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Biochar as a Potential Strategy for Enhancing Wheat Production in Arid Soils under deficit irrigation practices

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DEFICIT irrigations, combined with biochar, could be an effective solution to aleviate drought stress in wheat; thereby enhancing its productivity in arid soils. To test this hypothesis, a greenhouse experiment of a randomized complete block design was conducted, comprising two factors: (1) two levels of deficit irrigations at 60 and 80% of soil field capacity (designated as FC_{60} and FC_{80}, respectively) and (2) three biochar doses, i.e. 0, 5 and 10 g kg^{-1} (refered to as B_0, B_5 and B_{10}, respectively). Plants grown on a soil irrigated at 100% of the field capacity without biochar application served as a reference control treatment. This brought the total number of treatments to seven. Results obtained in this study revealed that root biomass increased significantly with deficit irrigation; yet wheat shoots and grains decreased considerably. On the other hand, the application of biochar, generally enhanced shoot and grain yields while decreasing root growth. This in turn augmented both shoo-to-root and grain-to-shoot ratios. In this regard, the highest increase in grain yield was observed for B_5+FC_{100}, while the highest increase in shoot –to-root ratio was recorded for the B_{10}+FC_{100} treatment. Biochar upgraded the coping strategies of wheat plants under drought stress by increasing the osmoregulator proline in shoots, Mn content in roots and Cu concentrations in different plant parts, especially at the highest application rate (B_{10}). These two nutrients (Mn and Cu) are incorporated into detoxifying enzymes that neutralize superoxide radicals which accumulate under abiotic stress. Nevertheless, the high dose of biochar likely immobilized soil nutrients and reduced their concentrations in different plant parts. Overall, residual organic matter increased in biochar-amended soil, and its consequences on soil pH were not significant. This could guarantee sustainable crop production in such soils. In conclusion, the combination of deficit irrigation and biochar application can be used successfully to increase wheat production in arid soils, while optimizing irrigation water use and sustaining soil productivity.

Keywords: wheat; biochar; proline; nutrient concentrations; soil characteristics.

1. Introduction

Rapid population growth has placed increasing pressure on the limited natural resources worldwide (Emami Bistgani *et al.*, 2024), including fresh water, whose availability is insufficient to meet the growing demands (van Beek et al., 2011; Wada et al., 2011). This limited access to water is one of the major environmental issues (van Beek *et al.*, 2011; Musie and Gonfa, 2023), particularly in arid and semi-arid regions (Nyaupane *et al.*, 2024). The agricultural sector consumes about 80% of the total water use or more, making this sector the most significantly impacted by drought (Tzanakakis *et al.*, 2020). In the Middle East zone, drought has led to a drop of about 50% in crop production (Emami Bistgani *et al.*, 2024).

Wheat is one of the primary cereal crops in daily human diet worldwide (Lalarukh *et al.*, 2022a; Farooq *et al.*, 2023; Nyaupane *et al.*, 2024; Parveen *et al.*, 2024). It is considered a key pillar of global food security (Slafer *et al.*, 2021). In Egypt, wheat is primary subsidized in the form of *baladi* bread; however this country remains largest wheat importer worldwide (Abdalla *et al.*, 2023; Farid *et al*., 2023 a &b). Egypt imports about 8.3 million tons of wheat annually (Ewaid *et al*., 2020). Despite this, wheat can be grown successfully on the sandy soils of this country (Dawood *et al.*, 2020; El-Metwally *et al*., 2025), which account for nearly 90% of the country’s land area (Niel, 2021). Plants cultivated on such soils are often susceptible to drought stress (Aboelsoud and Ahmed,

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2020). Even in the Nile delta region, soils are vulnerable to the climatic changes (Zhao *et al*., 2021) and may face severe water scarcity (Yassen *et al*., 2020).

To cope with drought stress, wheat induces several adaptive changes at the morphological, biochemical and physiological changes (Nyaupane et al., 2024), often resulting in a drop in crop productivity(Tahoun *et al.*, 2022). Maybe, biochar mitigate drought conditions (Lalarukh *et al.*, 2022b). Biochar is produced through the pyrolysis of organic residues under limited aeration conditions (Abdelhafez *et a*l., 2014; Mohamed *et al.*, 2018; Abdelhafez *et al.*, 2021; Tolba *et al*., 2021; Asaad *et al.*, 2022). It is characterized by the presence of hydrophilic functional groups, which increase water moisture retention (Chai *et al.*, 2024). This property can increase soil-crop productivity (Farid *et al.*, 2022; Khalil *et al.*, 2023; Zhang *et al*., 2023; Mohamed *et al.*, 2024; Abuzaid et al., 2025), while optimizing irrigation water use (Bassouny and Abbas, 2019; Baiamonte *et al*., 2020).

To lessen losses in crop productivity, deficit irrigation could be an effective strategy (Saad et al., 2023). In this approach, crops are irrigated with amounts of water below their full requirements (Ali et al., 2007). Additionally, soils can be ammended with organic additives such as biochar to increase their water holding capacity thereon (Bassouny and Abbas, 2019). The current study; therefore, aims to evaluate the feasibility of combining these two methods -deficit irrigation with 60 and 80% of soil field capacity (FC) and biochar application at two rates (5 and 10 g kg^{-1})- to alleviate drought stress in wheat plants. Plants grown on a soil irrigated with 100% of the field capacity without biochar application served as the reference control. In this study, soil chemical characteristics (soil pH, EC and organic matter content) were analyzed along with plant growth parameters, yield, morpho-physiological responses and biochemical changes (such as proline in shoots and concentrations of K, Mn, Zn and Cu in plant tissues.

