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ORIGINAL PAPER

# Soil and foliar applications of zinc sulfate and iron sulfate alleviate the destructive impacts of drought stress in wheat

**Md. Abdul Mannan**[1] · **Mahmuda Akter Tithi**[1] · **M. Rafiqul Islam**[1] · **Md. Abdullah Al Mamun**[1] · **Shamim Mia**[2] · **Md. Zillur Rahman**[3] · **Mohamed F. Awad**[4] · **Abdelaleim I. ElSayed**[5] · **Elsayed Mansour**[6] · **Md. Sazzad Hossain**[3]

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## Abstract

Water deficit is a major abiotic stress that devastatingly affects wheat growth and production, particularly in arid environments. Moreover, drought is expected to become more frequent and severe owing to current climate change. Consequently, it is necessary to find affordable approaches to enhance drought tolerance, principally for important crops such as wheat. The present study is a controlled pot experiment which was performed to investigate the efficiency of soil application or exogenous foliar of zinc sulfate ($ZnSO_4 \cdot 7H_2O$) or/and iron sulfate ($FeSO_4 \cdot 7H_2O$) to attenuate the deleterious impacts of drought stress in winter wheat. The plants were exposed to water deficit (40% field capacity) versus well-watered conditions (80% field capacity). Drought stress significantly declined relative water content and leaf chlorophyll content while increased proline accumulation, water saturation deficit, and water uptake capacity relative to well-watered conditions. Moreover, leaf characters (number and area) significantly diminished as a result of water deficit. The detrimental impacts on physiological and morphological attributes reflected a considerable reduction in grain yield and all contributed traits. However, the soil- and foliar-applied zinc sulfate or/and iron sulfate significantly enhanced all aforementioned depressed parameters which reflected markedly in enhancing yield traits under drought stress. Among the investigated treatments, the exogenous foliar applications were more effective in promoting drought tolerance particularly combined both micronutrients which can be employed in reducing the losses caused by drought stress in wheat-growing regions.

**Keywords** Micronutrients · Physiology parameters · Morphological traits · Agronomic traits · Drought tolerance · Wheat · Principal component analysis

## Introduction

Wheat (*Triticum aestivum* L.) is one of the most important food crops worldwide (Shewry and Hey 2015). Its total cultivated area is almost 215 million hectares which produce about 765 million tons annually (FAOSTAT 2021). There is a growing demand for wheat as a consequence of continuing population growth (Chowdhury et al. 2021). Notwithstanding, its growth and production are constrained by current extreme climatic events particularly in arid environments (Obembe et al. 2021). The shift in global climate has been causing considerable temperature rise and fluctuations in precipitation. Accordingly, climate change contributes to drought stress and it is projected to become more frequent and severe (Kim et al. 2020; Mansour et al. 2021a). Water deficiency is a major environmental stress that destructively impacts wheat growth and production, particularly in arid

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✉ Elsayed Mansour
sayed_mansour_84@yahoo.es

[1] Department of Agronomy, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur 1706, Bangladesh

[2] Department of Agronomy, Patuakhali Science and Technology University, Patuakhali, Bangladesh

[3] Department of Agronomy and Haor Agriculture, Sylhet Agricultural University, Sylhet 3100, Bangladesh

[4] Department of Biology, College of Science, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia

[5] Biochemistry Department, Faculty of Agriculture, Zagazig University, Zagazig 44511, Egypt

[6] Department of Crop Science, Faculty of Agriculture, Zagazig University, Zagazig 44519, Egypt

regions. Arguably, it causes yield losses of up to 50% (Zhang et al. 2018; Attia et al. 2021).

The plants grown under drought stress are imposed to several physiological and biochemical alterations including reduction leaf water status, $CO_2$ assimilation, and gas exchange rates (Farooq et al. 2017; Desoky et al. 2020). In addition, water deficit lowers stomatal conductance and, in turn, raises leaf temperature and leaf wilting (Sehgal et al. 2017; El-Mageed et al. 2021). Further consequence of drought stress is disturbing cell membrane permeability and synthesis of photosynthetic pigments (Awasthi et al. 2014; Mansour et al. 2021b). Moreover, reactive oxygen species (ROS) are induced under water scarcity and lead to oxidative injury and destructively impact the biosynthesis of proteins, sugars, lipids, nucleic acids, and other molecules (Hasanuzzaman et al. 2020; Zulfiqar and Ashraf 2021). These negative impacts destructively reflect on plant growth, production, and quality. However, the plants have tolerance mechanisms and complex responses to modulate drought-induced impacts by activating the antioxidant defense system to detoxify ROS (Jubany-Marí et al. 2010; Desoky et al. 2021a). Proline is an important non-enzymatic antioxidant that has a crucial role in the detoxification of ROS produced due to water scarcity. Furthermore, it enhances plant antioxidant systems and boosts their survival under water shortage (Desoky et al. 2021b). Accordingly, it has a decisive role in the osmotic adjustment under water deficit and enhancing drought tolerance.

