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## **Combined application of biochar and silicon nanoparticles enhance soil and wheat productivity under drought: Insights into physiological and antioxidant defense mechanisms**

Bilal Zulfiqar<sup>a,b,\*</sup>, Muhammad Aown Sammar Raza<sup>b</sup>, Muhammad Akhtar<sup>c</sup>, Zhang Nan<sup>a</sup>, Mamoon Hussain<sup>d</sup>, Junaid Ahmad<sup>e</sup>, Mostafa A. Abdel-Maksoud<sup>f</sup>, Hossam Ebaid<sup>g</sup>, Rashid Iqbal<sup>b,h</sup>, Muhammad Usman Aslam<sup>b</sup>, Mohamed A. El-Tayeb<sup>f</sup>, Shiming Su<sup>a,\*</sup>,

<sup>a</sup> Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences/Key Laboratory of Agro-Environment, Ministry of Agriculture, Beijing 100081, PR China

<sup>b</sup> Department of Agronomy, Faculty of Agriculture and Environment, The Islamia University of Bahawalpur, Pakistan

<sup>c</sup> Institute of Crop Science, Chinese Academy of Agricultural Sciences Beijing, China

<sup>d</sup> Department of Botany, The Islamia University of Bahawalpur, Pakistan

<sup>e</sup> Department of Plant Sciences, Quaid-i-Azam University, Islamabad 45320, Pakistan

<sup>f</sup> Department of Botany and Microbiology, College of Science, King Saud University, P.O. Box 2455, Riyadh 11451, Saudi Arabia

<sup>g</sup> Department of Zoology, College of Science, King Saud University, P.O. Box 2455, Riyadh 11451, Saudi Arabia

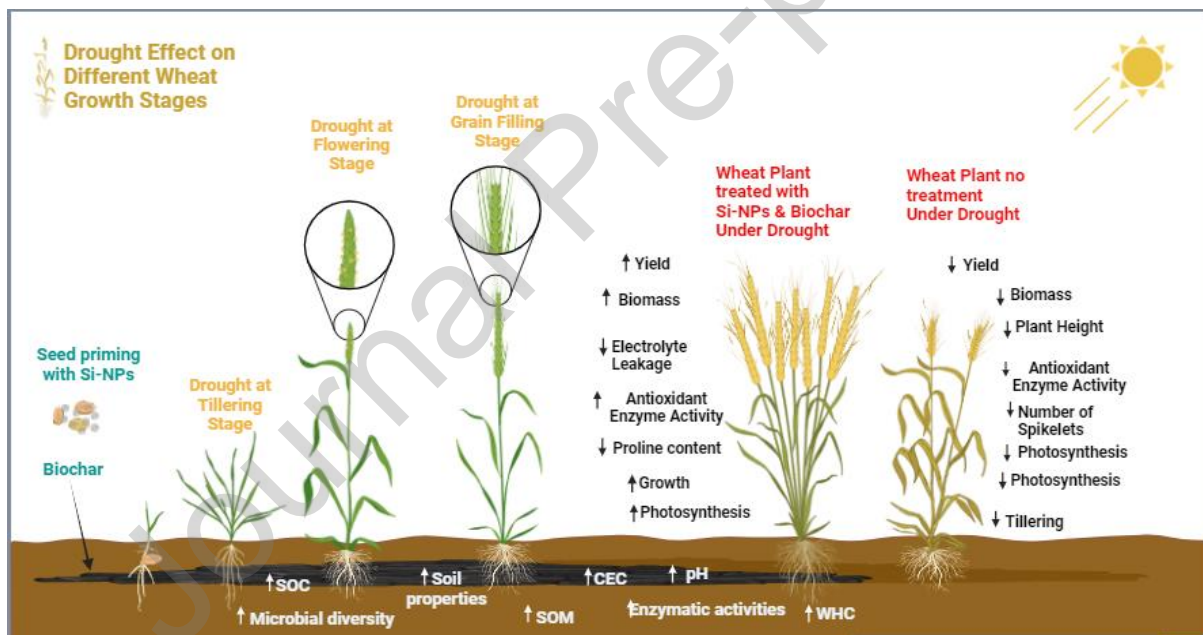
<sup>h</sup> Department of Life Sciences, Western Caspian University, Baku, Azerbaijan

\* Corresponding authors. E-mail addresses: chbilalch@gmail.com; sushiming@caas.cn

## Highlights

- Combined biochar and silicon nanoparticles improved the soil properties and wheat drought resistance.
- Biochar plays a significant role in enhancing soil fertility, including organic carbon, nitrogen, and mineral content.
- Co-application of biochar and silicon nanoparticles induces enhanced tolerance in wheat and increased yield in field experiments.
- Biochar revealed a better impact than silicon nanoparticles in semi-arid climates.

## Graphical abstract



## Abstract

Agricultural drought periods are enhanced by the change in global climate that threatens food security. One of the main factors affecting soil and wheat productivity worldwide is drought stress. Especially, in semi-arid climates, studies are not found about adding organic amendments may be a viable way to reduce the adverse impacts of drought on crops while enhancing soil qualities and water use efficiency. In this study, we aimed to explore the effects of combined application of biochar (BC = 5 %) and silicon nanoparticles (SiNP = 900 mg/L) on soil and wheat drought resistance. Drought stress was applied at the three most critical

growth stages of wheat, tillering (DTS), flowering (DFS), and grain filling (DGFS) stages, then evaluated the soil nutrients and wheat drought physiological resistance under applied treatments (BC, SiNP, BC+SiNP). Results showed that combined treatment of BC and SiNP greatly reduced the adverse effects of drought by enhancing plant height (9.36 %), spike length (25.63 %), number of fertile tillers (29.26 %), grains per spike (10.86 %), thousand-grain weight (18.25 %), and biological yield (16.34 %) with comparison to the control application. Additionally, physiological measures like water use efficiency (20.58 %), stomatal conductance (29.26 %), chlorophyll a (16.25 %), chlorophyll b (18.96 %), transpiration rate (21.65 %), photosynthetic rate (22.94 %), electrolyte leakage (-17.77 %), MDA (29.25 %), hydrogen peroxide (-19.88 %), superoxide dismutase (11.19 %), catalase (9.26 %), peroxidase (18.59 %), nitrogen (14.81 %), phosphorus (13.89 %), and potassium (17.61 %) were also meaningfully improved by treated application. BC and SiNP also significantly amended the organic carbon, nitrogen, and minerals percentage in soil. In conclusion, using the synergistic application of BC and SiNP could be a successful strategy to promote the biological soil properties, plant growth, yield, and quality of wheat crops as compared to all other treatments via dropping the dangerous effects of drought stress.

**Keywords:** Global climate, Food security, Biochar; Silicon nanoparticles; Wheat; Drought; Water use efficiency

## 1. Introduction

Agricultural progress face numerous challenges, including the reduction of arable land, environmental variations, water scarcity, temperature fluctuations, altered rain patterns, rising initial costs, soil degradation, and significant rural to urban migration (Webber et al., 2018). To meet the food demands of a rapidly growing global population, agricultural production must double by 2050 (Beddington, 2011; McKenzie and Williams, 2015). Consequently, innovative strategies are essential for improving crop cultivation (Go, 2019; Hassan et al., 2019). Instead of expanding cultivation areas, Araus et al. (2008) suggest focusing on optimal yields through alternative methods, as water scarcity and drought continue to severely impact agricultural

productivity (Mega et al., 2019). Drought stress, affecting over 50 % of wheat-growing areas, is a significant factor driving these challenges (Jabborova et al., 2021; I. Khan et al., 2021).

Drought, one of the most dangerous abiotic stressors, is responsible for significant global yield losses (Webber et al., 2018). Wheat, especially in its late embryonic phases, is susceptible to terminal drought, which causes an imbalance between evapotranspiration and soil water absorption under high temperatures and low soil moisture (Rahimi-Moghaddam et al., 2023; Rashid et al., 2021). The plants response to water scarcity depends on stress duration and severity, development stage, and genotype (Nawaz et al., 2021; Tricker et al., 2018). Furthermore, biochar (BC) has emerged as a potential soil amendment to mitigate drought impact by improving soil properties and water retention (Ahmad et al., 2016; Sánchez-Monedero et al., 2019). BC enhances soil fertility, enzyme activity, and crop yield under drought conditions, making it an increasingly valuable tool in agriculture (Lyu et al., 2016; Lehmann and Stephen, 2015).

Semi-arid environments, typified by low and variable rainfall, greatly impede farming by reducing water availability for agriculture (Ghaffar et al., 2022; Kumar et al., 2019). This fact results in inadequate soil moisture, decreased agricultural yields, and greater susceptibility to soil erosion (Mehwish et al., 2024). Insufficient water availability in these areas compels farmers to depend on restricted irrigation and drought-resistant crops, yet even these strategies often prove inadequate in maintaining profitable agriculture (Yang et al., 2023). Drought stress worsens the issue by intensifying the existing arid conditions, therefore aggravating crop failure and degrading the soil (Zulfiqar et al., 2024). Although drought stress may be transient, its impact in semi-arid climates is frequently more pronounced because of the ongoing water shortage, which poses long-term difficulties for sustainable agriculture (Elagib et al., 2024).

Biochar application to the soil increases the yield and growth of sunflower (Waqar et al., 2022), rapeseed (Jin et al., 2019), and wheat (Abbas et al., 2018b) under water deficit circumstances. The efficiency of water usage, photosynthesis, and stomatal conductance of tomato crops under water scarcity situations were all markedly enhanced by BC enrichment (Cui et al., 2017). Additionally, in drought conditions, it has been found that quinoa, wheat, and maize exhibit increased leaf gaseous exchange parameters that directly influence plant growth and yield (Nawaz et al., 2021; Raza et al., 2023; Zulfiqar et al., 2022). It has been shown that applying BC to crops increases the activity of protective enzymes and electron transfer, hence reducing the detrimental impacts of drought (Gharred et al., 2022).

Because of BC high porosity, cation exchange capacity, long-term carbon sink in the soil, and capability to promote beneficial bacteria, it is the most practical substitute to deal with drought circumstances for sustainable agricultural output (Go, 2019; Tripathi et al., 2017). Adding it to the soil enhances soil and microbial function and activity which directly influences the crop at the germination level (Haider et al., 2020). Hence, using BC to treat wheat during its crucial growth stages might be a positive step toward reducing the adverse consequences of drought (Iqbal et al., 2019). Furthermore, the use of BC in conjunction with other appropriate amendments, such as nanoparticles, has even greater benefits than BC solo in terms of reducing water stress (Lyu et al., 2016; Zhang et al., 2022). At the field level, less is known about how BC interacts with other modifications to mitigate drought (Bashir et al., 2021). Thus, additional study is required to determine how BC and other appropriate nanoparticles affect wheat crop water scarcity circumstances.

