

Biochar was produced from acacia (new name *Vachellia nilotica)* wood using slow pyrolysis at 480°C under limited oxygen conditions. The biochar was ground and sieved to a particle size of <2 mm and was mixed with the soil at a rate of 5 and 10 tons per hectare equivalent, ensuring homogeneous incorporation. Control soil treatments were prepared without biochar amendment. Wheat (*Triticum aestivum*) seeds of the three varieties were used for the experiment. Seeds were sown in pots filled with half kg of either biochar-amended or non-amended soil. Each pot received ten seeds, which were later thinned to five uniform seedlings per pot.

Pots were irrigated to maintain either 100% or 50% of field capacity at regular intervals. Field capacity was determined using the gravimetric method. Water was applied daily based on the weight difference of pots to ensure precise water regimes. Seed germination percentage and germination rate were assessed over a 7-day period following sowing (Trethowan, 1995). Germination percentage was calculated as:

$$\text{Germination Percentage (\%)} = \frac{\text{Number of germinated seeds}}{\text{Total number of seeds sown}} \times 100$$

Germination rate was calculated using the formula:

$$\text{Germination Rate (per day)} = \frac{\text{Number of germinated seeds on each day}}{\text{Days since sowing}}$$

At the end of the germination period, seeds were collected from each treatment and analyzed for mineral content. Samples were oven-dried at 70°C for 48 hours and ground to a fine powder. Nitrogen (N), phosphorus (P), and potassium (K) concentrations were determined following the method of Zheljazkov and Warman (2002). Nitrogen content was estimated through kjeldahl method after digesting samples in conc. H_2SO_4 and titrated against boric acid. Whereas potassium and phosphorous contents were estimated after digesting samples in muffle furnace at 550 °C for 5 hours and diluted in 1N solution of 5ml HCl and the volume was raised upto 50 ml.

This digest was then observed under flame photometer for potassium content and phosphorous was observed from spectrophotometer at ±823nm absorbance (AOAC, 1998). Biomass yield was observed as a sum of above and belowground biomass per meter square. Germination Index (GI) was calculated from the following formula (Yang *et al.,* 2021)

$$\mathrm{GI} = \sum \frac{\mathrm{G_t}}{\mathrm{t}}$$

Where G_t is the Number of seeds germinated on day t and t is the time in days from start of germinations. To measure the seedling length, including both shoot and root. Three seedlings were selected randomly from each replicate and the shoot and root lengths were measured using a ruler and mean values were calculated. Seedlings were dried at 70°C for 48 hours or until constant weight for dry weight calculations. Seedling Vigor Index (SVI) was calculated by integrating germination percentage and seedling growth as follows (Islam *et al.,* 2009):

$$\mathrm{SVI} = \mathrm{GP} \times \mathrm{SL}$$

Where GP shows germination percentage and SL presents seedling length. Seed Reserve Utilization Efficiency (SRUE) (Cheng *et al.,* 2015) was calculated to measure the nutrient use efficiency of seeds using seed reserves for germination using following equation:

$$\mathrm{SRUE} = \frac{\text{Deedling dry weight (mg)}}{\text{Initial seed weight (mg)}}$$

Water Uptake Rate (WUR) was calculated to quantify the water imbibition by seeds required for germination from following equation (Vidak *et al.,* 2022):

$$\mathrm{EUR} = \frac{\mathrm{W_t} - \mathrm{W_0}}{\mathrm{W_0}} \times 100$$

Where W_t indicates the seed weight imbibition at time and W_0 presents the Initial seed weight. Stress Tolerance Index (STI) (Khayatnezhad and Gholamin, 2020) was calculated as follows where GP is the germination percentage:

$$\mathrm{STI} = \frac{\text{GP under stress conditiona}}{\text{GP under control}} \times 100$$

Root to shoot ratio was calculated as root to shoot length ratios. Uniformity index was calculated to indicate the resource allocation between shoots and roots (Day *et al.,* 2003) by the following formula:

$$\mathrm{UI} = \frac{\text{Number of seeds germinated in peak periods}}{\text{Total number of seeds germinated}} \times 100$$

STATISTICAL ANALYSIS

Data was analyzed using SPSS. A two-way analysis of variance (ANOVA) was performed to determine the effects of biochar amendment, irrigation regimes, and their interaction on germination percentage, germination rate, and seed mineral content. Post hoc comparisons were conducted using Tukey's HSD at a significant level of 0.05.