Several research studies detected efficient and economic strategies of biofortification to attenuate the adversative impacts of drought stress in field crops (El-Sanatawy et al. 2021a; Zulfiqar et al. 2021). One of these promising approaches is the application of mineral nutrients to ensure the sustainable production of field crops. The role of mineral nutrients on plant development and growth is well explained, specifically zinc (Zn) and iron (Fe) (Baghizadeh and Shahbazi 2013; Hera et al. 2018). Several published reports disclosed the positive impact of Zn and Fe under drought stress on different field crops (Weisany et al. 2011; Umair et al. 2020). Zinc is an irreplaceable micronutrient for plant growth and plays an integral role as a structural, functional, and regulatory co-factor of various enzymes (Ma et al. 2017). Moreover, it is vital in several biomolecules like proteins and lipids; hence, it has an essential role in nucleic acid metabolism (Tsonev and Cebola Lidon, 2012). Besides, it is a vital multi-enzyme activator and participates directly in the biosynthesis of growth regulators as auxin (Umair et al. 2020). Likewise, iron plays a pivotal role in plant growth due to its essential functions in the physio-biochemical processes (Kim and Guerinot, 2007; Tripathi et al. 2018). Besides, it plays a crucial role in chlorophyll biosynthesis and the regulation of different enzyme functions (Khobra et al. 2014). Additionally, it fundamentally reinforces the activities of catalase and peroxidase, which are integral in antioxidant defense mechanisms (Kumar et al. 2010). Otherwise, the physiological role of foliar and soil applications of Zn and Fe in enhancing drought tolerance in wheat plants remains lacking (Weisany et al. 2011; Umair et al. 2020). Accordingly, the present study aimed at investigating the effectiveness of foliar application and soil application of zinc sulfate ($ZnSO_4{\cdot}7H_2O$) and/or iron sulfate ($FeSO_4{\cdot}7H_2O$) on physiological, morphological, and agronomic traits of wheat under water deficit conditions.

## Materials and methods

### Experimental treatments and growth conditions

A pot experiment was performed under controlled environment in greenhouse conditions at the Department of Agronomy, Bangabandhu Sheikh Mujibur Rahman Agricultural University (BSMRAU), Gazipur, Bangladesh (24° 5′ 23" N and 90° 15′ 36" E), during 2018–2019. The day and night temperatures were $28.5 \pm 1.6$ and $13.6 \pm 1.3$ °C, respectively. This experiment was performed in plastic pots (30 cm depth and 25 cm in diameter); each one was filled with 11 kg of soil. The used soil was sandy loam throughout the profile (54.21% sand, 34.60% silt, and 11.19% clay), with a field capacity of 28% and pH 6.93. The soil organic carbon, available P, total N, exchangeable K, CEC, and EC were 0.61%, 0.06 mg 100 $g^{-1}$, 0.07%, 0.79 cmolc $kg^{-1}$ dry soil, 13.05 cmolc $kg^{-1}$ dry soil and 0.04 $dSm^{-1}$, in the same order.

Winter wheat cv. BARI Gom-29 was utilized in the present study. Ten seeds were sown in each pot and well-watered to ascertain uniform germination. After full emergence, thinning was performed to keep three healthy seedlings in each pot. Each pot was fertilized with 0.9, 0.8, and 0.8 g (equivalent to 160–150-150) of urea, triple superphosphate, and potassium chloride to standard fertilization.

Moisture level in the pots was determined daily utilizing a portable digital moisture meter (POGO Soil Sensor II, Stevens, USA). The required water amount was applied daily to reach 80% of field capacity in five pots as a control (well-watered, WW) while thirty-five pots were subjected to water deficit conditions by maintaining field capacity at 40% throughout the growing season. The drought-stressed pots were treated with two compounds; zinc sulfate ($ZnSO_4{\cdot}7H_2O$) and/or iron sulfate ($FeSO_4{\cdot}7H_2O$) versus untreated plants (DS). Zinc sulfate and iron sulfate were applied at a rate of 11 mg/kg soil; hence, each compound was performed at a rate of 121 mg/pot. Both compounds were purchased from Merck KgaA, Darmstadt, Germany.

The utilized compounds were applied in the soil prior to sowing or as a foliar spray two weeks after the beginning of drought stress as described in Table 1. The experiment was

**Table 1** Applications of zinc sulfate ($ZnSO_4 \cdot 7H_2O$) and iron sulfate ($Fe_3SO_4 \cdot 7H_2O$) under water deficit conditions

| Treatment code | Treatment description |
|---|---|
| DS | Untreated |
| Zn-Soil | Treated in soil by zinc sulfate at a rate of 11 mg/kg soil |
| Fe-Soil | Treated in soil by iron sulfate at a rate of 11 mg/kg soil |
| (Zn+Fe)-Soil | Treated in soil by zinc sulfate+iron sulfate at rates of 11 mg/kg soil for both compounds |
| Zn-Foliar | Exogenously treated by zinc sulfate at a rate of 5 g/100 mL water (5%) as a foliar spray |
| Fe-Foliar | Exogenously treated by iron sulfate at a rate of 5 g/100 mL water (5%) as a foliar spray |
| (Zn+Fe)-Foliar | Exogenously treated by zinc sulfate+iron sulfate at rates of 5 g/100 mL water (5%) foliar spray for both compounds |

performed using completely randomized design (CRD) with five replicates.