The past ten years have seen a significant increase in the use of nanoparticles (NPs) in agriculture because of their special qualities, which include increased surface area, improved absorption capacity, effective localized delivery, and a variety of applications such as playing a role as fertilizer, growth promoter, resistance agent against biotic and abiotic stresses (Akhtar

et al., 2021; Gill et al., 2024; Rameshaiah et al., 2015). Recently, NP use in agriculture has seen a boom due to its unique properties and magnificent benefits against abiotic stresses (Janmohammadi and Sabaghnia, 2015). The application of NPs increased wheat growth, yield, chlorophyll content, and gas exchange properties while also reducing its water deficit. (Rizwan et al., 2019). Several investigations showed that applying NPs under drought stress sped up plant growth, antioxidant activity, and nutrient absorption because the particles strengthen the plants resilience (Tripathi et al., 2017, 2016; Zhang et al., 2018). In an intense environment, SiNP, among other NPs, is useful for enhancing photosynthesis and plant growth (Mousavi et al., 2018). Silica NPs promote photosynthesis under water-limited conditions improving the yield of *Cucurbita pepo* L (Siddiqui et al., 2014) and hawthorn seedlings (Ashkavand et al., 2015). Compared to other fertilizers, SiNP has a bigger influence on agriculture and enhances some plants photosynthetic characteristics during the dry season (Raza et al., 2021; Rea et al., 2022). SiNP significantly contributes to plants capacity to endure water shortages by enhancing the concentrations of amino acids, chlorophyll, lipids, and proteins (Rafi et al., 2022).

The exogenous application of NPs induces silicification in the root endodermis, triggers the antioxidant system, and regulates cell water content stability (Siddiqui et al., 2015). The utilization of nano-silicon has resulted in significant advancements in production and improved the water status of plants (Akhtar et al., 2021). Furthermore, SiO<sub>2</sub> NPs have been acknowledged as a substance that promotes plant development by enhancing the process of root endodermal silicification, improving the antioxidant system response to stress, and enhancing resilience to abiotic environmental factors while maintaining proper cell water balance (Siddiqui et al., 2015). The most effective technique for using nanoparticles in agriculture is seed priming, however, they may also be delivered via soil and foliar spray in biotic and abiotic conditions (Rizwan et al., 2019; Sundaria et al., 2019). Some features make seed priming a successful tactic, including reducing the harmful effects of abiotic stresses, promoting beneficial

physiological changes, aiding in the early stages of germination, increasing the rate at which seeds germinate, reducing the time it takes for seedlings to emerge, and —most importantly— being an economically viable method for farmers (Al-Huqail et al., 2023; Kakar et al., 2023; Wang et al., 2021; Yadav et al., 2018). The SiNP application has the potential to be a significant advancement in reducing the severe consequences of drought on wheat in drought circumstances.

The prime objective of this study was to examine the possible impacts of BC, SiNP, and SiNP+BC on soil parameters in semi-arid regions, as well as enhance the morpho-physiological and biochemical response of wheat throughout crucial growth stages under drought conditions. Significantly, our work is advanced to assess the influences of drought at the key growth phases of wheat with the treatment of BC and SiNP. We tested two main hypotheses: first, BC coupled with nanoparticles improves wheat growth and development; second, BC coupled with nanoparticles improves the semi-arid soil properties under drought.

## **2. Materials and Methods**

### **2.1. Experimental layout and crop husbandry**

This study was a field examination at The Islamia University of Bahawalpur, Pakistan (Latitude: 29° 23' 60.00" N, Longitude: 71° 40' 59.99" E). The study was replicated thrice with a factorial setup with RCBD. Four treatments of BC and SiNP such as (CK = control, SiNP = 900 mg/L, BC = 5 % (w/w), and SiNP+BC = 900 mg/L SiNP + 5 % BC) were used, these applications were carefully chosen from our previous research experiments (Raza et al., 2023; Zulfiqar et al., 2022). Drought was applied at DTS, DFS, and DGFS, with full irrigation serving as the control (CK). The Galaxy-2013 wheat variety, selected for this study, is recognized for its notable drought tolerance and adaptability to water-limited conditions. Raza et al. (2017) demonstrated that Galaxy-2013 outperformed other varieties in partial root zone drying (PRD)

experiments, underscoring its resilience under water stress. Similar findings have been noted by Wasaya et al. (2021), who investigated drought-adaptive traits in various wheat varieties and highlighted the physiological and molecular responses in Galaxy-2013 that enhance its water-use efficiency and tolerance. This variety proven performance under water stress conditions makes it ideal for evaluating physiological responses in controlled drought experiments, aligning well with the objectives of this study.

We received wheat seeds of Galaxy-2013 variety from Agricultural Office Bahawalpur and planted after SiNP seed priming in different 15 m<sup>2</sup> plots of BC mixed soil during 2020-2021. Table 1 provides the soil physiochemical analysis. Water was provided on three-acre inches per irrigation schedule, except during drought-imposed applications at DTS, DFS, and DGFS. Drought was imposed by skipped the one irrigation at that particular stage (40–50 days after sowing (DAS) for DTS, 80–90 DAS for DFS, and 100–110 DAS for DGFS) and after that stage again irrigated as normal irrigation. The control plots got four irrigations total utilizing the flood irrigation approach. Irrigation was done using tube well water with an EC of 886  $\mu\text{S cm}^{-1}$  and a pH of 6.5. Fertilizer was applied at 120 kg N and 80 kg P<sub>2</sub>O<sub>5</sub> per acre, using urea and diammonium phosphate (DAP).

**Table 1:** Physio-chemical properties of the investigational soil.

Soil Parameters	Soil Properties
Soil pH	7.22
Sand	56.3 %
Silt	33.2 %
Clay	10.5 %
Texture class	Sandy loam soil
SOM (%)	0.93

EC (dS m <sup>-1</sup> )	2.58
Ammoniac N (mg g <sup>-1</sup> )	1.60
Available Phosphorus (ppm)	6.85
Available Potassium (ppm)	110

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## 2.2. Silicon nanoparticles seed priming

The supplier of SiNP was SIGMA ALDRICH and the specific product number was 933767. SiNP possessed a specific surface area of  $> 80 \text{ m}^2 \text{ g}^{-1}$ , a molecular weight of 28.08, and a purity of  $> 99 \%$ . The diameters of the NPs were measured using a scanning electron microscope (Suppl. Fig. S1). After sterilizing wheat seeds (Galaxy-2013) for 120 seconds in a sodium hypochlorite solution (2.6 % active chloride), the seeds were washed with distilled water. Then SiNP was measured and mixed with deionized water before being ultrasonically treated (900 mg/L) for thirty minutes to ensure appropriate dispersion. After that, the wheat seedlings spent 20 hours in room temperature darkness submerged in SiNP solution (Raza et al., 2023). Deionized water was used to incubate seedlings for the control treatment. At last, the primed wheat seed was dried and stored at 4 °C awaiting further tests.

## 2.3. Biochar application

According to reports (Zhou et al., 2016), wheat straw was pyrolyzed at 500 °C in a vertical kiln to create the BC. It possesses the following qualities: 3 mm in particle size, 0.54 g cm<sup>-3</sup> in bulk density, 73.5 m<sup>2</sup> g<sup>-1</sup> in micropore surface area, 0.025 cc g<sup>-1</sup> in micropore volume, 13.4 – 14.7 c mol kg<sup>-1</sup> in cation exchange capacity, 20.7 % ash content, and pH 9.1 (Zulfiqar et al., 2022). BC (5 %) was mixed with soil in all plots before sowing wheat seeds except the control.

## 2.4. Growth and yield characteristics

Plant height (cm), spike length (cm), number of grains per spike (NGPS), number of spikelets per spike (NSPS), number of fertile tillers, 1000-grain weight (g), biological yield (kg ha<sup>-1</sup>), and grain yield (kg ha<sup>-1</sup>), were quantified using standard techniques and protocols. The following formula was used to obtain the harvest index (HI):

$$\text{HI} = \text{Grain Yield} / \text{Biological Yield} \times 100$$

## 2.5. Physiological parameters

The chlorophyll pigments were extracted by 0.5 g of recently harvested leaf tissue was slowly mixed with 10 mL of acetone (80 %) and quantified spectrophotometrically (Spectronic 601, Milton Roy Company, Rochester, NY, USA) by Metzner et al. (1965). A movable fluorometer was utilized to assess chlorophyll fluorescence in leaves. For thirty minutes, the leaves in a leaf clip were dark-adapted. Every treatment included thirty measurements, each of three sets of 10 leaves from a separate plant. The performance index and PS II maximum efficiency (Fv/Fm) were calculated using the gathered data on an absorption basis (Strasser et al., 2004) according to the equations reviewed by (Stirbet, 2011). The equation for determining water use efficiency (WUE) is WUE = grain yield divided by total water applied, as explained by (Haider et al., 2020). Automatic porometer MK-3 Delta-T Devices, BC, England, was used to measure the transpiration rate (TR) and stomatal conductance (SC).

## 2.6. Antioxidant activities

### 2.6.1. Electrolyte leakage (EL)

After sixty-five days of wheat planting, antioxidant activities were assessed for control treatment and for drought-imposed treatments were assessed after 3 days of drought imposed. The percentage of EL was determined in the shoots after the samples were arranged straight up in tubes and heated for two hours at a steady temperature of 32 °C in a specified amount of distilled water. After that, the EC result was calculated to be EC1, and it was heated for a further

twenty minutes at a steady temperature of 121 °C. Ultimately, an equation that had already been established was used to compute the EL (Dionisio-Sese and Tobita, 1998).

$$EL = EC1 / EC2 \times 100$$

#### 2.6.2. Hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>)

A 50 mg sample was combined with phosphate buffer solution (3.0 mL) and centrifuged for 30 minutes at 4 °C and 6000 g to detect hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>). After that, 0.1% titanium sulphate was added to the supernatant, and the mixture was centrifuged at 6000 g for 20 minutes at 4 °C. The absorbance of the supernatant was measured at 410 nm. An extinction value of 0.28 mol<sup>-1</sup> cm<sup>-1</sup> was used to compute H<sub>2</sub>O<sub>2</sub>.

#### 2.6.3. Superoxide dismutase (SOD)

The technique outlined by Giannopolitis and Ries, (1977) was used to determine the superoxide dismutase (SOD) activity. A 3 mL reaction mixture was prepared by adding 2 µM riboflavin to 50 mM phosphate buffer (pH 7.8), 13 mM methionine, 75 µM nitro blue tetrazolium, 0.1 µM EDTA, and 0-100 µl of enzyme extract. A 15-W fluorescent tube was used to light the tubes after they had been shaken. After 10 minutes of reaction time, the light was turned off, and the absorbance at 560 nm was measured. The quantity of enzyme needed to provide a 50 % inhibition of the rate of nitroblue tetrazolium chloride reduction was defined as one unit of SOD activity.