RESULTS

The seed germination percentage varied significantly among wheat varieties, biochar levels, and irrigation regimes ($p < 0.05$). Across all treatments, V1 exhibited the highest germination percentage (98%) due to its drought-resistant nature, while V2 showed the lowest, particularly under 50% irrigation (Figure 2a).

Under 100% irrigation, V1 recorded the highest germination percentage in 2.50 g/pot biochar-amended soil (98 %), V3 (93 %), and V2 (90 %). In the Control, germination percentages were lower across all varieties, with V2 recording the lowest (82).

Under 50% irrigation, the trend remained consistent, with V1maintaining a relatively high germination percentage (85) in Level 2, while V2 dropped significantly (70) in the control (Figure 2a). The positive effect of biochar was more pronounced under water-limited conditions, particularly in Dilkash-2020.

GERMINATION RATE

Germination rates reflected the trends observed in seed germination percentages. V1 consistently demonstrated the highest rates, while V2 lagged behind. Under 100% irrigation, V1 recorded the highest germination rate in 2.50 g/pot biochar (0.35 day^{-1}). In the control, V2 had the lowest rate (0.26 day^{-1}). Under 50% irrigation, germination rates declined overall, but V1 maintained a higher rate (0.28 day^{-1}) compared to V2, which fell to 0.18 day^{-1} in the control. Biochar application was effective in mitigating the decline, particularly for Faisalabad-2008 (Figure 2b).

Under normal irrigation, the GI increased progressively with biochar levels, peaking at 2.50 g/pot (88.33). Under deficit irrigation, a similar trend was observed, with the highest GI recorded for 2.50 g/pot (87.33) (Table 1). Biochar improved GI under both irrigation regimes, demonstrating its ability to enhance germination under water stress. GI showed minor variation under normal irrigation, with a slight increase at 2.50 g/pot. Interestingly, deficit irrigation with no biochar (control) resulted in the highest GI (89.33). This suggests V2's adaptability to water stress, although biochar application showed limited benefits in GI improvement. GI was highest under normal irrigation and control (90.33) (Table 1). However, under deficit irrigation, the GI improved consistently with biochar application, peaking at 2.50 g/pot (88.66) (Table 1).

Biochar was effective in maintaining GI under water deficit. Seedling length increased with biochar application across varieties, especially under normal irrigation, demonstrating enhanced early growth potential. Under deficit irrigation, the improvement was less pronounced but still notable with higher biochar levels, particularly in V1 and V3. Biochar significantly increased seedling dry weight across all varieties under both irrigation regimes. V3 exhibited the highest dry weight under normal irrigation and control (140 mg), while under deficit irrigation, V2 (control) recorded the highest dry weight (139 mg). V1 and V3 demonstrated better responses to biochar under deficit conditions, indicating their potential for water-stressed environments.

SVI consistently increased biochar application across all varieties and irrigation regimes, highlighting biochar's role in enhancing seedling establishment. The highest SVI was observed in V3 under normal irrigation with control (17.00), while under deficit conditions, V2 showed the highest SVI in control (16.00) (Table 1). The decline in SVI under deficit conditions was mitigated by biochar application, with higher doses (2.50 g/pot) showing better results. Biochar application increased SRUE across all varieties and irrigation regimes, reflecting improved mobilization of stored reserves for seedling growth. V3 exhibited the highest SRUE under normal irrigation (1.22), while V2 had the highest SRUE under deficit irrigation (1.21) in control. V3 showed stable SRUE across treatments and irrigation regimes, suggesting efficient utilization of seed reserves even under stress (Table 1).