## Estimation of chlorophyll and proline contents

Fully expanded uppermost leaf samples were collected at flowering and chlorophyll content was estimated according to the methods of Witham et al. (1971). The fresh leaf sample of 20-mg was collected in small vials including 20-ml of 80% acetone and covered with aluminum foil, and then preserved in the dark for 72 h. Thereafter, the reading was performed at 663- and 645-nm wavelengths by a double beam spectrophotometer (Model 200–20) and the findings were expressed as mg/g fresh weight.

## Measurement of water status

Leaf relative water content (RWC), water saturation deficit (WSD), and water uptake capacity (WUC) were measured in wheat leaves at flowering. For measuring water status parameters (RWC, WSD, and WUC), fully expanded uppermost leaf samples were collected and freshly weighted directly. Then, the leaves were soaked in distilled water for 24 h in the dark at room temperature. These leaves were weighed to obtain the saturated (turgid) weight after excess water was removed by lightly wiping the leaves using a paper towel. The leaves were dried later in an oven for 48 h at 72 °C to measure their dry weight. The values of the fresh (FW), turgid (TW), and dry (DW) weights of the leaves were employed to estimate RWC, WSD, and WUC following the formulas of Schonfeld et al. (1988):

$$\text{RWC (\% )} = \frac{\text{FW - DW}}{\text{TW - DW}} \times 100,\ \text{WSD} = \frac{\text{TW - FW}}{\text{TW - DW}} \times 100,\ \text{WUC} = \frac{\text{TW - FW}}{\text{DW}}$$

Proline extractions were performed applying the method of Bates et al. (1973). Plant materials (0.5 g leaf sample) were mixed in 10 ml of 3% aqueous sulfosalicylic acid and the homogenate filtrate using Whatman filter paper (grade 42). Two ml of filtrate was reacted with 2 ml acid ninhydrin and 2 ml of glacial acetic acid in a test tube for 1 h at 100 °C, and the reaction ended in an ice bath. The reaction mixture was obtained using 4 ml toluene, mixed strongly using a test tube stirrer for 15–20 s. The chromophore including toluene was extracted from the aqueous phase, heated up to room temperature and the absorbance read at 520-nm by toluene blank. The proline concentration was identified from a standard curve and determined on a fresh weight basis as follows: Proline content ($\mu$ mol $g^{-1}$ FW) = [($\mu$ g proline $ml^{-1} \times$ ml toluene)/115.5 $\mu$ g $mole^{-1}$].

## Growth and agronomic traits measurements

Growth-related parameters, number of leaves and leaf area were determined at flowering, while, at physiological maturity, grain yield and its contributing traits were recorded. Data were recorded on spike length (cm), number of spike plant$^{-1}$, 1000-grain weight (g), grain yield plant$^{-1}$ (g), and biological yield plant$^{-1}$ (g).

## Statistical analysis

The recorded data underwent an analysis of variance (ANOVA) using R statistical software version 4.4.1. All treatments were compared using Tukey's HSD test at 1% level of significance. In addition, the principal components analysis biplot was applied to investigate the interrelationship among studied treatments and evaluated traits.