Specifically, we anticipate that deficit irigations would raise proline content in wheat shoots, while significantly reducing plant growth and productivty (hypothesis I). However, the application of biochar could mitigate the negative effects of drought on wheat plants and enhance productivity (hypothesis II). In particular, K, Mn, Cu and Zn-supplied by biochars- play important roles as osmoregulators and compounds of detoxifying enzymes that neutralize superoxide radicals; thereby improve plant capability to cope with drought (hypothesis III). Finally, biochar amendment improves soil chemical characteritics, ensuring the sustainability of agricultural land use (hypothesis IV).

2. Materials and methods

2.1. Materials of study

2.1.1. Soils of study

Soil samples were collected from the topsoil layer (0-30 cm depth) of the experimental farm at the Faculty of Agriculture, Benha University (Egypt). These samples were thoroughly mixed together, air dried, crushed, sieved and analysed for their chemical and physical properties according to **Sparks *et al.* (2020) and Klute (1986)**, respectively.

Table 1. Soil chemical and physical properties.

Character	Soil pH	Soil EC (dS m^{-1})	$CaCO_3$ content (g kg^{-1})	Organic matter (g kg^{-1})	Field capacity (%)	Particle size distribution (%)				
						Fine sand	Coarse sand	Silt	clay	Textural class
Value	7.97	1.49	17.31	14.23	32.00	1.05	1.30	19.25	46.72	Clay

*Soil pH was determined in soil:water (1:2.5) suspension, while EC was determined in soil paste extract.

2.1.2. Biochar production

Maize stover was used as a feedstock for production of biochar. These residues were oven-dried at 65°C overnight, and then pyrolyzed in a muffle furnace (Magma Term Laboratory Furnace- Model SNOL 8,2/1100) at 550°C for 2 h under limited oxygen conditions. E resulting biochar was alkaline, with a pH of 8.57, a salinity of 13.28 dS m^{-1}, and contained 8.02% C, 0.52% N, 0.75% H, 5.82% O, and 0.33% S. Further characteristics of biochar were conducted at the Atomic Energy Authority, Cairo, Egypt as follows:

(1) Scanning electron microscopy (SEM) using a JEOLJSM-5400scanning microscope (Japan)

(2) X-ray diffraction analysis using Philips PW 1730 powder X-ray diffractometer

(3) Fourier transform infrared spectroscopy (FTIR) analysis via Thermo Scientific-Nicolet iS10 over the range 400-4000 cm^{-1}

(4) The surface charge (zeta potential) of biochar measured using Zeta Sizer Advance Series (Japan), for particles within the range of 0.3 -10 micrometre.

2.2. Methods of study

Twenty-one plastic pots (25 cm diameter ×19 cm depth) were filled with about 4 kg of the studied soil. Each pot was germinated with 10 seeds of wheat (Giza 171) and fertilized with the recommended doses of N and P fertilizers, i.e. 75.6g urea (46%) per kg soil (≈302 g N per pot) and 31.5 g calcium super phosphate(15.6 % P_2O_5 per kg soil (≈126 g P_2O_5 per pot). The experimental treatments (3 replicates each) were arranged in a randomized complete block design comprising:

1)No biochar + 100% of FC (T_1, Conrol:B_0+FC_{100})

2) 5 g kg^{-1} biochar + 60% of FC (T_2, B_5+FC_{60})

3) 5 g kg^{-1} biochar + 80% of FC (T_3, B_5+FC_{80})

4) 5 g kg^{-1} biochar + 100% of FC (T_4, B_5+FC_{100})

5) 10 g kg^{-1} biochar + 60% of FC (T_5, B_{10}+FC_{60})

6) 10 g kg-1 biochar + 80% of FC (T_6, B_{10}+FC_{80})

7) 10 g kg-1 biochar + 100% of FC (T_7, B_{10}+FC_{100})

Soil moisture was monitored periodically using aTensiometer (model Theta-θ-Probe ML2x) and maintained at the specified levels gravimetrically. At physiological maturity, whole plants were removed from every pot, and their heights and numbers per pot were measured.

2.3. Plant Analyses.

Roots, shoots and grains of wheat plants were separated, oven dried at 70 °C for 48 h, and then wet-digested with perchloric and sulfuric acids on a sandy hot plate at 250 °C according to Cottenie et al. (1982). Potassium in plant digest was determined using a flame photometer (model JENWAY PFP7), while Mn, Zn and Cu were assessed by ICP-OES (model Ultima-Expert LT). Proline was determined in shoots after 50 days of planting according to Bates *et al.* (1973).

2.4. Data processing

Data was subjected to one-way ANOVA and Dunken's test using SPSS statistical software (version 18). Graphs were created using Sigma Plot (version 10). Shoot-to-root ratio was calculated as a ratio between shoot biomass to root biomass (Kurepa et al., 2022), while grain-to-shoot ratio was computed as the ratio between grain yield to shoot biomass (Farid *et al.*, 2025).

3. Results

3.1. Characterization of the used biochar

The examination of the biochar samples using scanning electron microscopy (SEM) (Fig 1A) shows that non-acidified biochar possesses high porosity and a large surface area. X-ray diffraction (XRD) analysis (Fig 1B) show a gradual increase in intensity up to around 6° 2-theta, suggesting the development of some structural orders, followed by significant intensity fluctuations, whose peaks were at approximately 9.7°, 11.74°, 16.84°, 18.52°, 20.92°, and 26.02°, indicating the presence of crystalline phases within the biochar. Noteably, the high-intensity peaks near 26.02° and 18.52° are associated with carbonaceous structures, such as graphite-like or amorphous carbon, further highlighting the structural complexity and diversity of the biochar (Pariyar *et al.*2020; Liu et al.2022). It unravels a fascinating combination of both ordered and amorphous phases within the biochar.