Under normal irrigation in V1, water uptake increased with increasing levels of biochar, reaching its highest value (31.57%) with 2.50 g/pot biochar (Table 2). Similarly, under deficit irrigation, biochar application improved water uptake, with 2.50 g/pot showing the maximum value (30.57%) (Table 2). For V2, Biochar application under normal irrigation resulted in a moderate increase in water uptake, from 22.17% (control) to 27.50% (2.50 g/pot). Under deficit irrigation, a similar trend was observed, with water uptake increasing from 21.17% (control) to 26.50% (2.50 g/pot). V3 showed the highest water uptake as Under normal irrigation, the control showed 33.57%, which slightly decreased at 1.25 g/pot (29.67%) but increased again to 32.50% at 2.50 g/pot biochar (Table 2). Under deficit irrigation, the highest water uptake (32.57%) was seen in the 2.50 g/pot (31.50%) biochar amendment.

Stress tolerance was significantly improved with biochar application. Under normal irrigation, the highest index (115%) was observed with 2.50 g/pot, and under deficit irrigation, the same level of biochar yielded 113% (Table 2). Highest Root-Shoot Ratio was observed as 1.70 from V1 and V3 under normal condition and 1.60 in V1 under deficit condition with 2.50 g/pot biochar. Uniformity improved with biochar application, reaching 94% under normal irrigation and 92.80% under deficit irrigation at 2.50 g/pot among all cultivars (Table 2).

PLANT MINERAL CONTENT

The application of biochar significantly enhanced seed mineral content, including nitrogen (N), phosphorus (P), and potassium (K), across all wheat varieties and irrigation regimes (Figure 2 c-e). The improvements were more pronounced under 50% irrigation, highlighting the potential of biochar in mitigating nutrient deficiencies under water-limited conditions.

Nitrogen content was highest in seeds of V1 under 2.50 g/pot, with 20.0 mg/g under 100% irrigation and 17.0 mg/g under 50% irrigation. V2 consistently recorded the lowest nitrogen content across all treatments, particularly under the Control and 50% irrigation (12.0 mg/g). Biochar application significantly increased nitrogen content across all varieties and irrigation regimes, with an average improvement of 15–25% (Figure 2c).