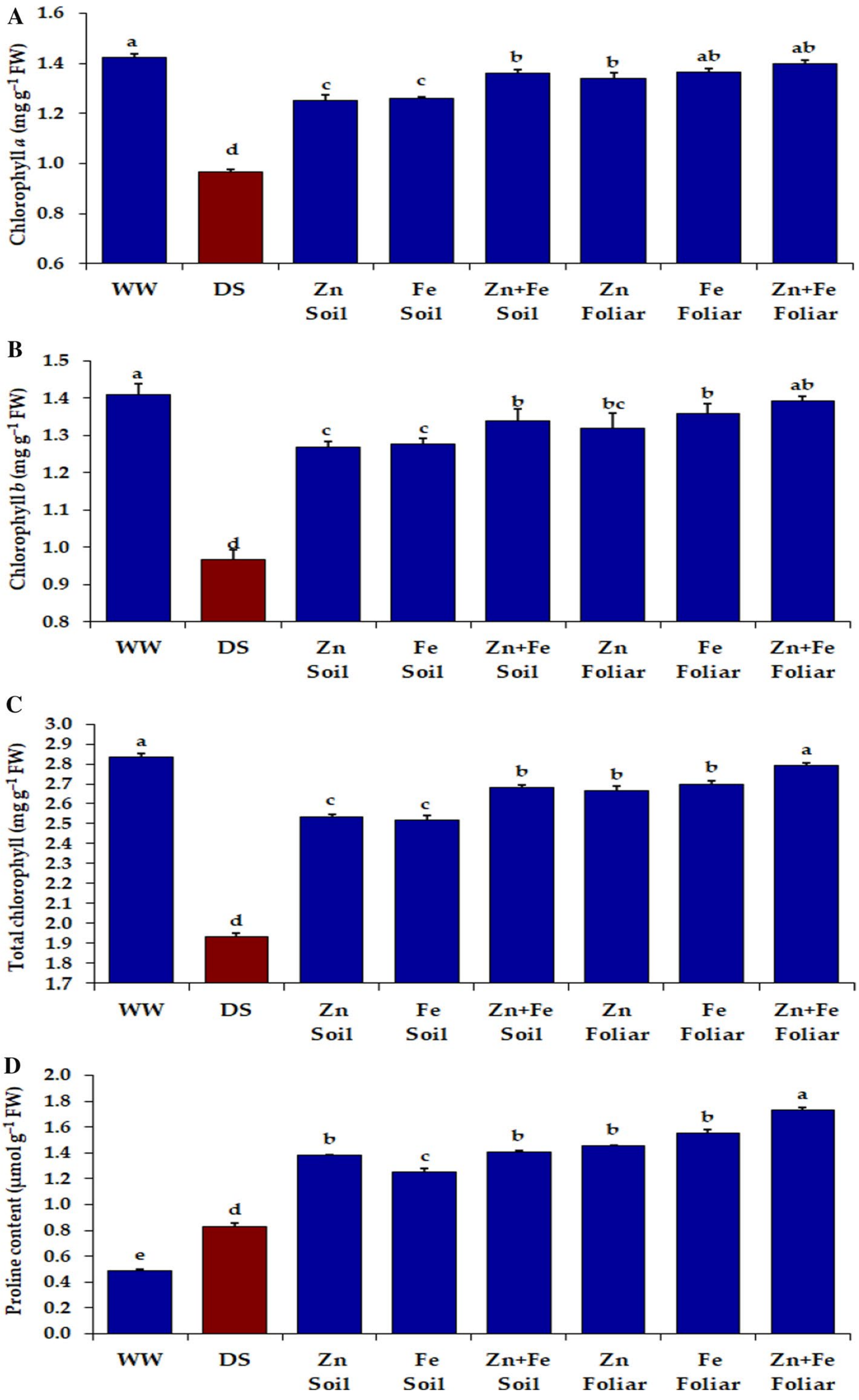

**Fig. 1** Impact of zinc sulfate and iron sulfate on **a** content of chlorophyll *a*, **b** content of chlorophyll *b*, **c** total chlorophyll content, and **d** proline content of wheat under water deficit conditions. The bars on the columns represent SE, and distinct letters differ significantly by Tukey's HSD ($p < 0.01$)

## Results

### Physiological traits

Drought stress significantly decreased the content of chlorophyll *a*, chlorophyll *b*, and total chlorophyll in wheat leaves by 32.1, 31.5, and 31.8% compared to well-watered plants (Fig. 1a–c). On the other hand, the soil and exogenous applications of zinc sulfate and/or iron sulfate alleviated the devastating impacts of water deficit and increased chlorophyll content under drought stress. Apparently, the highest values of chlorophyll content were obtained by combined exogenous foliar of both micronutrients. This application enhanced chlorophyll *a* by 44.4%, chlorophyll *b* by 44.2%, and total chlorophyll by 44.3% relative to untreated plants under drought stress. Furthermore, the exogenous foliar of iron sulfate elevated the three aforementioned parameters by 41.0, 40.8, and 39.7% in the same order. Besides, soil application of both zinc sulfate and iron sulfate increased the three parameters by 40.6, 38.7, and 38.6%, respectively.

Water deficit substantially increased proline content in stressed wheat plants by 70.2% compared to well-watered ones (Fig. 1d). The soil application and exogenous foliar of both compounds increased proline content in wheat leaves under water deficit conditions compared with untreated plants under drought stress. The highest proline content was assigned for exogenous foliar of both compounds and increased proline content by 98.6% compared to untreated plants under drought stress followed by exogenous foliar of iron sulfate solely (81.7%) and exogenous foliar of zinc sulfate (74.1%).