Fourier transform infrared spectroscopy (FTIR) analysis (Fig. 1C) revealed a broad peak at 3400 cm^{-1}, indicating hydroxyl groups which may increase biochar's capability to retain soil moisture and nutrients. Additional peaks at 2956, 1623, 1346 and 1022 cm^{-1} correspond to "C–H stretching vibrations", "C=C stretching in aromatic rings", "C–O / C–H bending" and "C–O stretching in ether or ester linkages", respectively. This biochar exhibited a zeta potential of 14.6 mV (Fig 1D), indicating moderate colloidal stability and a relatively low surface charge.

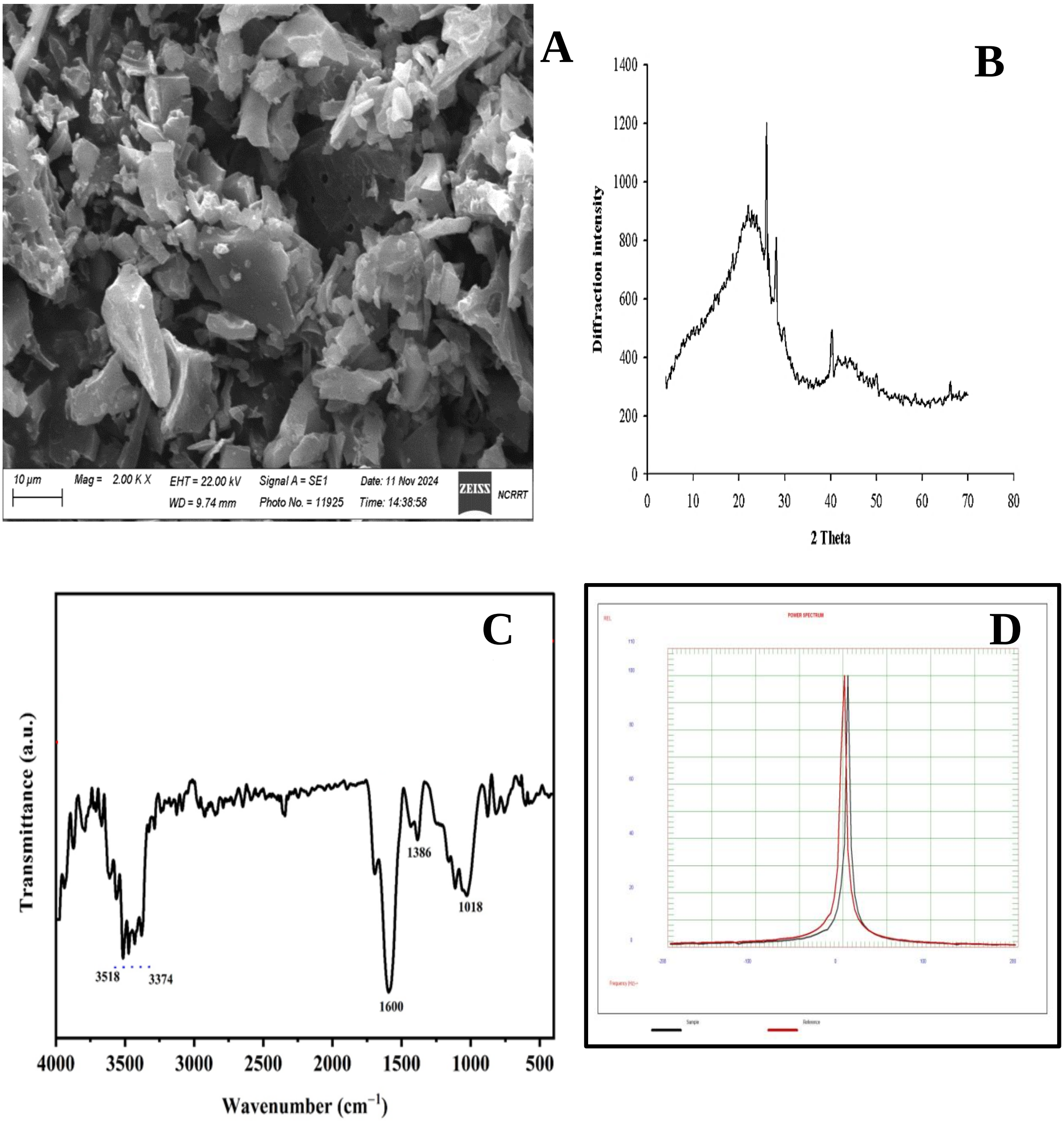

Fig. 1. Scanning Electron Microscopy (SEM, A) and X-ray diffraction analysis (XRD, B), FTIR spectrum (C) and zeta potential analyses (D) of the used biochar.

3.2. Effect of biochar application on growth parameters of plants under drought stress conditions

Plants subjected to drought stress exhibited significant increases in root biomass compared to the non-stressed ones, as shown in Figure 2A. The highest increases were observed in the soil maintained at 60% of field capacity (FC_{60}), followed by 80% FC (FC_{80}) and 100% FC (FC_{100}). In contrast, shoot biomass (Figure 2B) and grain yield (Figure 2C) decreased significantly under drought stress conditions.

The application of biochar enhanced shoot biomass while decreased root growth, leading to a considerable increase in shoot/root ratio considerably, particularly with higher biochar application rate (Fig 2D). Also, grain yields improved with increasing biochar application rate. The highest shoot–to-root ratio was observed in the treatment T_7 (B_{10}+FC_{100}), while the variations between the two treatments: T_4 (B_5+FC_{100}) and T_1 (B_0+FC_{100}) were statistically insignificant.

The effects of the applied treatments on the number of plants per pot (Fig 2E) were somewhat comparable to their impacts on shoot biomasses. Nevertheless, there were no significant disparities among treatments in terms of plant height (Fig 2F).