#### 2.6.4. Catalase (CAT) & Peroxidase (POD)

CAT activity measurement by monitoring the rate of H<sub>2</sub>O<sub>2</sub> degradation at 240 nm. (Hwang et al., 1999). The guaiacol oxidation technique was used to quantify POD activity (Maechlay and Chance, 1954) with a small modification: 3 ml reaction mixture consisting of 50 mM potassium phosphate buffer (pH 6.1), 1 % guaiacol, 0.4 % H<sub>2</sub>O<sub>2</sub>, and enzyme extract.

An increase in the absorbance due to the oxidation of guaiacol ( $E = 25.5 \text{ mM}^{-1} \text{ cm}^{-1}$ ) was measured at 470 nm (Zhang et al., 2007). The estimation of MDA contents was assessed as defined by Wu et al. (2003).

## 2.7. Grain quality parameters

The concentrations of the seed nutrients (N, P, and K) were determined using Wolf (1982) methodology.

## 2.8. Soil parameters

Soil organic matter (SOM) was assessed using established methodologies as outlined by Sparks et al. (2020). The technique outlined by Smolander and Kitunen (2002) was used to assess dissolved organic nitrogen (DON) and carbon (DOC). Based on soil samples taken both before and after a 10-day incubation period at 30 °C, the rate of nitrogen mineralization ( $N_{\text{MIN}}$ ) was calculated. The method of measuring soil respiration (SR) was as stated by Dinesh et al. (2013).

## 2.9. Statistical analysis

The current data were screened to a two-way analysis of variance (ANOVA) using Statistix software (version 8.1) for Windows, and a comparison of the mean data was performed using the LSD at a 5 % probability level. Principal component analysis (PCA) was accomplished on the data, and Origin Pro 9.1 software was used to create a biplot graph and correlation matrix that displayed the analysis findings.

# 3. Results

## 3.1. Impact of amendments on wheat growth and yield

The impact of treatments under control as well as drought conditions on plant height, spike length, NGPS and NSPS have been shown in supplementary Table S1. In comparison to

the control treatment, drought stress significantly decreased plant height in DTS, DFS, and DGFS by 32.1 %, 21.8 %, and 12.9 %, and spike length in DTS, DFS, and DGFS by 24.1 %, 31.4 %, and 38.9 %, respectively. Drought stress was reduced and plant height and spike length increased by 5.4 %, 4.3 %, 9.3 %, 16.5 %, 11.6 %, and 25.6 %, respectively, at DTS, DFS, and DGFS, with the application of BC, SiNP, and SiNP+BC (Table S1). SiNP+BC was shown to be the most effective treatment option under normal and drought. Drought stress minimized the NSPS (20.1 %, 28.6 %, and 34.2 %) and NGPS (12.9 %, 15.9 %, and 27.6 %). Table 2 shows that the application of BC, SiNP, and SiNP+BC under both control and drought had a substantial impact on the yield characteristics. Drought stress minimized the number of fertile tillers (16.6 %, 31.4 %, and 48.1 %), 1000 grain weight (9.7 %, 22.4 %, and 28.6 %), grain yield (8.4 %, 22.1 %, and 29.7 %), and biological yield (7.4 %, 15.8 %, and 26.8 %) at DTS, DFS and DGFS, respectively, with comparison to CK. BC and SiNP have a valuable effect on drought or control conditions. However, when combined SiNP+BC treatment was applied, the rate of biological yield increased by 17.6 % than individual treatments under normal and stressful conditions. The BC, Si-NP, and SiNP+BC treatments considerably reduced the impacts of dryness on the wheat yield-related metrics throughout critical growth phases (Table 2). It was demonstrated that under both normal and drought stressed conditions, SiNP+BC was the most effective treatment selection.

**Table 2:** Effects of BC and SiNP during drought on the number of fertile tillers (NFT), 1000-grain weight (GW, g), grain yield (GY, kg ha<sup>-1</sup>), biological yield (BY, kg ha<sup>-1</sup>), and harvesting index (HI).

Treatments		NFT (%)	GW (g)	GY (kg ha <sup>-1</sup> )	BY (kg ha <sup>-1</sup> )	HI (%)
Drought	Nutrients					
CK	CK	6.33 abc	28.33 cde	4253.3 d	8618 d	49.34 a
	SiNP	6.83 ab	30.03 bcd	4577.6 c	9597 b	47.68 cd

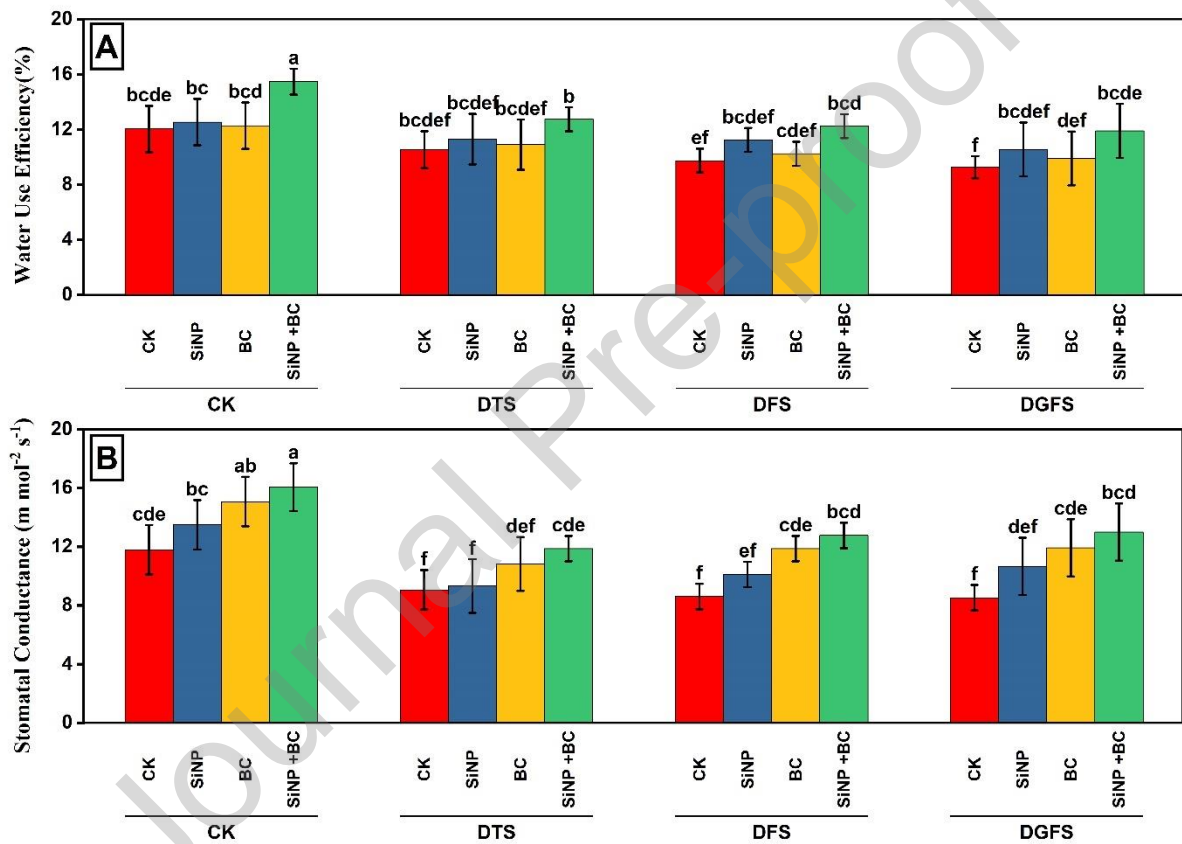
	<b>BC</b>	7.23 ab	30.73 bc	4703.3 b	9748 b	48.23 b
	<b>SiNP+BC</b>	7.42 a	35.08 a	4982.6 a	10389 a	47.95 bc
<b>DTS</b>	<b>CK</b>	4.90 efg	25.93 efg	4010.3 f	8197 e	48.91 a
	<b>SiNP</b>	5.44 cdef	27.40 efg	4147.3 e	8768 cd	47.29 def
	<b>BC</b>	6.06 bcde	28.50 cde	4214.8 d	8927 c	47.20 efg
	<b>SiNP+BC</b>	7.44 a	31.34 b	4716.6 b	9827 b	47.98 bc
<b>DFS</b>	<b>CK</b>	4.54 fgh	23.04 ij	3473.9 j	7428 gh	46.76 h
	<b>SiNP</b>	5.24 cdefg	24.94 ghi	3672.9 h	7808 f	47.03 fgh
	<b>BC</b>	4.94 defg	25.64 fgh	3811.5 g	8078 e	47.17 efg
	<b>SiNP+BC</b>	6.44 abc	27.84 def	4203.5 d	9782 b	42.95 i
<b>DGFS</b>	<b>CK</b>	3.63 h	21.50 j	3401.3 k	7210 h	47.14 efg
	<b>SiNP</b>	4.04 gh	23.10 hij	3468.1 j	7333 gh	47.27 defg
	<b>BC</b>	4.96 defg	25.40 fghi	3573.4 i	7507 g	47.57 cde
	<b>SiNP+BC</b>	6.13 bcd	26.60 efg	3837.2 g	8190 e	46.84 gh
<b>LSD</b>	<b>SiNP</b>	***	***	***	***	***
	<b>BC</b>	***	***	***	***	***
	<b>SiNP+BC</b>	NS	***	***	***	***

Control, drought at tillering, flowering, and grain-filling phases are indicated by CK, DTS, DFS, and DGFS, in that order. Control, 5 % BC, 900 mg/L SiNP, and 5 % BC + 900 mg/L SiNP are indicated by the symbols CK, BC, SiNP, and SiNP+BC, respectively. At a 5 % probability level, means with the same letter case do not differ appreciably. where \*\*\* = significant at  $p \leq 0.001$  and NS non-significant at  $p \leq 0.05$  are indicated.