Drought stress considerably declined relative water content (RWC) by 21.2% compared to well-watered conditions (Fig. 2a). The soil- and foliar-applied zinc sulfate and/or iron sulfate promoted RWC, with superiority of exogenous foliar of both microelements. This combined foliar application

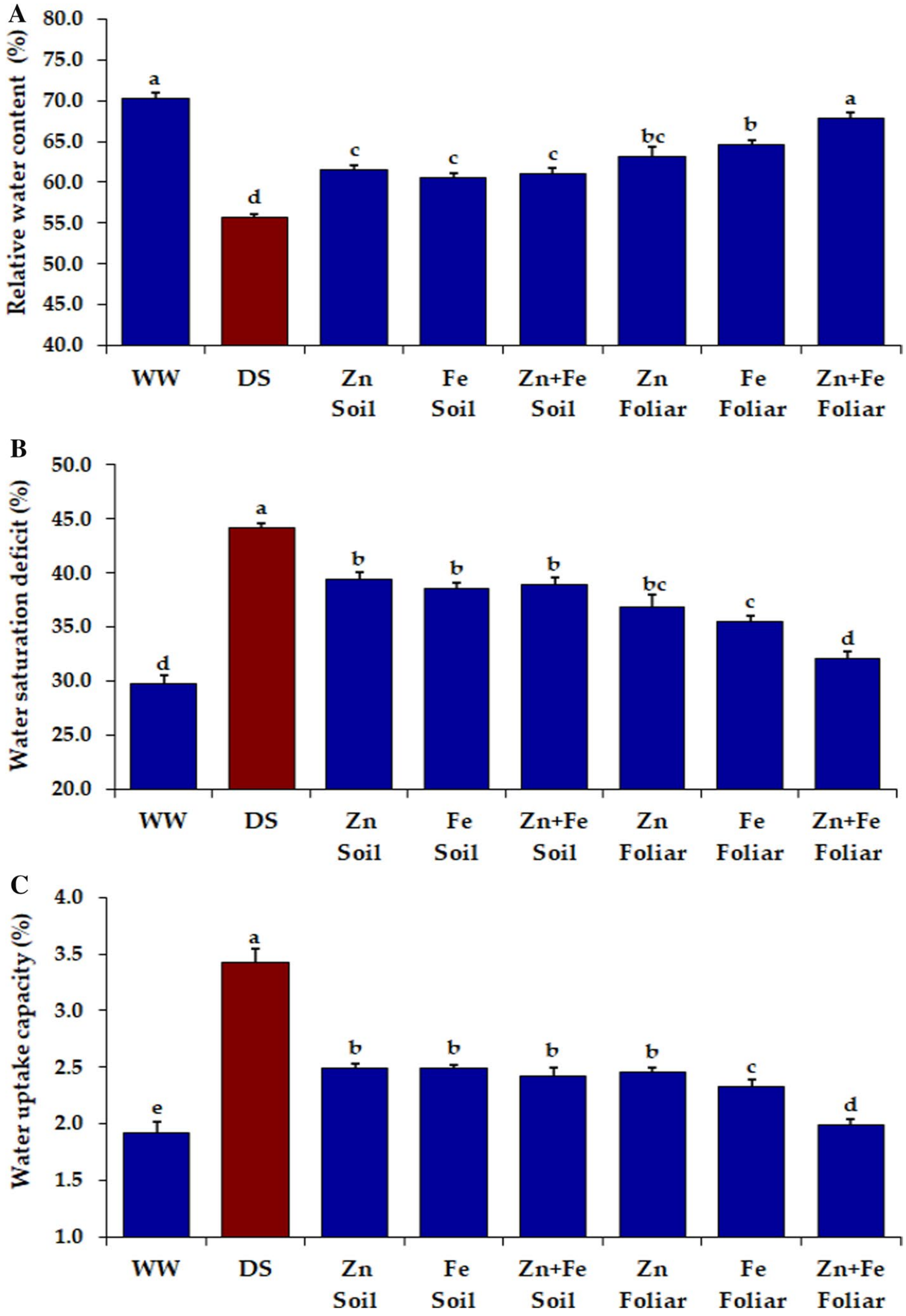

**Fig. 2** Impact of zinc sulfate and iron sulfate on **a** relative water content, **b** water saturation deficit, and **c** water uptake capacity of wheat under water deficit conditions. The bars on the columns represent SE, and distinct letters differ significantly by Tukey's HSD ($p < 0.01$)

ameliorated RWC by 21.7% followed by foliar application of iron sulfate which enriched RWC by 15.7% and zinc sulfate by 13.3% compared with untreated plants under drought stress. In contrast, water deficit significantly increased water saturation deficit (WSD) and water uptake capacity (WUC) in stressed plants by 48.5 and 78.4%, respectively relative to well-watered plants (Fig. 2b and c). However, the soil and foliar applications of used micronutrients significantly improved the plant water status under drought conditions. Drought stress-related increase in WSD and WUC considerably was declined by 27.4 and 41.9%, respectively, using the foliar spray of combined both compounds. Moreover, the applied-foliar of iron sulfate solely boosted WSD and WUC 19.8 and 31.7%, respectively, compared to untreated plants. Additionally, the foliar application of zinc sulfate improved WSD and WUC by 16.8 and 28.3%, respectively.