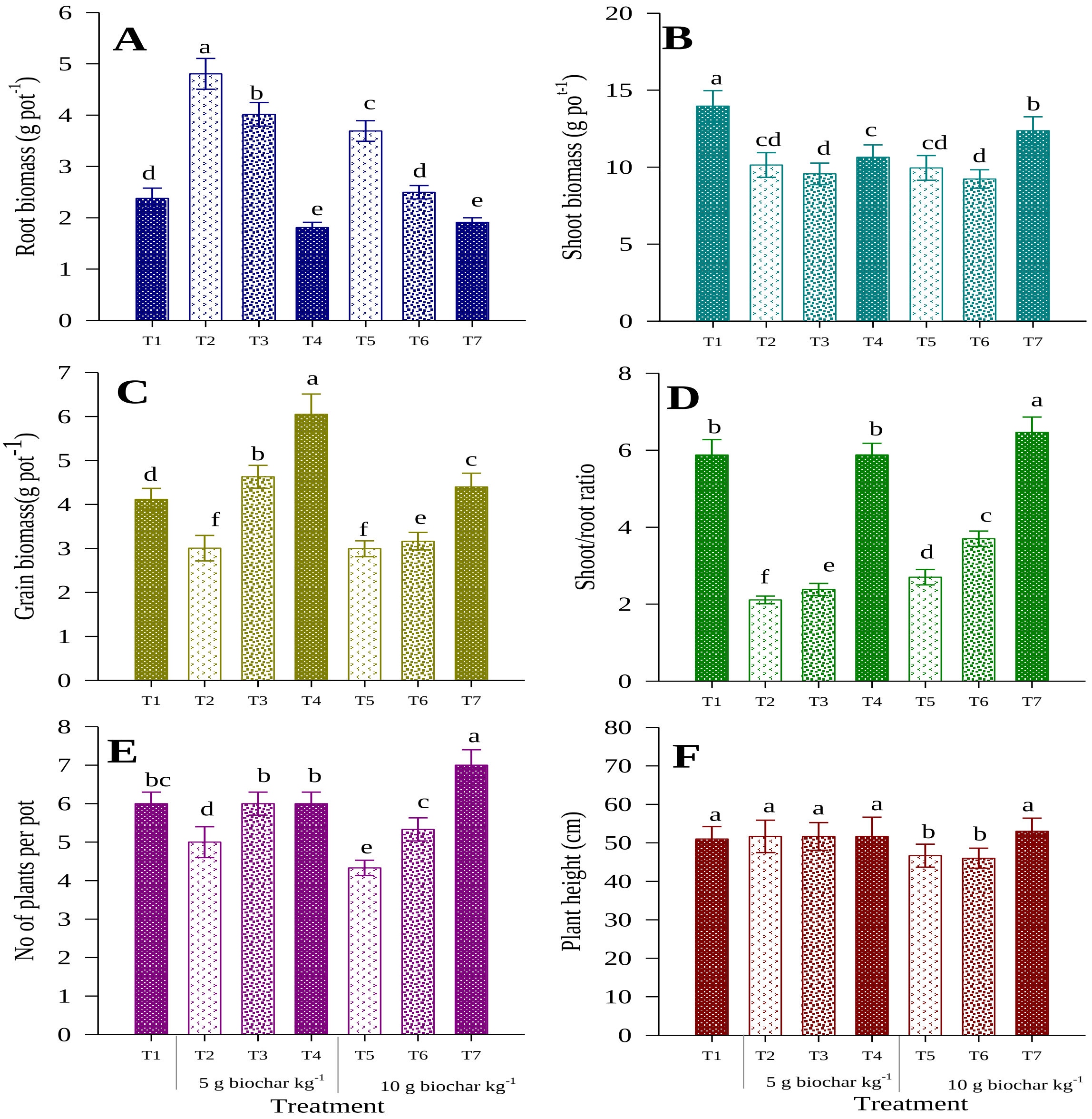

Fig. 2. Wheat growth parameters (means± standard deviations) as affected by deficit irrigations and biochar application levels.

Note: T_1: No biochar + 100% of FC (Conrol:B_0+FC_{100}), T_2: 5 g kg^{-1} biochar + 60% of FC (B_5+FC_{60}), T_3: 5 g kg^{-1} biochar + 80% of FC (B_5+FC_{80}), T_4: 5 g kg^{-1} biochar + 100% of FC (B_5+FC_{100}), T_5: 10 g kg^{-1} biochar + 60% of FC (B_{10}+FC_{60}), T_6: 10 g kg-1 biochar + 80% of FC (B_{10}+FC_{80}) and T_7: 10 g kg-1 biochar + 100% of FC (T_7, B_{10}+FC_{100}). Treatments assigned the same Duncan's letters showed no significant variations.

3.2. Effect of biochar application on proline content in wheat shoots and grain-to-straw ratio

The results presented in Fig 3B show the effects of the studied treatments on the grain-to-straw ratio. Since, high grain productivity is a logic outcome of increased plant shoots; thus, no significant differences could be deduced in this ratio among many treatments: T_1 (B_0+FC_{100}), T_4 (B_5+FC_{100})and T_7 (B_{10}+FC_{100}). However, the application of biochar notably augmented this ratio, especially in plants amended with 5 g kg^{-1}, with the highest increases observed in plants irrigated with FC_{80}.

Regarding proline content in plants (Fig 3 A), this osmoregulator maintains the osmotic balance within plant cells; accordingly a significant increase was found in proline concentration was found in shoots of drought stressed plants. The highest concentrations were observed in T_2 (B_5+FC_{60}), followed by T_3 (B_5+FC_{80}), then T_5 (B_{10}+FC_{60}), and T_6 (B_{10}+FC_{80}). For non-stressed plants that were irrigated at FC_{100}: (T_1 , B_0), (T_4, B_5), and T_7, B_{10}), no significant differences in proline contents were found among their shoots.