### 3.2. Water use efficiency and stomatal conductance

Fig. 1 shows how treatments affect SC and WUE in both normative and drought stress scenarios. Utilizing BC, SiNP, and SiNP+BC at varying stages of growth enhanced wheat water consumption efficiency in the expression of water scarcity. WUE dropped by 15.0 %, 20.3 %, and 25.7 % under drought stress at DTS, DFS, and DGFS, respectively, compared to

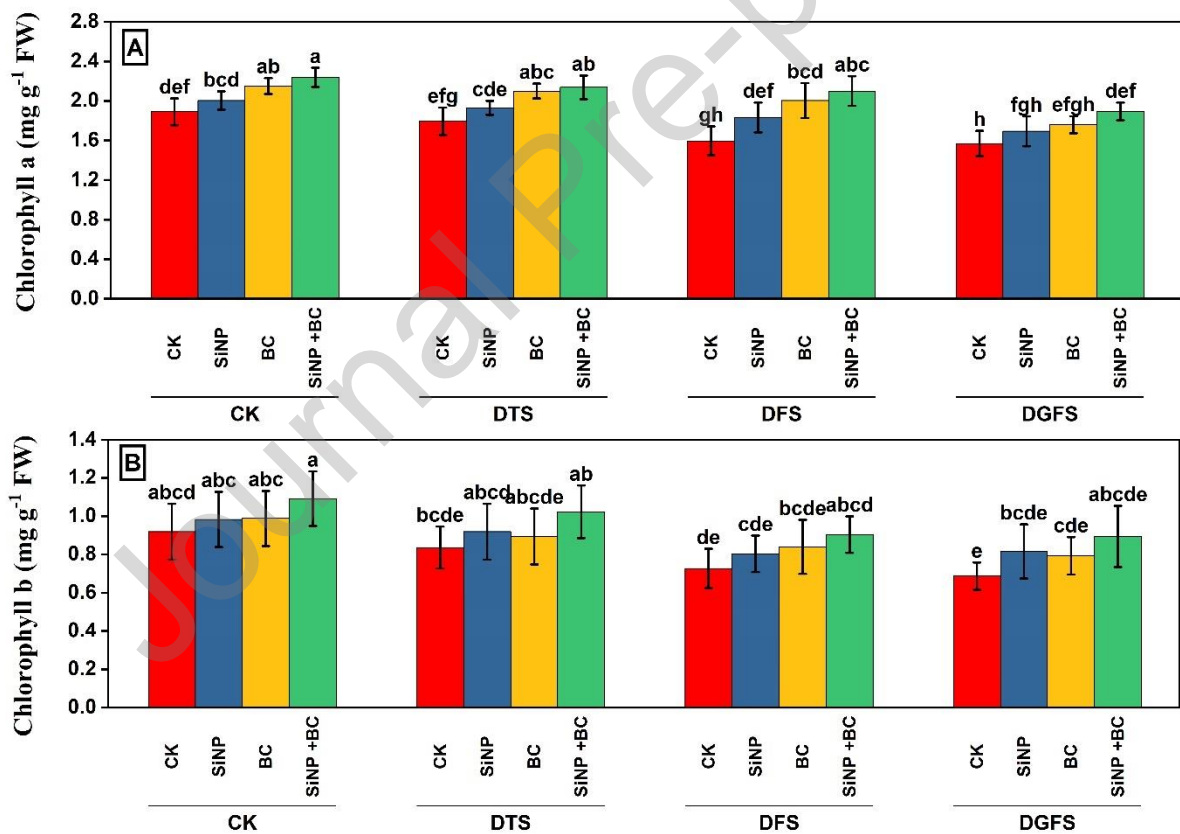
the CK. The applications of BC, SiNP, and SiNP+BC significantly enhanced the WUE and reduced the drought impact by 8.8 %, 4.0 %, and 20.6 %, correspondingly, in comparison to the treatment under control. Similarly, SC dropped by 37.4 %, 30.1 %, and 27.9 % under drought stress in comparison to the CK at DTS, DFS, and DGFS, respectively. Combining SiNP and BC increased the SC by 29.3 % in contrast to CK. On the contrary, the SC of SiNP and BC were enhanced by 12.8 % and 23.5 %, respectively, then the SC of CK.



**Fig 1.** WUE and SC are influenced by BC and SiNP treatments during drought stress. CK, DTS, DFS, and DGFS indicate control, and drought at tillering, flowering, and grain-filling stages, respectively. CK, SiNP, BC, and SiNP+BC indicate control, 5 % BC and 900 mg/L SiNP and 5 % BC + 900 mg/L SiNP. Error bars show a standard error (n = 3). Different letters indicate significant differences at 0.05 level as determined by LSD 0.05 test.

### 3.3. Impact on chlorophyll concentrations

Fig. 2 depicts the impact of applications on chlorophyll pigments. Drought significantly lowers the amounts of chlorophyll a (4.1 %, 9.9 %, and 19.7 %) and b (8.4 %, 21.6 %, and 24.8 %) in DTS, DFS, and DGFS, respectively, as compared to well-watered plants (CK). The amount of chlorophyll a and b (Fig. 2A-2B) in plant material increased dramatically with the application of all treatments (BC, SiNP, SiNP+BC). The quantity of chlorophylls ‘a’ and ‘b’ were uppermost in the combined application, and lowermost in the CK under drought at DGFS. As compared to CK, the amount of chlorophyll ‘a’ improved by 8.2 %, 14.5 %, and 18.1 % with the application of SiNP, BC, and SiNP+BC, while the amount of chlorophyll ‘b’ improved by 9.9 %, 9.8 %, and 19.0 %, respectively.

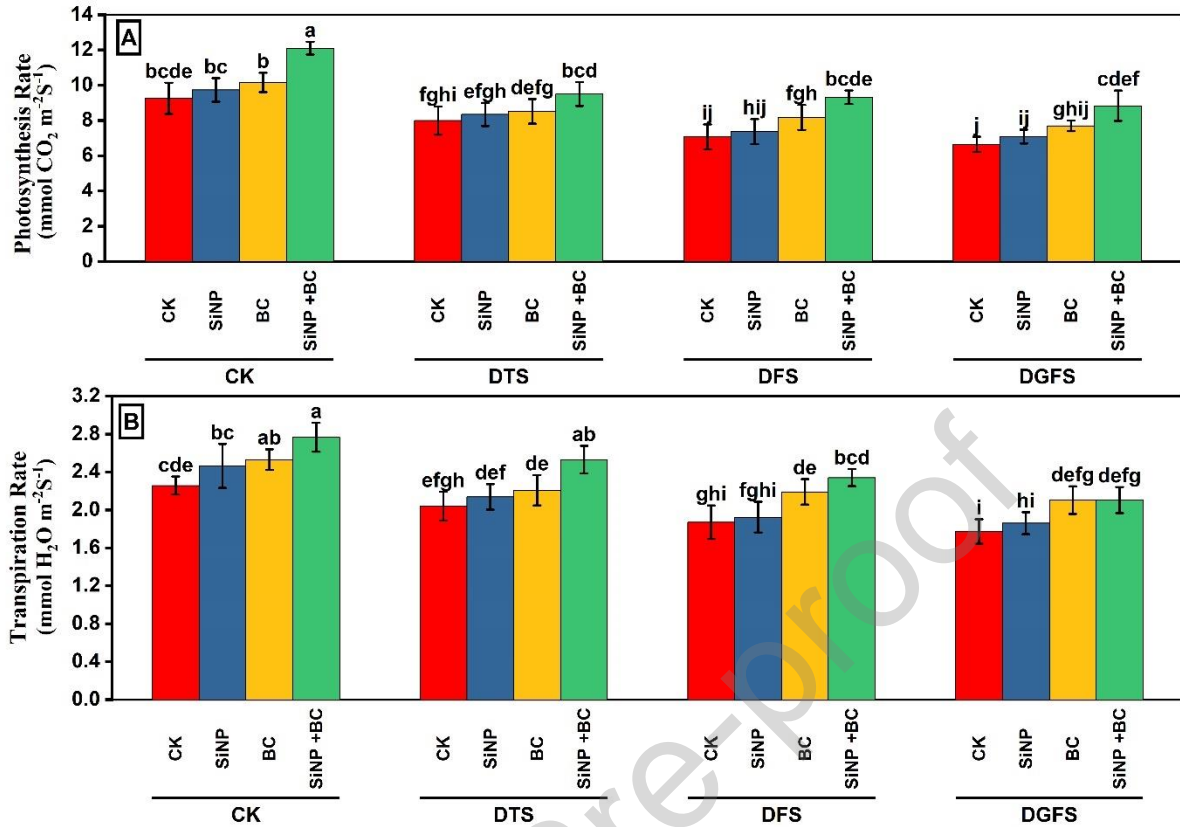


**Fig 2.** Chlorophyll a and b (mg g<sup>-1</sup> FW) contents affected by BC and SiNP treatments during drought stress. CK, DTS, DFS, and DGFS indicate control, and drought at tillering, flowering, and grain-filling stages, respectively. CK, SiNP, BC, and SiNP+BC indicate control, 5 % BC

and 900 mg/L SiNP and 5 % BC + 900 mg/L SiNP. Error bars show a standard error ( $n = 3$ ). Different letters indicate significant differences at 0.05 level as determined by LSD 0.05 test.

#### 3.4. Impact on gaseous exchange attributes

SiNP, BC, and SiNP+BC significantly improved photosynthetic activity. All of the treatments substantially enhanced wheat gaseous metrics as compared to CK (Fig. 3A-3B). Transpiration and photosynthesis rates suggestively fell by 12.3 %, 20.3 %, 27.7 %, and 18.1 %, 29.4 %, 33.8 % under drought stress at DTS, DFS, and DGFS, respectively, as related to the CK. Additionally, the application of SiNP, BC, and SiNP+BC suggestively minimized the stress and transpiration rate enhanced by 5.3 %, 12.1 %, and 18.4 % as compared to CK while the photosynthesis rate enhanced by 5.9 %, 8.6 %, and 22.9 %, respectively. The collective treatment of SiNP+BC provided higher photosynthesis and transpiration rates as comparability to all other treatments.