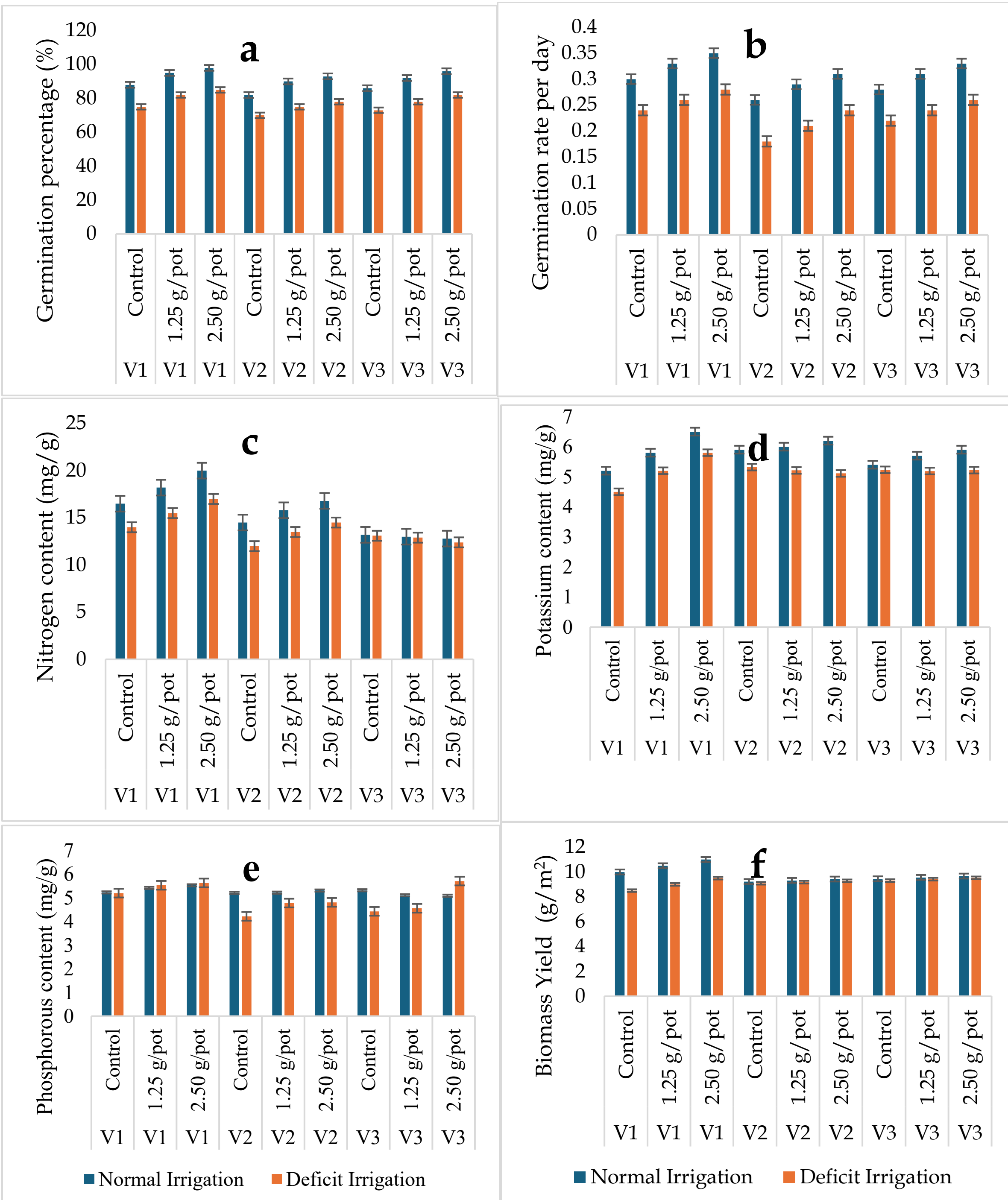

Figure 2: Effect of different levels of biochar on (a) germination percentage (%) (b) germination rate per day (c) nitrogen content (mg g^{-1}) of leaves (d) potassium content (mg g^{-1}) of leaves (e) phosphorous content (mg g^{-1}) of leaves (f) biomass yield (g/m^2) of leaves of V1 (Dilkash-2020), V2 (Akbar-2019), and V3 (Faisalabad-2008) under normal and deficit irrigation (100% and 50% Field capacity, respectively)

content followed a similar trend. V1 recorded the highest phosphorus content under 2.50 g/pot biochar (6.5 mg/g under 100% irrigation and 5.8 mg/g under 50% irrigation). In contrast, V2 had the lowest phosphorus content under all treatments, with the least value observed in control under 50% irrigation (4.0 mg/g) (Figure 2d).

Potassium content exhibited significant increases with biochar application. Under 2.50 g/pot biochar, V1 recorded the highest potassium content (18.0 mg/g under 100% irrigation and 15.0 mg/g under 50% irrigation). V3 responded positively to biochar, showing increases of up to 20% compared to the control. V2 again showed the lowest potassium content under water-limited conditions (11.0 mg/g in control under 50% irrigation) (Figure 2e). Biomass yield followed similar trends, with the highest values observed in V1 under 100% irrigation and Level 2 biochar (11.0 g/m^2). V3 showed significant increases, while V2 recorded the lowest values under all conditions (Figure 2f).

MULTIVARIATE ANALYSIS

Figure 3 shows marginal plots presenting interactive effects of germination rate and germination percentage with positive interaction. Among nutrients, nitrogen and potassium were highly positively correlated with biomass accumulation but potassium showed a lower positive correlation with biomass yield under applied conditions. Figure 4a shows the PCA results revealing distinct groupings of variables and wheat varieties, offering valuable insights into their relationships under the studied conditions. The right upper quadrant, where PC1 and PC2 are both positive, features variables such as potassium, nitrogen, germination percentage, and germination rate, alongside the wheat varieties V1 and V3. This placement indicates that these varieties are strongly associated with higher nutrient uptake (potassium and nitrogen) and superior germination performance. These traits are likely significant contributors to the primary axis of variation (PC1), which explains 50.81% of the total variance. This suggests that V1 and V3 thrive under treatments favoring nutrient availability, possibly enhanced by biochar amendments or optimal irrigation levels.

In contrast, the right bottom quadrant, characterized by positive PC1 and negative PC2 values, includes variables such as biomass accumulation and phosphorus, with contributions from V1, V2, and V3. This alignment suggests that these varieties share an affinity for treatments promoting phosphorus uptake and biomass production, albeit with more variation captured along PC2 (20.71%). The overlap of V1 across both quadrants highlights its versatile response to the conditions, excelling in both nutrient accumulation and growth-related traits. Pearson correlation presented an overall interaction among different germination attributes (Figure 4b), where blue color presents negative correlation and res shows positive correlation.