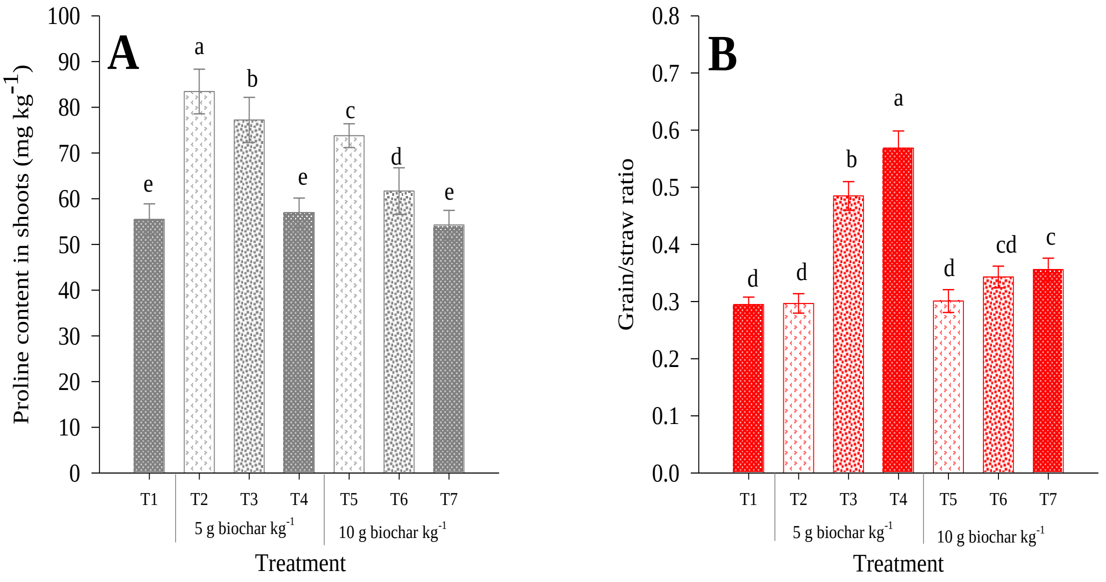

Fig. 3. Proline content in shoots (A) and grain/shoot ratio (B) (means± standard deviations) as affected by deficit irrigations and biochar application levels.

Note: T_1: Conrol:B_0+FC_{100}, T_2: B_5+FC_{60}, T_3: B_5+FC_{80}, T_4: B_5+FC_{100}, T_5: B_{10}+FC_{60}, T_6: B_{10}+FC_{80} and T_7: T_7, B_{10}+FC_{100}. Treatments assigned the same Duncan’s letters showed no significant variations,

3.3. Effect of biochar application on nutrient concentrations in different plant parts

This section considers the effects of deficit irrigations and biochar applications on accumulation of potassium (K), manganese (Mn), zinc (Zn), and copper (Cu) in different wheat parts (Fig 4). Concentrations of K did not vary significantly in wheat roots among studied treatments, but this concentration decreased in plant shoots treated with biochar. Significant changes in K levels were also observed in the wheat grains, where the highest concentrations were found in treatments that received biochar at a rate of 10 g kg^{-1}. These concentrations increased further with higher soil moisture content.

In case of Mn, application of biochar significantly raised its concentration in wheat roots, shoots and grains. The highest increases were found in plants that received 5 g kg^{-1} biochar, especially with increasing soil moisture content. Although, Mn concentrations in T_5(B_{10}+FC_{60}), T_6 (B_{10}+FC_{80}) and T_7 (B_{10}+FC_{100}), were significantly higher than the control, they were lower than those in plants that received 5 g kg^{-1} biochar. Generally, Mn concentrations followed the order of FC_{60}> FC_{80} >FC_{100}. Notably, Mn concentrations were much higher in roots compared to shoots or grains.

Concerning zinc (Zn) and copper (Cu), these two essential elements were high in the control plants (no biochar). Their levels decreased in plants amended with 5 g kg^{-1} biochar, probably due to the dilution effect on plants, but increased at the higher biochar doses (10 g kg^{-1}). Soil moisture significantly influenced the absorption of Zn and Cu from the soil, with concentrations following FC_{100}> FC_{80} > FC_{60} and also, these two nutrients increased in wheat grains with higher biochar application rates.