## Leaf characters

Drought stress considerably decreased the number of leaves per plant and leaf area by 51.1% and 35.9 relative to well-watered plants, respectively (Fig. 3a and b). The soil- and foliar-applied zinc sulfate and iron sulfate elevated the number of leaves and leaf area under drought stress. The exogenous foliar of combined both compounds exhibited the highest number of leaves per plant and leaf area under drought stress. Compared with untreated plants, the exogenous foliar application of both elements boosted number of leaves per plant and leaf area under drought stress by 71.4 and 38.6%, respectively. In addition, the exogenous foliar of iron sulfate considerably elevated number of leaves per plant and leaf area by 63.1 and 26.0% compared to untreated plants under water deficit conditions. Moreover, exogenous foliar of zinc sulfate increased number of leaves per plant and leaf area by 63.0 and 20.9%, respectively, relative to untreated plants under drought stress.

## Yield and yield attributes

Spike length, number of spikes plant$^{-1}$, and 1000-grain weight reduced significantly under drought stress by 19.1, 59.2, and 23.1%, respectively, compared to well-watered conditions (Table 2). The soil or foliar applications of both microelements solely or in combination appreciably alleviated the adverse impacts of drought stress and enhanced all yield attributes. The exogenous foliar of combined both

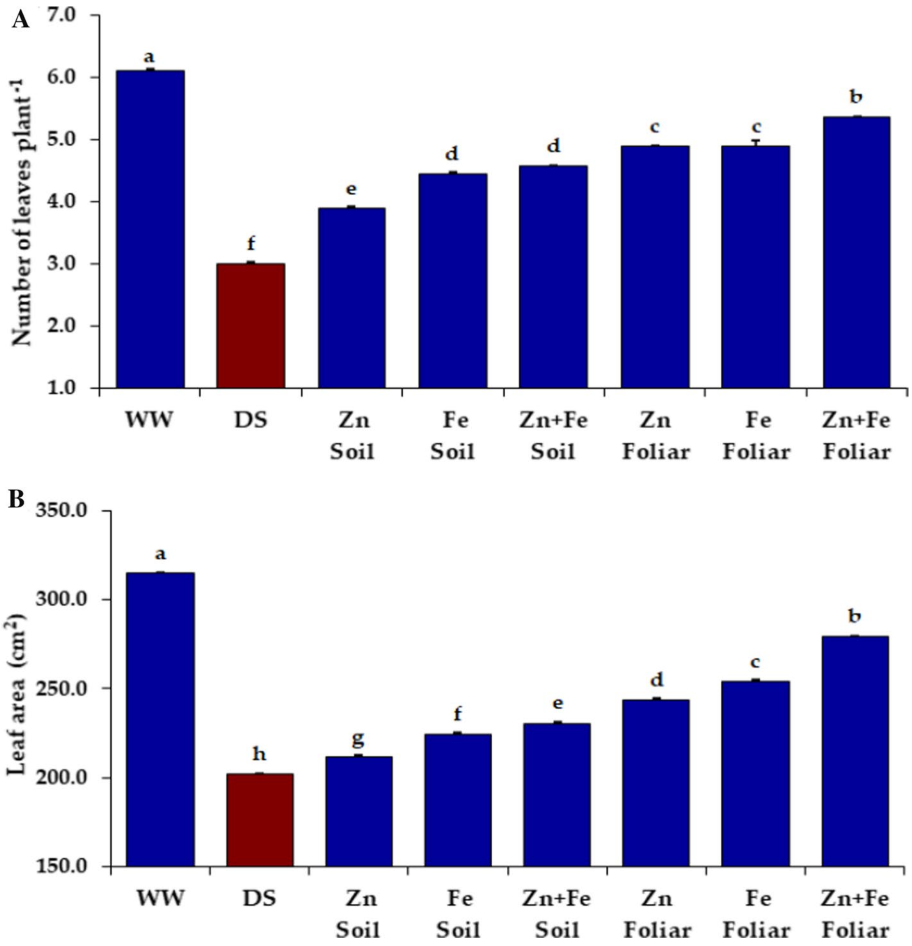

**Fig. 3** Impact of zinc sulfate and iron sulfate on **a** number of leaves plant$^{-1}$ and **b** leaf area of wheat under water deficit conditions. The bars on the columns represent SE, and distinct letters differ significantly by Tukey's HSD ($p < 0.01$)