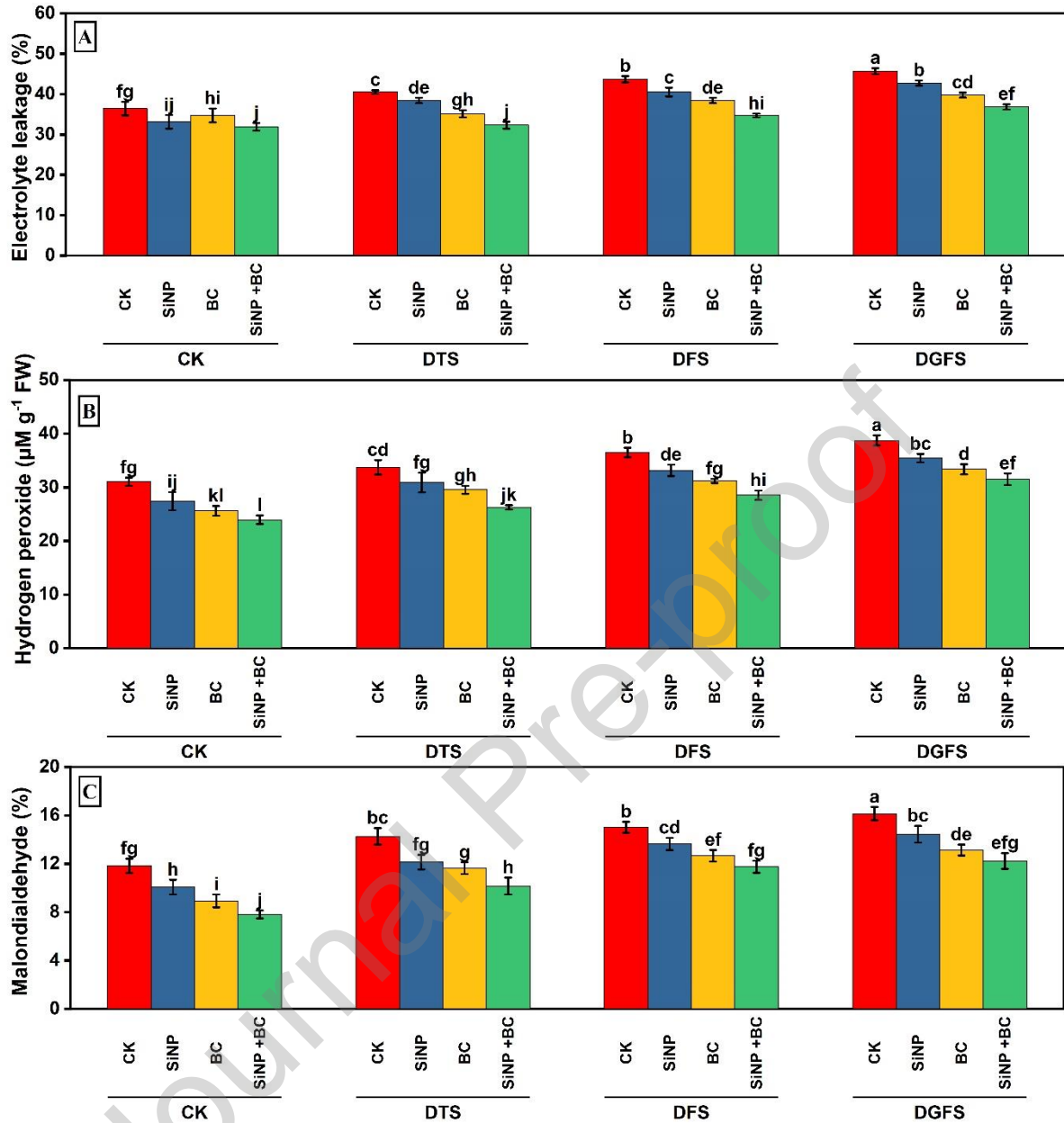
**Fig 3.** Photosynthetic rate and transpiration rate impacted by the use of BC and SiNP during drought conditions at crucial growth phases of wheat. CK, DTS, DFS, and DGFS indicate control, and drought at tillering, flowering, and grain-filling stages, respectively. CK, SiNP, BC, and SiNP+BC indicate control, 5 % BC and 900 mg/L SiNP and 5 % BC + 900 mg/L SiNP respectively. Error bars show a standard error (n = 3). Different letters indicate significant differences at 0.05 level as determined by LSD 0.05 test.

### 3.5. Impact on antioxidant enzyme activities

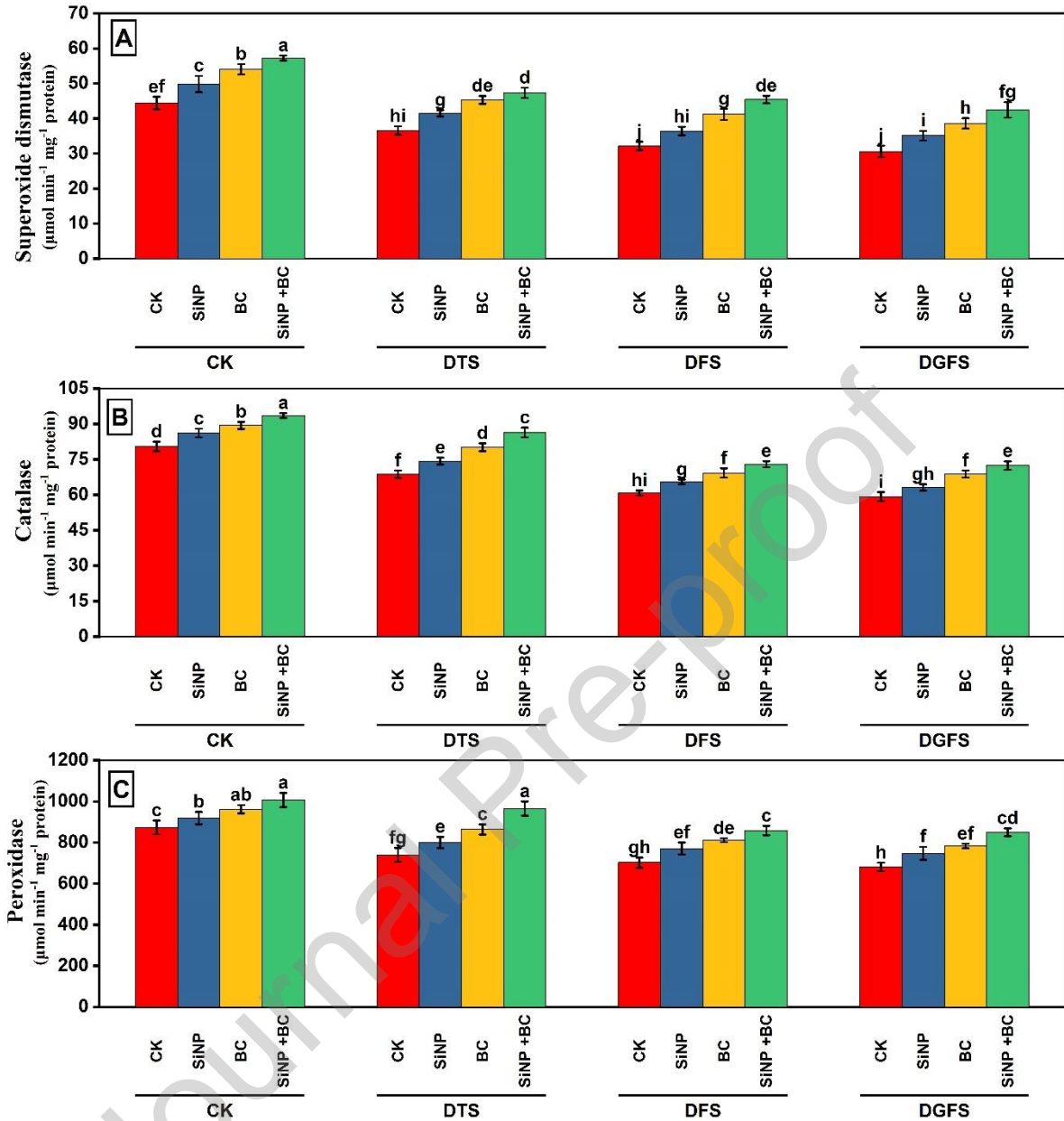
Activities of antioxidant enzymes and reactive oxygen species (ROS) were estimated for each treatment (SiNP, BC, and SiNP+BC) to monitor oxidative damage in wheat leaves, as seen in Figs. 4-5. Throughout all of the drought-imposed development phases, the uppermost EL level exhibited the CK treatments, while the SiNP+BC treatments exhibited the lowermost level. The SiNP+BC therapy reduced EL values by 22.5 % compared to the CK group. The SiNP alone (7.4 %) and BC alone (12.4 %) exhibited the greatest reductions in EL values (Fig.

4A). A similar pattern was seen for H<sub>2</sub>O<sub>2</sub> and MDA, showing that combined actions of SiNP and BC produced better outcomes. MDA contents were significantly diminished by 13.8 %, 23.5 %, and 36.3 %; and the H<sub>2</sub>O<sub>2</sub> was diminished by 10.3 %, 16.4 %, and 27.0 % in SiNP, BC, and SiNP+BC over the respective controls (Fig. 4B-4C).

To evaluate the activity of antioxidant enzymes under drought, the levels of SOD, POD, and CAT activities were evaluated in leaves (Fig. 5). When SiNP, BC, and SiNP+BC treatments were used in place of the control, the SOD activity (Fig. 5A) increased by 11.7 %, 19.82 %, and 25.3 %, respectively. A comparable pattern was seen for CAT and POD, showing that combined actions of SiNP and BC produced better outcomes. CAT contents were significantly enhanced by 6.9 %, 12.5 %, and 17.2 % (Fig. 5B); and the POD was enhanced by 7.4 %, 12.3 %, and 18.5 % in SiNP, BC, and SiNP+BC over the respective controls (Fig. 5C). The treatments greatly enhanced the antioxidant enzyme component, but the combined treatment of SiNP+BC showed the most notable.



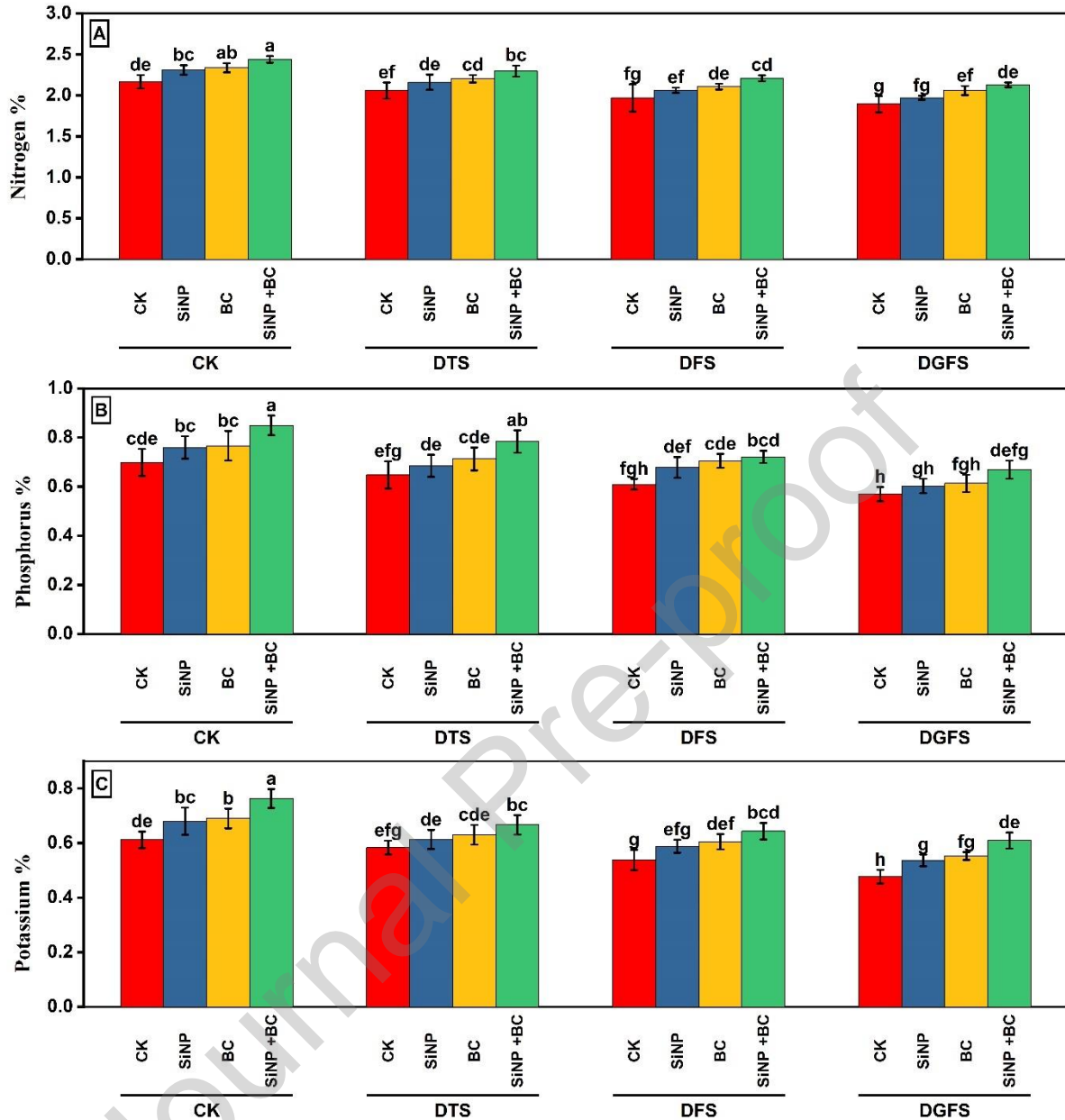
**Fig 4.**  $\text{H}_2\text{O}_2$  ( $\mu\text{M g}^{-1} \text{FW}$ ), EL (%), and MDA (%) are influenced by BC and SiNP treatments during drought stress. CK, DTS, DFS, and DGFS indicate control, and drought at tillering, flowering, and grain-filling stages, respectively. CK, SiNP, BC, and SiNP+BC indicate control, 5 % BC and 900 mg/L SiNP and 5 % BC + 900 mg/L SiNP. Error bars show a standard error (n = 3). Different letters indicate significant differences at 0.05 level as determined by LSD 0.05 test.