DISCUSSION:

The results demonstrate that biochar application significantly improved seed germination, seedling growth, mineral content, and yield across all wheat varieties under deficit irrigation. These effects are linked to biochar's enhancement of soil physicochemical properties, nutrient availability, and water retention. Under 50% irrigation, biochar notably increased germination percentage and rate by improving soil moisture retention and aeration. Biochar's porous structure supports water availability and gas exchange, creating optimal conditions for germination, particularly under drought stress (Gharred *et al.,* 2022; Joseph *et al.,* 2021). The variety Dilkash-2020 displayed the highest germination rates and vigor, underscoring the importance of selecting resilient genotypes for biochar applications. On the contrary, lower performance of Akbar-2019 highlights its susceptibility to water stress despite biochar amendment. These observations can be attributed to varietal specificity based on genetic composition.

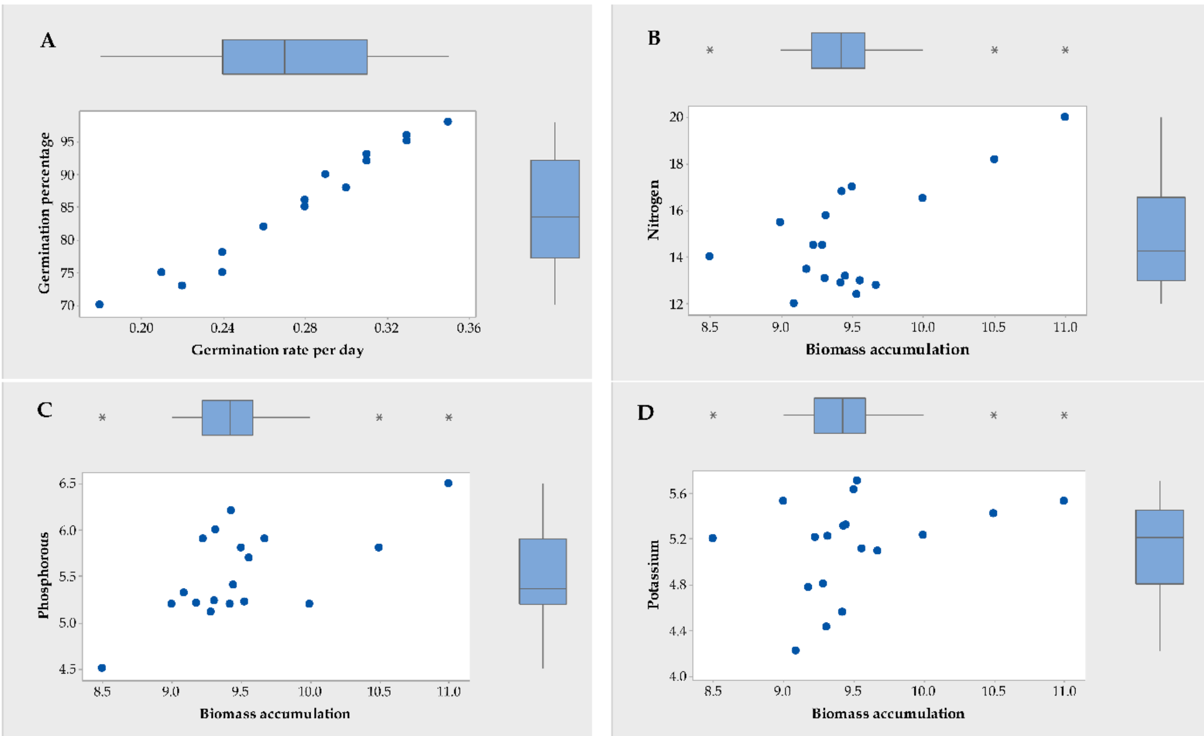

Figure 3: Marginal plots presenting the interactive effects of A) Germination percentage and germination rate, B) nitrogen content and biomass yield C) Phosphorous content and biomass yield D) Potassium content and biomass yield