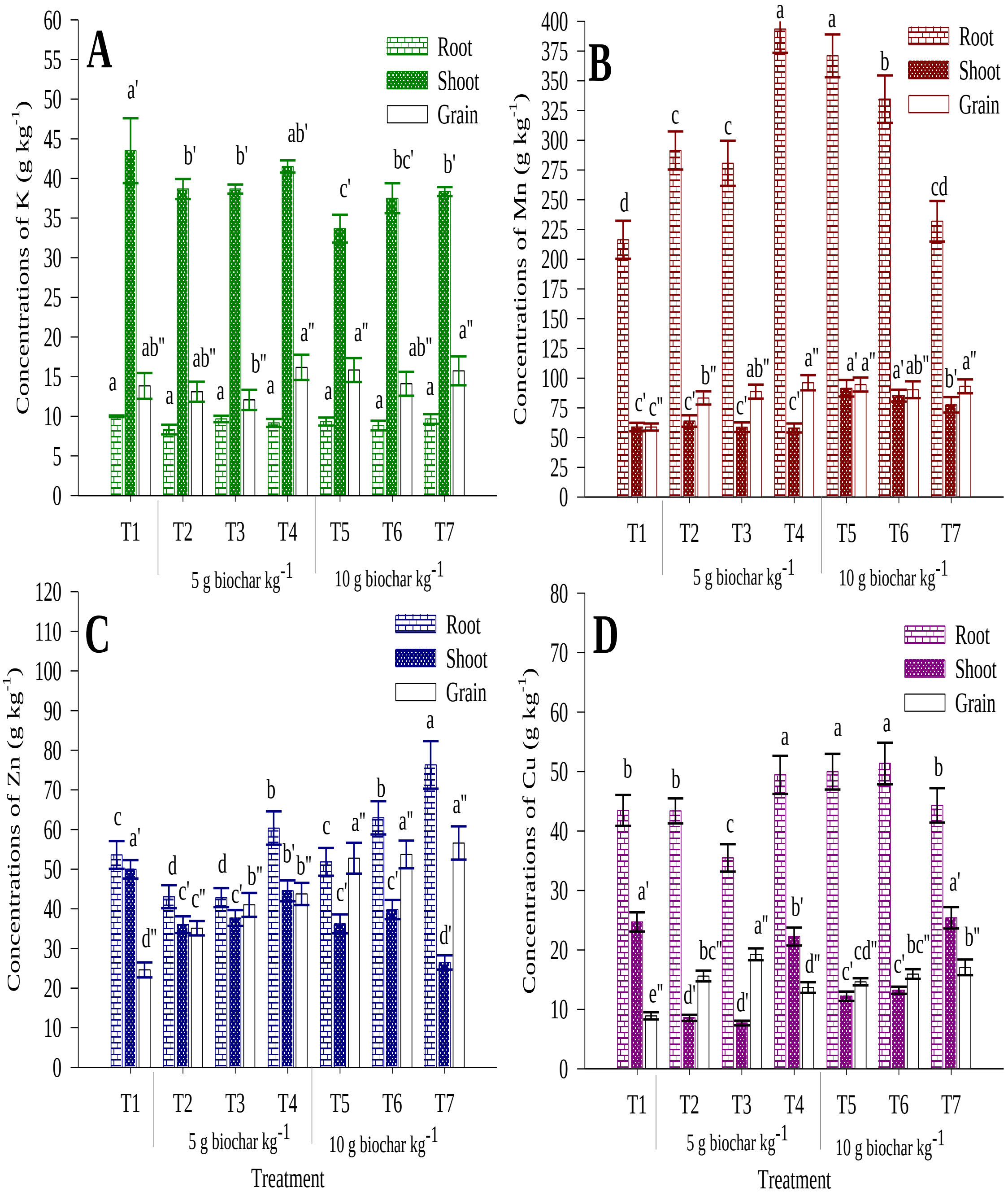

Fig. 4. Distribution of K (A), Mn (B), Zn (C) and u (D) among different wheat parts as affected by deficit irrigations and biochar application levels.

Note: T_1: Conrol:B_0+FC_{100}, T_2: B_5+FC_{60}, T_3: B_5+FC_{80}, T_4: B_5+FC_{100}, T_5: B_{10}+FC_{60}, T_6: B_{10}+FC_{80} and T_7: T_7, B_{10}+FC_{100}. Treatments assigned the same Duncan's letters showed no significant variations.

3.4. Effect of biochar application on soil chemical characteristics after plant harvest

Application of biochar significantly raised soil salinity (Fig 5A), with the most pronounced increases observed in the soil that received either FC_{60} or FC_{100}. In contrast, the effect was less significant in the soil that received FC_{80}. On the other hand, these additions had no significant effects on soil pH (Fig 5B) but increased soil organic matter by the end of the growing season. The highest increases in SOM were found in the soil that received the highest application rate of biochar (Fig 5C). Notably, treatment T_2 (B_5+FC_{60}) showed comparable organic matter content to the control, suggesting high degradation of biochar at this low rate in such a soil; thus the build-up of organic matter was low.

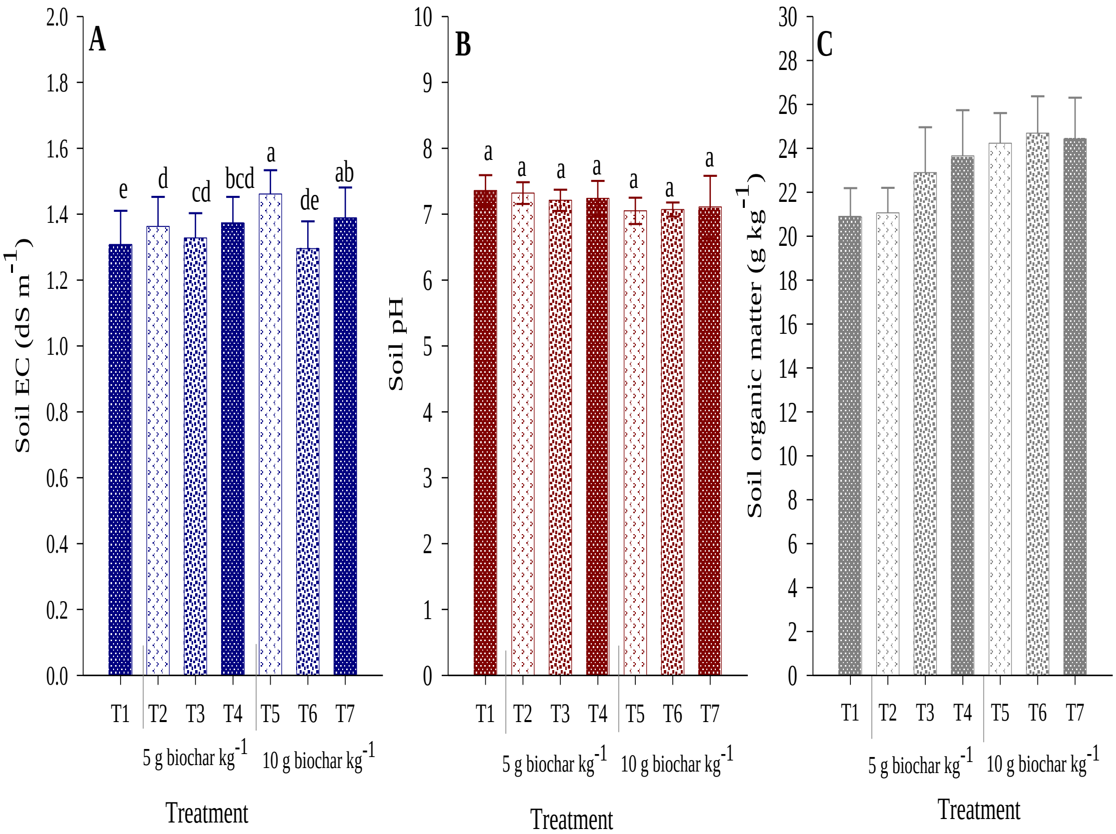

Fig. 5. Soil EC (A) , pH (B) and organic matter content (C) as affected by deficit irrigations and biochar application levels.