**Fig 5.** SOD ( $\mu\text{mol min}^{-1} \text{mg}^{-1} \text{protein}$ ), CAT ( $\mu\text{mol min}^{-1} \text{mg}^{-1} \text{protein}$ ), and POD ( $\mu\text{mol min}^{-1} \text{mg}^{-1} \text{protein}$ ) activities influenced by BC and SiNP treatments during drought stress. CK, DTS, DFS, and DGFS indicate control, and drought at tillering, flowering, and grain-filling stages, respectively. CK, SiNP, BC, and SiNP+BC indicate control, 5 % BC and 900 mg/L SiNP and 5 % BC + 900 mg/L SiNP. Error bars show a standard error (n = 3). Different letters indicate significant differences at 0.05 level as determined by LSD 0.05 test.

### 3.6. Impact on nutrient uptake attributions

Wheat plants treated with SiNP, BC, and SiNP+BC significantly enhanced the values of N, P, and K under drought at different growth stages as compared to CK (Fig. 6). 6.1 %, 10.8 %, and 14.9 % decrease in 'N' uptake were noted at DTS, DFS, and DGFS (Fig. 6A), while 'P' uptake dropped by 8.6 %, 13.2 %, and 25.1 % under drought stress related to the CK treatment (Fig. 6B). Additionally, a comparable pattern was observed in the 'K' percentage, which showed a significant decrease of 10.1 %, 15.6 %, and 26.2 % during water stress at DTS, DFS, and DGFS (Fig. 6C). Furthermore, the use of BC, SiNP, and SiNP+BC suggestively compact the influence of drought stress and increased N, P, and K levels by 4.8 %, 7.1 %, 10.8 % and 7.3 %, 9.7 %, 16.4 %, and 8.6 %, 10.8 %, 17.6 % in contrast to the CK, respectively. In drought conditions, SiNP and BC combined treatment produced better outcomes for N, P, and K when related to other treatments and controls.



**Fig 6.** Seed Nitrogen, Phosphorus, and Potassium are influenced by BC and SiNP treatments during drought stress. CK, DTS, DFS, and DGFS indicate control, and drought at tillering, flowering, and grain-filling stages, respectively. CK, SiNP, BC, and SiNP+BC indicate control, 5 % BC and 900 mg/L SiNP and 5 % BC + 900 mg/L SiNP. Error bars show a standard error ( $n = 3$ ). Different letters indicate significant differences at 0.05 level as determined by LSD 0.05 test.

### 3.7. Impact on soil attributes

The impact of treatments on SOC, DON, DOC,  $N_{MIN}$ , and SR was highest in soil under control without drought but was lowest under drought at DGFS without any treatment of BC and SiNP (Table 3). The SOC and DOC amounts were expanded by 13.5 %, 23.0 %, 25.6 %, and 5.6 %, 16.8 %, 27.6 % as compared to control with SiNP, BC, and, SiNP+BC treatments, respectively. A similar pattern was seen for DON,  $N_{MIN}$ , and SR, showing that combined actions of SiNP and BC produced better outcomes. DON contents were significantly enhanced by 5.6 %, 16.8 %, and 27.5 %; the  $N_{MIN}$  was enhanced by 3.8 %, 16.4 %, and 24.1 %; and the SR was enhanced by 8.2 %, 15.7 % and 24.6 % in SiNP, BC, and SiNP+BC over the respective controls. The treatments applied widely improved these parameters, and the greatest development was recorded in the combined application of BC and SiNP during both drought and control conditions.

**Table 3:** The impact of BC and SiNP during drought on soil organic carbon (SOC,  $g\ kg^{-1}$ ), dissolved organic carbon (DOC,  $\mu g\ g^{-1}$ ), dissolved organic nitrogen (DON,  $\mu g\ g^{-1}$ ), Nitrogen mineralization ( $N_{MIN}$ ), and soil respiration (SR).

Treatments		SOC	DOC	DON	$N_{MIN}$	SR
Drought	Nutrients	( $g\ kg^{-1}$ )	( $\mu g\ g^{-1}$ )	( $\mu g\ g^{-1}$ )		
CK	CK	1.21 c	138.33 d	18.28 cdef	59.67 d	20.25 defg
	SiNP	1.25 bc	141.13 c	19.21 bcde	62.36 c	22.47 bcd
	BC	1.38 a	144.53 b	21.77 b	69.47 b	24.53 b
	BC+SiNP	1.43 a	150.89 a	25.93 a	74.54 a	27.49 a
DTS	CK	1.02 d	120.53 jk	16.41 fghi	51.66 f	19.15 fghi
	SiNP	1.19 c	128.30 fg	16.80 efgh	53.64 ef	20.55 defg
	BC	1.34 ab	133.60 e	19.43 bcd	62.60 c	21.75 cde
	BC+SiNP	1.39 a	138.44 d	21.59 b	69.39 b	24.70 b
DFS	CK	0.97 d	117.44 l	14.44 hi	46.34 gh	17.34 hi
	SiNP	1.20 c	124.44 hi	15.58 ghi	48.14 g	19.10 fghi

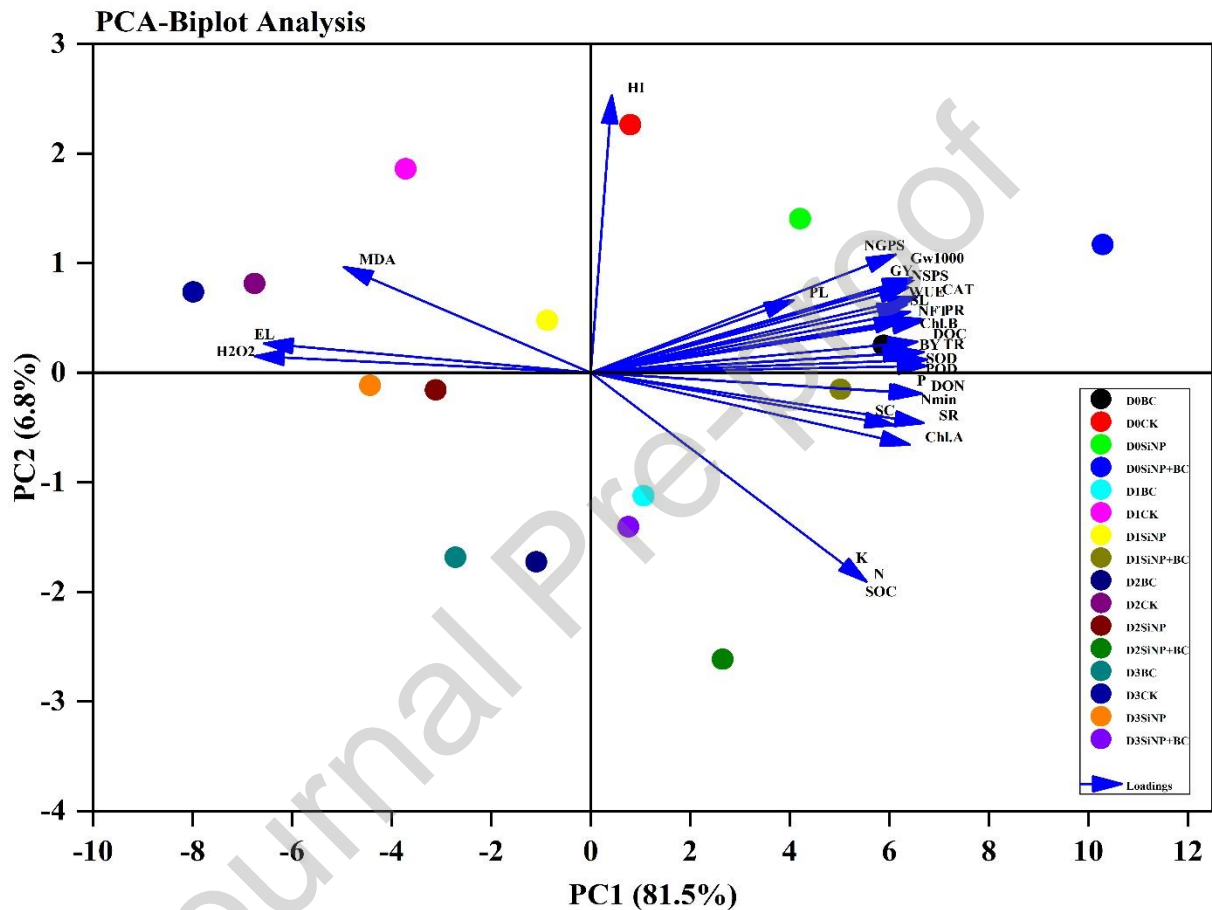
	<b>BC</b>	1.35 a	130.34 f	17.30 defg	55.37 e	21.47 cdef
	<b>BC+SiNP</b>	1.40 a	136.34 d	19.44 bcd	62.44 c	23.17 bc
	CK	0.96 d	118.40 kl	14.14 i	44.70 h	16.90 i
<b>DGFS</b>	<b>SiNP</b>	1.17 c	122.90 ij	15.46 ghi	46.30 gh	18.13 ghi
	<b>BC</b>	1.33 ab	126.90 gh	17.60 defg	54.70 e	19.64 efgh
	<b>BC+SiNP</b>	1.37 a	125.40 hi	20.40 bc	60.53 cd	22.42 bcd
<b>LSD</b>	<b>SiNP</b>	***	***	***	***	***
	<b>BC</b>	***	***	***	***	***
	<b>BC+SiNP</b>	NS	***	NS	NS	NS

Control, drought at tillering, flowering, and grain-filling phases are indicated by CK, DTS, DFS, and DGFS, in that order. Control, 5 % BC, 900 mg/L SiNP, and 5 % BC + 900 mg/L SiNP are indicated by the symbols CK, BC, SiNP, and SiNP+BC, respectively. At a 5 % probability level, means with the same letter case do not differ appreciably. where \*\*\* = significant at  $p \leq 0.001$  and NS non-significant at  $p \leq 0.05$  are indicated.