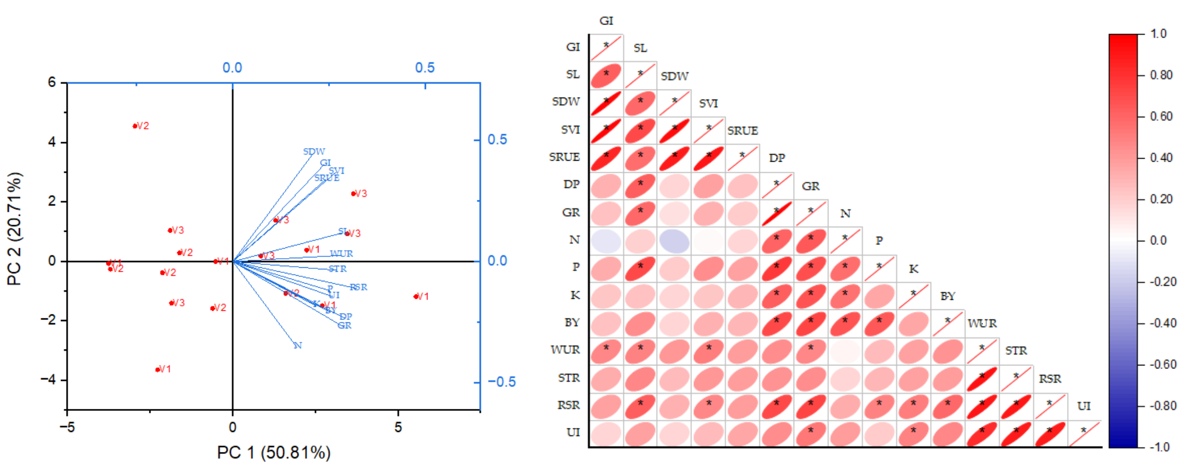

Figure 4: a) Principal component analysis (b) Pearson correlation presenting interactions among GI= Germination Index, SL= Seedling Length, SDW= Seedling Dry Weight, SVI= Seedling Vigor Index, SRUE= Seed Reserve Use Efficiency, GP= Germination percentage, GR= Germination rate per day, N= Nitrogen, P= Phosphorous, K= Potassium, BY= Biomass Yield, WUR= Water Uptake Rate, STI= Stress Tolerance Index, RSR= Root-Shoot Ratio, and UI=Uniformity Index.

The application of Biochar improved seed nitrogen, phosphorus and potassium content also through its nutrients-holding capacity that increases CEC, and checked the nutrient leaching and made nutrient more available (Kumari *et al.,* 2024). In a similar way, Wang *et al.* (2023), when Wang *et al.* (2023) noted that in under-watered condition, biochar nutrient and moisture conservation worked best in seeds that were drought tolerant than in the seeds that were drought sensitive with little mineral uptake. Biochar enhanced soil water retention and its acquisition was significant especially at the higher biochar application rates, this was due to the large surface area and porosity of biochar (Ajayi *et al.,* 2016). The drought tolerant variety Dilkash-2020 was the most responsive with using the additional water available in biochar hydraulic conductivity while the drought susceptible Akbar-2019 had limited benefits as they could not develop proper root structure and water uptake structures (Huang, 2000). Biochar as well increases canopy conductance and osmotic adjustment by increasing potassium, which helps to minimize water deficit stress (Farhangi-Abriz and Torabian, 2017).

Komal *et al.* (2025) reported that biochar can improve plant physiology by enhancing water retention, nutrient availability, and antioxidant activity. Oxidative stress is reduced by biochar, and it improves enzyme activity, supporting better germination and seedling vigor under stress. As the study was conducted under control conditions over a short duration. Results may vary under field conditions, across seasons, or with different soil types, limiting generalizability. Despite a sustainable approach of using biochar as depicted in current study, a field experiment is required to check the response of progeny under varying environmental conditions. While biochar shows promising effects, its large-scale application may be limited by production costs, transport, and application methods. Assessing cost-benefit ratios and exploring locally available feed stocks can help improve feasibility as well.