Note: T_1: Conrol:B_0+FC_{100}, T_2: B_5+FC_{60}, T_3: B_5+FC_{80}, T_4: B_5+FC_{100}, T_5: B_{10}+FC_{60}, T_6: B_{10}+FC_{80} and T_7: T_7, B_{10}+FC_{100}. Treatments assigned the same Duncan's letters showed no significant variations.

3.5. Correlations among proline content, nutrient concentrations within different wheat parts and plant growth parameters

Root biomasses were significantly and negatively correlated with shoot and grain biomasses; while being positively correlated with both soil organic matter and proline content in shoots. In particular, organic matter (SOM) enriched soils with nutrients during its degradation; thus Mn, Zn and Cu concentrations in wheat roots were correlated positively with SOM content. This was probably the reason beyond the significant increases that took place in root biomasses which were significantly correlated with concentrations of K, Zn and Cu in roots.

On the contrary, shoot biomasses and grain yields were correlated significantly and negatively with proline content in shoots. It's worth noting that Mn concentrations in roots were correlated significantly and negatively with shoot biomasses, while Mn content in shoots was negatively correlated with the grain yield. Additionally, the grain yield was positively correlated with K and Cu concentrations in shoots.

Table 2. Correlations between wheat growth parameters as affected by proline content in straw and distribution of K, Mn, Zn and Cu within different plant parts.

			Plant biomass				K-content			Mn-content			Zn content			Cu content		
		Organic matter (SOM)	root	shoot	grain	Proline	root	shoot	grain	root	shoot	grain	root	shoot	grain	root	shoot	grain
	SOM		**-0.434***	-0.172	0.209	-0.253	0.304	-0.066	**0.655****	**0.485***	**0.566****	**0.644****	**0.615****	-0.173	**0.779****	**0.575****	0.168	0.314
Plant biomass	**root**			**-0.483***	**-0.569****	**0.971****	**-0.445***	-0.384	**0.626****	0.033	-0.032	0.019	**-0.814****	-0.135	0.245	-0.370	**-0.863****	0.329
	shoot				0.298	**-0.578****	**0.693****	**0.688****	0.294	**-0.589****	-0.257	**-0.629****	0.349	0.343	-0.444*	-0.042	**0.819****	**-0.668****
	grain					**-0.461***	**0.465***	**0.606****	0.354	0.137	**-0.589****	0.137	0.262	0.294	-0.101	-0.094	**0.521***	-0.069
	Proline						-0.427	-0.363	**-0.509***	0.216	-0.005	0.151	**-0.775****	-0.122	-0.133	-0.269	**-0.891****	0.416
K-content	**root**							**0.578****	0.312	-0.289	-0.099	-0.286	0.289	0.371	-0.141	-0.073	**0.565****	-0.297
	shoot								0.140	-0.252	**-0.612****	**-0.489***	0.111	**0.673****	**-0.579****	-0.045	**0.546***	**-0.504***
	grain									**0.444***	0.378	0.371	**0.672****	0.022	**0.449***	**0.737****	**0.627****	-0.278
Mn-content	**root**										0.300	**0.684****	-0.047	0.161	0.418	**0.635****	-0.276	0.165
	shoot											0.437*	0.407	-0.364	**0.750****	**0.636****	-0.088	0.206
	grain												0.316	**-0.483***	**0.841****	0.380	-0.219	**0.726****
Zn content	**root**													-0.274	**0.609****	**0.498***	**0.736****	0.027
	shoot														**-0.625****	0.190	0.181	**-0.642****
	grain															**0.472***	-0.023	**0.609****
Cu content	**root**																0.264	-0.223
	shoot																	**-0.524***
	grain																	

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

4. Discussion

4.1. Impacts of drought stress on wheat growth and productivity

Drought stress led to significant increases in proline content within wheat shoots. This osmoregulator accumulates in higher concentrations in tissues of drought-stressed plants (Du *et al*., 2023; Abd El-Hady *et al*., 2025; Ibrahim *et al*., 2025; Salama *et al*., 2025) to increase cell osmosis and become capable of absorbing more water (Hong-Bo *et al*., 2006; Hosseinifard *et al*., 2022). This biochemical mechanism increases plant tolerance to drought stress (Nyaupane *et al*., 2024).

Also, drought stimulated root growth (Ali *et al*., 2020) to explore new area rich in nutrients (Wang *et al*., 2016) and to search for water (hydrotropism) (Kang *et al*., 2022). On the other hand, the increased biosynthesis of proline lessened the availability of metabolites essential for plant growth and productivity, leading to significant decreases in shoot and grain yields. Consequently, the shoot-to-root ratio decreased substantially. Proline also mediated stomatal closure to minimize transpiration from plants (Muhammad Aslam *et al*., 2022). Similar results were reported by Nyaupane *et al*. (2024) who observed significant reductions in the shoot-to-roo ratio and wheat grain yield under drought conditions. Thus, the first hypothesis is validated.