**Table 2** impact of zinc sulfate and iron sulfate on wheat grain yield and its contributing traits under water-deficit conditions

| Treatment | Spike length (cm) | Number of spike plant$^{-1}$ | 1000-grain weight (g) | Grain yield plant$^{-1}$ (g) | Biological yield plant$^{-1}$ (g) |
|---|---|---|---|---|---|
| WW | 11.14$^{a}$ | 3.42$^{a}$ | 54.10$^{a}$ | 35.89$^{a}$ | 56.10$^{a}$ |
| DS | 9.01$^{e}$ | 1.39$^{f}$ | 41.63 g | 10.85$^{c}$ | 17.55$^{e}$ |
| Zn-Soil | 9.75$^{d}$ | 1.76$^{e}$ | 43.53$^{f}$ | 11.13$^{c}$ | 18.25$^{de}$ |
| Fe-Soil | 9.82$^{d}$ | 1.89$^{de}$ | 44.93$^{e}$ | 11.28$^{c}$ | 18.61$^{de}$ |
| (Zn + Fe)Soil | 9.87$^{cd}$ | 2.03$^{cd}$ | 46.80$^{d}$ | 11.29$^{c}$ | 18.86$^{d}$ |
| Zn-Foliar | 10.01 cd | 2.06$^{c}$ | 48.37$^{c}$ | 14.97$^{b}$ | 23.26$^{c}$ |
| Fe-Foliar | 10.18$^{c}$ | 2.14$^{c}$ | 49.17$^{c}$ | 15.06$^{b}$ | 23.54$^{c}$ |
| (Zn + Fe)Foliar | 10.53$^{b}$ | 2.45$^{b}$ | 51.60$^{b}$ | 16.09$^{b}$ | 25.21$^{b}$ |

Means followed by distinct letters differ significantly by Tukey's HSD at $p < 0.01$

nutrients exhibited the highest values of spike length, number of spikes plant$^{-1}$, and grain index under drought stress by improving the three attributes by 16.9, 66.3, and 24.0%, respectively, compared to untreated plants. Likewise, the exogenous foliar of iron sulfate elevated the three traits by 13.0, 51.9, and 18.1% in the same order compared to untreated plants under drought stress. Additionally, the foliar application of zinc sulfate promoted the yield attributed by 11.1, 48.2, and 16.2%, respectively, compared to untreated plants under drought stress.

Grain yield and biological yield per plant were destructively impacted by drought stress and reduced by 69.8 and 68.7%, respectively, compared to well-watered conditions (Table 2). The soil application and exogenous foliar of zinc sulfate and/or iron sulfate considerably attenuated the devastating impacts of water deficit conditions and enhanced grain yield and biological yield. Exogenous foliar of combined elements followed by exogenous foliar of iron sulfate and exogenous foliar of zinc sulfate exhibited the highest enhancement of grain yield under drought by 48.3, 38.8, and 38.0% in the same order relative to untreated drought-stressed plants. Likewise, the aforementioned three treatments displayed the highest biological yield under drought with 43.7, 34.1, and 32.5% increase compared to untreated plants under drought stress.

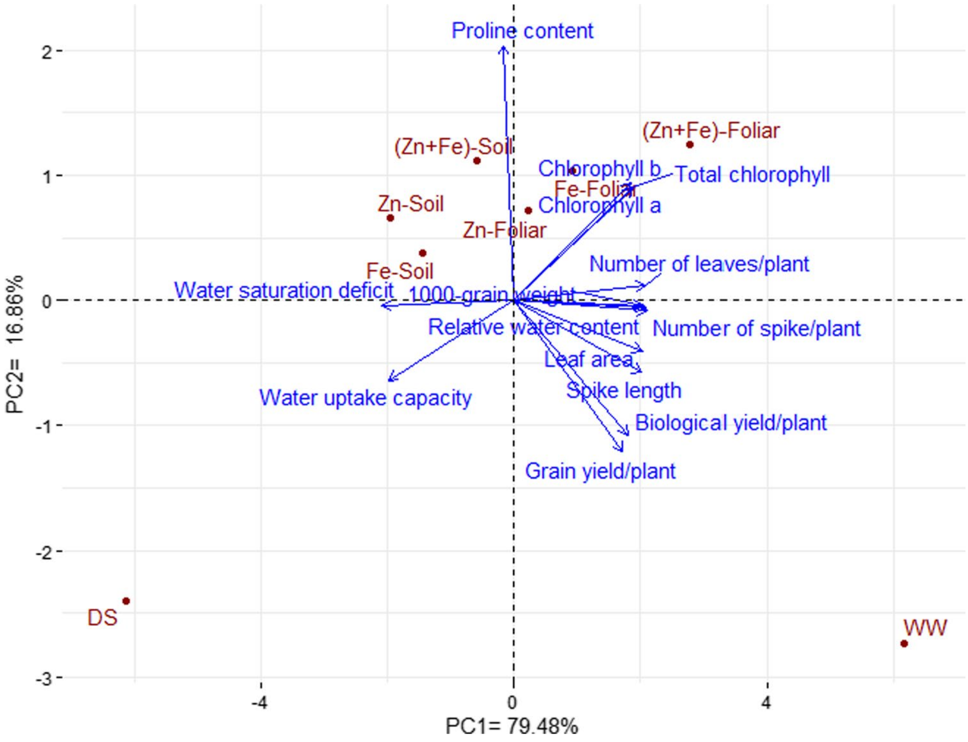

**Fig. 4** PC biplot for the studied physiological, morphological, and agronomic traits of wheat under eight treatments; untreated well-watered (WW) and drought-stressed (DS) treatments, soil applications of zinc sulfate and iron sulfate solely and in combination (Zn-Soil, Fe-Soil and (Zn + Fe)-Soil) and foliar applications of zinc sulfate and iron sulfate solely and in combination (Zn-Foliar, Fe-Foliar and (Zn + Fe)-Foliar)