In the soil treated with biochar, root-shoot ratio declined, suggesting that root development was promoted under deficit irrigation. This proportional root-shoot development corroborates with data presented by Bruun *et al.* (2014) who recorded a higher root biomass in plants treated with biochar under drought stress. Genetic traits resulted in only a little additional improvement for varieties with inherently higher root-shoot ratios, such as Faisalabad-2008. The ability of biochar to affect soil porosity, aeration and favor microbial activity made possible the retention of high grain biomass yield possible through the application of the higher biochar level (Alkharabsheh *et al.,* 2021). Maximum yield increase was observed with drought resistant hybrid like Dilkash-2020 which proves that biochar has positive impact on soil health for rich nutrients and lessen water deficit condition (Aggarwal *et al.,* 2024).

Consequently, these studies indicate the necessity of using biochar as a bio-input for enhancing DR and crop yield in response to water-deficit conditions and recommend utilizing DR wheat variety Dilkash-2020 for this purpose. Additionally, the application of biochar was variable in terms of type of biochar, rates at which it is applied, and crop genotype, therefore needs to be done on a site basis.

Table 1. Effect of Effect of different levels of biochar on germination Index, seedling length (cm), seedling dry weight (mg), seedling vigor index, seed reserve use efficiency of V1 (Dilkash-2020), V2 (Akbar-2019), and V3 (Faisalabad-2008) under normal and deficit irrigation (100% and 50% Field capacity, respectively)

Variety	Irrigation	Biochar	Germination Index	Seedling Length (cm)	Seedling Dry Weight (mg)	Seedling Vigor Index	Seed Reserve Use Efficiency
V1	Normal	Control	74.00 ± 2.00	7.50 ± 0.01	109.00 ± 2.02	9.00 ± 1.03	0.99 ± 0.02
		1.25 g/pot	85.33 ± 0.24	9.20 ± 0.10	125.00 ± 2.20	14.00 ± 1.10	1.12 ± 0.02
		2.50 g/pot	88.33 ± 1.28	9.50 ± 0.05	131.33 ± 1.53	16.33 ± 0.58	1.21 ± 0.01
	Deficit	Control	79.33 ± 1.42	8.00 ± 0.06	119.00 ± 1.00	11.00 ± 0.01	1.04 ± 0.01
		1.25 g/pot	84.33 ± 1.53	8.20 ± 0.05	124.00 ± 2.00	13.00 ± 1.30	1.11 ± 0.02
		2.50 g/pot	87.33 ± 1.24	8.50 ± 0.10	130.33 ± 1.53	15.33 ± 0.58	1.20 ± 0.31
V2	Normal	Control	80.33 ± 1.01	9.00 ± 0.03	120.00 ± 1.00	12.00 ± 1.20	1.05 ± 0.04
		1.25 g/pot	80.66 ± 2.08	8.70 ± 0.11	115.00 ± 2.00	12.00 ± 1.04	1.05 ± 0.02
		2.50 g/pot	82.66 ± 2.01	9.10 ± 0.12	121.33 ± 1.53	14.33 ± 0.58	1.11 ± 0.01
	Deficit	Control	89.33 ± 1.24	8.60 ± 0.01	139.00 ± 2.10	16.00 ± 1.00	1.21 ± 0.02
		1.25 g/pot	79.66 ± 0.21	7.70 ± 0.37	114.00 ± 2.01	11.00 ± 0.99	1.04 ± 0.03
		2.50 g/pot	81.66 ± 0.26	8.10 ± 0.39	120.33 ± 1.53	13.33 ± 0.58	1.10 ± 0.41
V3	Normal	Control	90.33 ± 1.26	9.60 ± 0.27	140.00 ± 2.00	17.00 ± 0.89	1.22 ± 0.02
		1.25 g/pot	86.33 ± 1.53	9.20 ± 0.10	126.67 ± 1.54	14.33 ± 0.48	1.05 ± 0.02
		2.50 g/pot	89.66 ± 1.24	9.40 ± 0.01	133.67 ± 1.56	16.00 ± 0.01	1.15 ± 0.01
	Deficit	Control	75.00 ± 1.82	8.50 ± 0.23	110.00 ± 2.00	10.00 ± 0.98	1.00 ± 0.03
		1.25 g/pot	85.33 ± 1.53	8.20 ± 0.12	125.67 ± 1.54	13.33 ± 0.38	1.04 ± 0.22
		2.50 g/pot	88.66 ± 1.15	8.40 ± 0.20	132.67 ± 1.43	15.00 ± 1.00	1.14 ± 0.01
Variety*Irrigation*Biochar (P≤0.05)			**	***	**	*	**