4.2. Biochar as a solution to cope with drought stress.

Application of biochar alleviated this stress, especially when at the higher rate, resulting in notable improvements in shoot dry weight, shoot-to-root ratio, and grain yield. Remarkably, the increase in grain yield surpassed that of the non-stressed plants without biochar (B_0+FC_{10}0). These results align with several studies (Mansour *et al*., 2019; Zulfiqar *et al*., 2022; Boudjabi *et al*., 2023; Farid *et al*., 2025). Probably, biochar mitigated drought effects by increasing soil moisture retention, and improving soil fertility (Haider *et al*., 2020; Abdel-Salam *et al*., 2025). Also, biochar stimulated the activities of helpful microorganisms that promote plant growth and productivity (Zaheer *et al*., 2021).

Though biochar did not significantly affect plant heights, it boosted the number of plants per pot, with the highest increase observed in the "B_{10}+FC_{100}" treatment. Interestingly, biochar had no significant impact on proline content, as the lowest proline levels were found in plants irrigated with FC_{100} regardless of biochar application rate.

The grain/straw ratio was generally low in the non-amended control soil, and remained low in soils that received 5 g kg^{-1} biochar under FC_{60}. This suggests that stressed plants may shorten vegetative growth periods to cope with drought (Oguz *et al*., 2022). Increases in the grain/straw ratio were only noticed in biochar-amended plants with higher soil moisture (FC_{80} and FC_{100}), especially at the 5 g kg^{-1} biochar rate. This is because of the high ability of biochar to retain soil moisture that is needed for proper plant growth (Bassouny and Abbas, 2019) and provides essential nutrients (Elshony *et al*., 2019), growth hormones and other stimulating growth substances (Farhangi-Abriz and Torabian, 2018). Moreover, biochar can suppress plant pathogens (Poveda *et al*., 2021).

However, a higher biochar dose, i.e. 10 g kg^{-1} partially immobilized some nutrients, hindering plant growth and transition from vegetative to reproductive stages (Kocsis *et al*., 2020). Biochar also stimulated soil biota activity (Kocsis *et al*., 2020), increasing biological immobilization processes of many soil nutrients (Bandara et al., 2020). These results support the 2nd hypothesis.

4.3. Nutrient distribution in different plant parts.

Distribution of four nutrients (K, Mn, Zn and Cu) within different plant parts were evaluated in this study. In case of K, biochar application raised substantially K concentrations, especially in shoots, enhancing shoot and grain biomasses. Its mode of action in alleviating drought stress is probably through its osmotic adjustment role, sustaining stomatal conductance (Egilla *et al*., 2005), and activation of many enzymes (Ahmad et al., 2018). This nutrient also increases carbohydrate metabolism in plants (Zahoor *et al*., 2017)

Manganese, zinc, and copper also play crucial roles in activation of detoxifying enzymes that target superoxide radicals; consequently, accumulating in plant cells under abiotic stresses (Tavanti *et al*., 2021; Carmo de Carvalho e Martins *et al*., 2022; Zhou *et al*., 2022). Biochar significantly increased Mn levels in roots, shoots, and grains, with the highest accumulation in roots, where Mn-SOD (a general isozyme) is prevalent (Saed-Moucheshi *et al*., 2021). Generally, Mn concentrations were highest in FC_{60}-irrigated plants, then FC_{80} and finally FC_{100}.

Concenring Zn and Cu, these nutrients were found high in the non-amended control plants while decreased in biochar amended ones, especially at 5 g kg^{-1}. This dilution effect was likely due to increased plant dry weight (Wan *et al*. 2023). It is worth noting that Cu/Zn-SOD -a genotype specific isozyme (Saed-Moucheshi *et al*., 2021) - raised radical oxygen scavenging system (Tavanti *et al*., 2021). Higher biochar dose of could partially immobilize these nutrients in soil (Wang *et al*., 2021); hence decrease their uptake and concentrations within different plant parts (Wang *et al*., 2021). Mobility of these two nutrients in soil moisture is relatively high (Wang *et al*., 2021), explaining their higher concentrations in FC_{100} treatments compared to FC_{80} and FC_{60} . The above results supported the 3rd hypothesis.

4.4. Effects of biochar on some soil properties (soil organic matter, pH and EC)

Application of biochar raised significantly soil EC and organic matter content by reducing mineralization (Liu *et al*., 2022). The most noticeable changes in soil EC occurred with higher biochar doses. However, soil pH was not significantly impacted by these additional organics. It's possible that the alkaline effects of biochar are temporary and only noticeable shortly after it is added to the soil (Chen *et al*., 2021). Over time, non-alkaline highly stable aromatic carbon dominated, which does not significantly alter soil pH (Patra *et al*., 2021). Biochar also acted as a pH buffer (Arwenyo *et al*., 2023). Moreover, it enriched soil with nutrients and enhanced their uptake and bioaccumulation in roots, specifically Mn, Zn and Cu. This explains the significant correlation between root biomass and the concentrations of K, Zn, and Cu in roots. Accordingly, these results validate the 4th hypothesis.

5. Conclusion and Future Prospective

Drought stress severely hampers wheat growth and productivity. To cope with this stress, plants stimulated further root growth in search of water and nutrients. Additionally, they exhibited high proline levels content in plant tissues. However, the application of biochar offered a promising solution to counteract these negative effects particularly at 5 g kg^{-1} under deficit irrigation (80% field capacity), provides a viable solution, while rationalizing irrigation water and sustaining soil productivity. Biochar improves drought stress by increasing levels of the proline, increasing Mn and Cu contents within plant parts for detoxifying processes of radical free oxygen, which is produced under abiotic stress. Besides, it increased residual organic matter by the end of the growing season. These improvements led to better plant growth and productivity, making biochar a valuable tool for sustainable wheat cultivation in arid regions. These findings collectively validate the hypotheses of the study. Nevertheless, further investigation into plant nutrition under drought conditions is essential to maximize crop resilience and yield.

Declarations

Ethics approval and consent to participate

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