### 3.8. Principal component analysis and correlation matrix

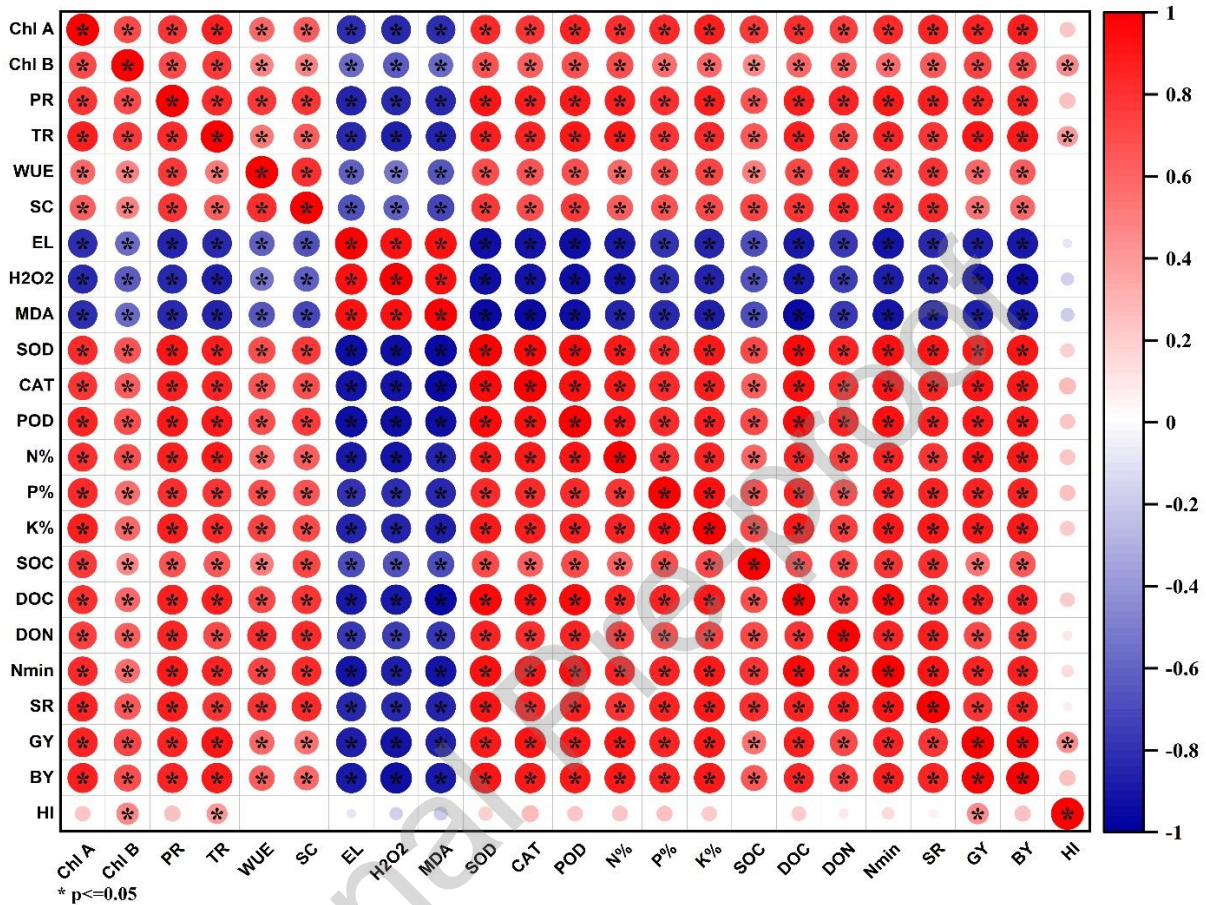
The degree of variation and associations between the different morpho-physiological parameters of wheat was assessed using principal component analysis (PCA) under the application of BC, SiNP, SiNP+BC, and drought stress (Fig. 7). The parameters were shown as vectors, and the treatments were scattered among many biplots. PC1 and PC2, the two PCA dimensions, worked together to explain about 88.3 % of the dataset variability among the 28 parameters. PC1 made up 81.5 % of the total, while PC2 only contributed 6.8 %. Variation was encountered. The impact patterns of each treatment on wheat plants were unique and easy to observe. All the studied parameters tended toward PC1, although we observed that the contents of EL, MDA, and H<sub>2</sub>O<sub>2</sub> contributed primarily to PC2. Fig. 8 shows the correlation matrix, which provided further validation for the PCA-biplot results. During different growth stages and treatments, wheat exhibited varying responses to drought stress in BC, SiNP, and

SiNP+BC treatments (CK, DTS, DFS, and DGFS). Between EL, MDA, and H<sub>2</sub>O<sub>2</sub>, the correlation matrix showed a significant positive association. The physiology of plants, oxidants, antioxidants, yield, and soil properties are all strongly correlated negatively with them simultaneously.



**Fig. 7.** Principal component analysis of BC and SiNP amendments during drought. PCA-biplot analysis illustrates how various traits and treatments interact. PH: plant height; SL: spike length; NSPS: number of spikelets per spike; NGPS: number of grains per spike; NFT: number of fertile tillers; GW1000: 1000-grain weight; GY: grain yield; BY: biological yield; HI: harvesting index; WUE: Water use efficiency; SC: stomatal conductance; Chl. A and Chl. B: Chlorophyll a and b; PR: Photosynthetic rate; TR: transpiration rate; H<sub>2</sub>O<sub>2</sub>: Hydrogen peroxide; EL: Electrolyte leakage; MDA: Malondialdehyde; SOD: Superoxide dismutase; CAT: Catalase; POD: Peroxidase; N: Nitrogen; P: Phosphorus; K: Potassium; SOC: Soil

organic C; DOC: Dissolved organic C; DON: Dissolved organic N; Nmin: Nitrogen mineralization; SR: Soil respiration.



**Fig. 8.** The correlation matrix displays the effects of treatments and drought on plant physiology, oxidants, antioxidants, yield, and soil nutrients during important growth stages of wheat. Dark blue and red circles indicate significantly positive and significantly negative associations, respectively.

#### 4. Discussion

Currently, the world population is facing significant challenges related to global climate change and food security. With the population continuing to grow and a limited amount of arable land available, there is a pressing need to address the threat of severe droughts and find ways to increase agricultural production to feed the entire population. The Galaxy-2013 wheat variety

demonstrated notable drought resilience (Wasaya et al., 2021), which aligns with our study observations of its stable physiological responses under water-limited conditions. In this study, our objective was to investigate the potential effects of BC, SiNP, and combined BC+SiNP treatments on soil properties during drought stress in semi-arid environments, as well as wheat yield throughout the three critical developmental stages.

#### 4.1. Impact of BC and SiNP on wheat growth

The application of NPs and BC for mitigating drought stress is gaining popularity (Forján et al., 2024; Mahmoud et al., 2022a). Various NPs and BC have been tested on wheat crops, separately and in combination, and have shown promising results under water deficit conditions (Raza et al., 2023b). Drought stress significantly decreased plant height in wheat throughout crucial development phases. Our findings are comparable with similar results published by Aown et al. (2012) and Zhao et al. (2006) in wheat and Brassica napus under water stress, respectively. The application of BC and SiNP during drought significantly increased wheat plant height as compared to the control. Plant height increased most significantly as a result of applying SiNP and BC together (Suppl. Table S1). Similar results were seen regarding the beneficial influence of BC and NPs on plant height in the rice and brassica crops (Hussain et al., 2008). These effects arise from their ability to enhance photosynthetic rate, soil microbial activity, and nutrient absorption (Ali et al., 2019; Haider et al., 2020; Rafi et al., 2022; Raza et al., 2021; Shahzad et al., 2018).

#### 4.2. Impact of BC and SiNP on wheat yield

SiNP and wheat straw BC both positively impact crop growth and yield (Table 3). Drought circumstances caused a reduction in several growth and yield metrics of wheat (Onyemaobi et al., 2021; Rashid et al., 2021). The negative impacts of drought on the aforementioned characteristics were ameliorated by the application of BC and SiNP. The

results of Haider et al. (2020) corroborate our findings, which showed that the application of BC enhanced wheat growth and yield in both drought-prone and controlled environments. Plant growth and development were improved by enhancing the soil structure brought forth by BC treatment (Boora et al., 2023; Cornelissen et al., 2013). Iqbal et al. (2019) reported that water-stressed conditions decreased plant metabolic activity, which in turn shortened spike length. Zaid Khan et al. (2021) stated that the use of BC increased spike length, and, ultimately, enhanced grain output by improving source-sink relationships and nutritional availability. Plant biomass is also increased due to enhanced photosynthetic activity following SiNP treatment (Gill et al., 2024; Mahmoud et al., 2022b). Following a prior study, we found that BC amended soil and significantly boosted plant biomass (Zulfiqar et al., 2022). Many studies revealed that the combined treatment of nanoparticles and BC enhances the yield of plants under abiotic stresses such as heavy metals, salinity, and water deficit conditions (Ali et al., 2019; Gill et al., 2024; Mahmoud et al., 2022a; Raza et al., 2023a). Soil treatment with NP-BC combinations boosted soil fertility and ryegrass biomass (Forján et al., 2024).