Where *= significant, ** moderately significant, and *** = highly significant

Table 2. Effect of Effect of different levels of biochar on water uptake rate (%), stress tolerance index, root-shoot ratio, and uniformity index of V1 (Dilkash-2020), V2 (Akbar-2019), and V3 (Faisalabad-2008) under normal and deficit irrigation (100% and 50% Field capacity, respectively)

Variety	Irrigation	Biochar	Water Uptake Rate (%)	Stress Tolerance Index	Root-Shoot Ratio	Uniformity Index
V1	Normal	Control	24.50 ± 0.49	100.00 ± 1.00	1.50 ± 0.00	90.00 ± 0.24
		1.25 g/pot	28.47 ± 0.34	110.33 ± 1.53	1.60 ± 0.00	92.00 ± 1.00
		2.50 g/pot	31.57 ± 0.48	115.00 ± 1.00	1.70 ± 0.04	94.00 ± 1.02
	Deficit	Control	23.50 ± 0.40	98.00 ± 1.00	1.40 ± 0.06	88.80 ± 0.89
		1.25 g/pot	27.47 ± 0.35	108.33 ± 1.53	1.50 ± 0.30	90.80 ± 0.99
		2.50 g/pot	30.57 ± 0.28	113.00 ± 1.00	1.60 ± 0.04	92.80 ± 1.01
V2	Normal	Control	22.17 ± 0.72	95.00 ± 1.00	1.40 ± 0.03	85.00 ± 1.29
		1.25 g/pot	25.17 ± 0.36	105.00 ± 2.00	1.50 ± 0.20	88.00 ± 0.00
		2.50 g/pot	27.50 ± 0.56	111.00 ± 1.00	1.60 ± 0.10	90.00 ± 1.00
	Deficit	Control	21.17 ± 0.66	93.00 ± 1.00	1.30 ± 0.00	83.80 ± 1.00
		1.25 g/pot	24.17 ± 0.36	103.00 ± 2.00	1.40 ± 0.00	86.80 ± 0.06
		2.50 g/pot	26.50 ± 0.50	109.00 ± 1.00	1.50 ± 0.00	88.80 ± 0.05
V3	Normal	Control	33.57 ± 0.40	120.00 ± 2.00	1.70 ± 0.00	95.00 ± 0.07
		1.25 g/pot	29.67 ± 0.29	105.33 ± 1.53	1.57 ± 0.06	88.00 ± 0.03
		2.50 g/pot	32.50 ± 0.20	116.67 ± 1.53	1.70 ± 0.00	92.00 ± 0.07
	Deficit	Control	31.50 ± 0.50	118.00 ± 2.00	1.60 ± 0.00	93.80 ± 0.03
		1.25 g/pot	28.67 ± 0.29	103.33 ± 1.53	1.47 ± 0.06	86.80 ± 0.05
		2.50 g/pot	32.57 ± 0.41	114.67 ± 1.53	1.60 ± 0.00	90.80 ± 0.09
Variety*Irrigation*Biochar (P≤0.05)			**	*	***	*

Where *= significant, ** moderately significant, and *** = highly significant

CONCLUSION

This study demonstrates the potential of biochar for improved wheat germination enhancing wheat crop stand under water stress. Among the treatments, biochar application, particularly at 2.50 g/pot, was deemed to promote seed germination, growth and mineral content of the seedlings, as well as overall biomass production. Such changes were prominent under 50% irrigation implying the potential of biochar in reducing drought stress severity in germinating seeds and growing seedlings. Therefore, biochar can be viewed as an effective long-term approach in the cultivation of wheat under conditions of increasing water deficiency. Additional research must be conducted to determinate the impact of biochar on soil fertility and crop yields in the long run and under different climate conditions.

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AUTHOR CONTRIBUTION

Lubaba Komal: Wrote the original manuscript, collected data, analyzed and conducted the research work. Atif Kamran and Summera Jahan: Reviewed and edited the manuscript, supervised, visualized, and investigated the study.

CONFLICT OF INTEREST

Authors have no competing interests.

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