#### 4.3. Impact of BC and SiNP on gaseous exchange attributes

Wheat plants that had received treatment showed enhanced growth as a result of increased stomatal conductance and photosynthetic activity, which reduced moisture content during drought stress. When BC was added to soil together with SiNP, the cation exchange capacity and physicochemical properties increased, leading to an increase in photosynthetic and soil water efficiency (Hafez et al., 2021; Zarmeena Khan et al., 2021). Improved WUE, SC, chlorophyll pigments, and other gas exchange attributes were observed with the application of BC and NPs during drought (Fig. 2-4). Comparable findings have been described (Raza et al., 2023b, 2021; Zaheer et al., 2021), and increased chlorophyll concentration and photosynthetic activity are due to BC-alleviated drought effects (Ali et al., 2017). Numerous studies have shown evidence for the combined beneficial effects of BC and NPs on plant gasses

exchange attributes, either directly or indirectly. However, they promote the rate of photosynthesis in plants by increasing transpiration, stomata conductance, intercellular gas levels, and transpiration (Gholami et al., 2022; Mahmoud et al., 2022a; Vuković et al., 2022; Waqar et al., 2022). These results are consistent with research by Wahab et al. (2022), who observed enhanced levels of carotenoid, chlorophyll a and b in plants under drought stress.

#### 4.4. Impact of BC and SiNP on oxidative stress and antioxidants attributes

We also discovered that drought stress caused significant plant damage as seen by elevated MDA, H<sub>2</sub>O<sub>2</sub>, and EL levels whereas reduced SOD, POD, and CAT activities (Fig. 4-6). Drought stress modifies the composition of cell membranes, leading to changes in membrane permeability, integrity, and stability (Batool et al., 2022; Mega et al., 2019). Plants are capable of ROS detoxification, and for the best plant development, a balance between ROS and breakdown is needed (Ahanger et al., 2017). However, oxidative stress occurs in plants because they are unable to detoxify ROS, particularly under stressful situations (Rizwan et al., 2016). Plants have a defense mechanism of antioxidant enzymes to overcome drought-induced reactive oxygen species (ROS) accumulation (Ahanger et al., 2017; Dusenge et al., 2019). Rizwan et al. (2015) have demonstrated that oxidative stress affects several plant species as a result of water constraints. Zhang et al. (2022) found that BC increased plant stress tolerance by decreasing oxidative stress and increasing antioxidant enzyme activity. Park et al. (2023) discovered that BC enhances plant development during drought stress by lowering MDA levels and enhancing SOD, CAT, and POD activities. We discovered that using BC minimized the deleterious effects of drought on wheat, as evidenced by lower EL, H<sub>2</sub>O<sub>2</sub>, and MDA levels. Since these amendments enhanced plant metabolic processes, cell development, decreased ROS formation, and improved soil, plant, and water relations, they enhanced SOD, POD, and CAT activities (Khalili et al., 2020; Raheem et al., 2018; Zahedi et al., 2023). Moreover, many researchers studied that the collective treatments of BC with NPs give rise to maximal

antioxidant production (Rafi et al., 2022), confirming the efficacy of our treatments against drought stress.

#### 4.5. Impact of BC and SiNP on NPK

In comparison to soils that are continuously watered, exposure to drought dramatically reduced the concentrations of nutrients (N, P, and K) in the field. Reduced soil water content during drought inhibits microbial activity which slows the breakdown of organic materials. In contrast to soil with an ideal water content of  $-0.078$  MPa, Marschner et al. (2015) discovered that soil respiration and phosphorus pools were reduced in low water content soil ( $-1.700$  MPa). Increased soil nutrient content in soils that get continuous irrigation may indicate that soil bacteria are involved in the breakdown of soil organic matter, which leads to nutrient mineralization. Comparing BC amendment to unamended soils improved the concentrations of soil nutrients in both drought-exposed and continuously watered soils. Comparable outcomes were seen by Karimi et al. (2020). According to our results, under combined application of BC+SiNP, the percentage of N, P, and K is the highest by 10.8 %, 16.4 %, and 17.6 %, respectively, as compared to the control treatment. Many studies elaborated on BC-nanoparticles combined application has a better result than individual application (Rahimi-Moghaddam et al., 2023; Tourajzadeh et al., 2024) which is in line with our findings.

#### 4.6. Impact of BC and SiNP on drought resistance in soil physiology

Drought stress reduces big macroaggregates in the SOC pool, affecting soil stability. Carbon metabolism is largely dependent on soil moisture (Liu et al., 2022). Water stress reduces DOC, SOC, and DON levels, which are related to soil moisture availability. Ritson et al. (2017) discovered that water stress increased DOC production from peatland. According to Védère et al. (2023), the majority of BC contains carbon, hence adding it to soil improves SOC and DOC. According to Li et al. (2022), BC improves soil organic matter and microbial

activity, leading to higher DON. According to Rhymes et al. (2024), soil moisture availability has an impact on nitrogen mineralization. Drought causes a lag between mineralization and plant absorption of nitrogen, leading to increased nitrogen loss (Ali et al., 2017). Soil additions that increase organic matter can help reduce nitrogen loss (Seyedsadr et al., 2022). BC improves soil organic matter and reduces nitrogen loss, leading to improved nitrogen mineralization (Šimanský et al., 2016). The application of BC and NPs enhances the physiochemical characteristics of the soil, its ability to exchange cations, hold onto water and nutrients, and lessens the effects of drought, all of which benefit metabolic processes, biomass production, wheat development, and yield (Manolikaki and Diamadopoulos, 2019; Rea et al., 2022). These results were in line with those of earlier research (Abideen et al., 2022; Bashir et al., 2021; Elshayb et al., 2022; Forján et al., 2024).

## 5. Conclusion

Our study unveiled the significant benefits of soil application of BC and seed priming with SiNP in enhancing soil quality, promoting wheat growth, and alleviating water stress during drought conditions. SiNP seed priming particularly stands out for its ability to boost wheat biomass, plant height, and yield. Additionally, BC proves effective in improving soil properties, enhancing wheat yield, and mitigating drought effects. Moreover, SiNP seed priming enhances enzyme activities, leading to reduced concentrations of ROS in wheat leaves. This indicates that SiNP seed priming holds promise for improving wheat resilience under both normal irrigation and drought stress. Furthermore, the detrimental impact of drought stress on wheat crop growth and yield is notable. However, soil BC application effectively mitigates these effects by enhancing soil fertility, water, and nutrient retention, and optimizing crop source-sink relationships. BC treatment not only recovers wheat growth and physiological parameters but also boosts yield under both normal and stressful circumstances. Particularly, the grain-filling stage emerges as highly sensitive to drought, making BC treatment a valuable

strategy for countering its negative effects on wheat. The combined application of BC and SiNP significantly enhances antioxidant activities, and gas exchange attributes, and minimizes water stress in wheat plants. This finding underscores the potential of synergistic BC and SiNP application in vindicating the adversative impacts of drought, promoting wheat productivity, and enhancing soil health and resilience. However, further investigations are warranted to gain deeper insights into how BC and nanoparticles initiate these beneficial impacts under drought and other abiotic stresses in wheat.

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### **Credit authorship contribution statement**

**Bilal Zulfiqar:** Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization, Resources, Software. **Muhammad Aown Sammar Raza:** Writing – review & editing, Supervision, Investigation, Project administration. **Muhammad Akhtar:** Writing – review & editing, Software. **Zhang Nan:** Writing – review & editing. **Mamooona Hussain:** Writing – review & editing, Visualization. **Junaid Ahmaad:** Writing – review & editing, Resources, Software. **Mostafa A. Abdel-Maksoud:** Writing – review & editing, Funding acquisition. **Hossam Ebaid:** Writing – review & editing, Funding acquisition. **Rashid Iqbal:** Writing – original draft, Investigation, Formal analysis, Visualization. **Muhammad Usman Aslam:** Supervision, Investigation, Validation, Methodology. **Mohamed A. El-Tayeb:** Writing – review & editing. **Shiming Su:** Writing – original draft, review & editing, Resources, Software, Methodology.

**Declaration of Interest Statement:** The authors declare that there is no conflict of interest.

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**Author Statement**

The authors declare that there is no conflict of interest.

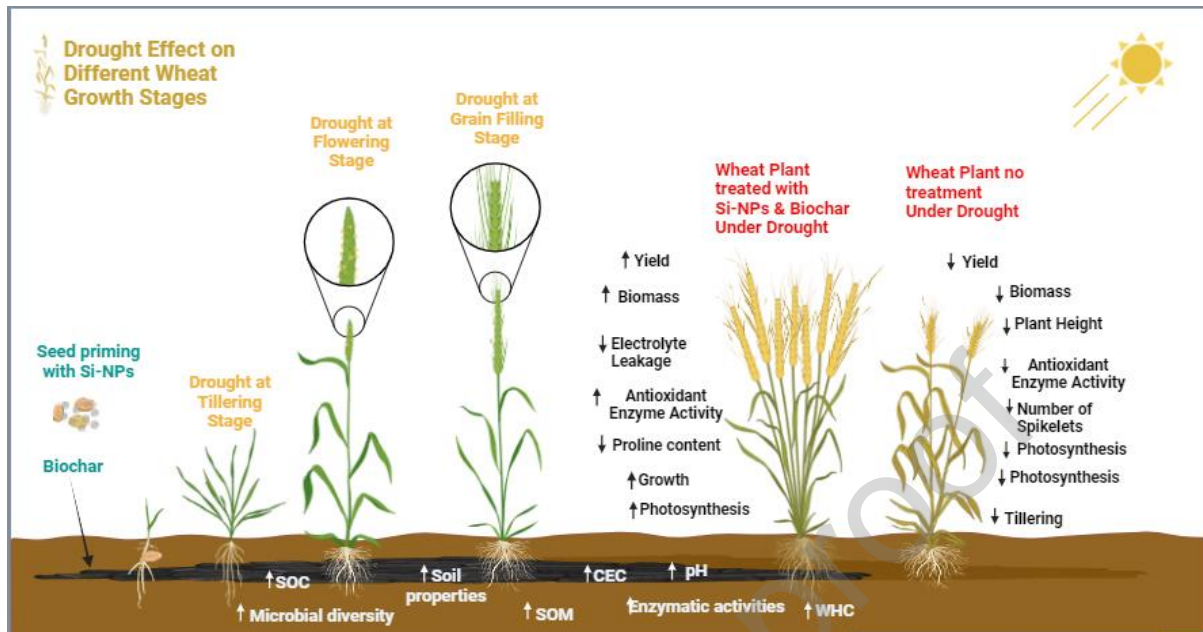
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**Declaration of Interest Statement:**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Graphical abstract



**Highlights**

- Combined biochar and silicon nanoparticles improved the soil properties and wheat drought resistance.
- Biochar plays a significant role in enhancing soil fertility, including organic carbon, nitrogen, and mineral content.
- Co-application of biochar and silicon nanoparticles induces enhanced tolerance in wheat and increased yield in field experiments.
- Biochar revealed a better impact than silicon nanoparticles in semi-arid climates.