### Interrelationship among studied treatments and evaluated traits

The analysis of principal components (PCs) was performed to visualize the interrelationships among the evaluated treatments and traits, as shown in Fig. 4. The first two PCs account for most of the variation which was approximately 96.34% (79.48 and 16.86% by $PC_1$ and $PC_2$), hence were employed to construct the PC-biplot. The irrigation regimes were situated on opposite sites, since well-watered treatment was located on the positive side of $PC_1$ and drought-stressed one was suited on the extreme negative side. Moreover, the applied exogenously of both elements solely or in combination were located on the positive side of $PC_1$ while the soil applications were situated on the negative side. Appreciably, the foliar application of zinc sulfate combined with iron sulfate exhibited the highest values on both PCs compared to the other soil and foliar applications. Additionally, the traits were displayed by parallel vectors or were close to each other, indicating a strong positive relationship, whereas those that were situated approximately opposite proved a negative association. A strong positive correlation was determined between grain yield and all contributing traits, morphological traits as well as chlorophyll content and RWC. Otherwise, a negative association was found between yield traits and WSD, WUC, and proline content.

## Discussion

Drought is decisive environmental stress that devastatingly impacts wheat growth and production. Accordingly, finding effective and sustainable approaches to attenuate the negative impacts of drought stress has become more decisive particularly under current climate variability (Desoky et al. 2021c; El-Sanatawy et al. 2021b). The present study investigated the efficiency of soil and foliar applications of zinc sulfate and iron sulfate to mitigate the deleterious impacts of water deficit in winter wheat. Zinc plays a major role in enhancing plant tolerance against drought stress by regulating several physiological mechanisms (Hassan et al. 2020). It contributes to improving ionic equilibrium, elevating concentrations of proline, improving activity of superoxide dismutase, reducing lipid peroxidation (Zafar et al. 2014; Marreiro et al. 2017). Besides, Zn regulates the stomatal opening, hence, reduces water loss under water and increases water use efficiency under water deficit conditions (Hussain et al. 2012; Tabatabai et al. 2015). Correspondingly, iron plays an integral role in alleviating drought stress by improving photosynthetic pigments and activating enzymatic antioxidants like catalase, superoxide dismutase, peroxidase which are scavengers of reactive oxygen species (Tripathi et al. 2018).

Soil application of micronutrients often is less effective than exogenous foliar application since a small amount of fertilizers interacts with soil-reactive surfaces (Hussain et al. 2012; Ram et al. 2016). However, the uptake of micronutrients after the foliar application is affected by several factors. Therefore, it is important to investigate the impact of both soil and foliar spray in mitigating drought stress.

The obtained results displayed that drought stress considerably reduced the content of both chlorophylls *a* and *b* (Fig. 1). The photosynthetic pigments are highly sensitive to drought stress and their decline is an initial reaction to oxidative stress and decreasing metabolite accumulation (Ohashi et al. 2006; Farooq et al. 2009; Keyvan, 2010; Terzi et al. 2010). Notwithstanding, the foliar and soil applications of zinc sulfate and iron sulfate intrinsically increased the chlorophylls content of wheat leaves under drought stress compared to untreated plants. The uppermost enhancement was assigned for foliar-supplied combined zinc sulfate with iron sulfate. This positive influence could be caused by increasing cell content of zinc and iron nutrients which are crucial for the biosynthesis of chlorophyll pigments. Moreover, the applications of zinc sulfate and iron sulfate could enhance cell wall structure and further physiological processes which improve the synthesis of enzymes and proteins related to chlorophyll biosynthesis. From this perspective, Babaeian et al. (2011); Sharifi et al. (2020); Ashkiani et al. (2020); and El-Desouky et al. (2021) elucidated that the application of zinc and iron considerably enhanced chlorophyll content in sunflower, wheat, rapeseed, tomato, respectively, under drought stress.

Wheat plants accumulated higher proline content under water deficit conditions compared to well-watered ones. Moreover, the soil and foliar applications of both compounds increased leaf proline content under drought stress conditions compared to untreated plants. Exogenous foliar application of combined both micronutrients displayed the highest values compared to the other soil and foliar treatments. Accumulation of osmolytes as proline is a crucial reaction of plant cells under drought stress that enhances plant antioxidant systems and osmotic adjustment (Zali and Ehsanzadeh 2018). Moreover, proline plays a vital adaptive role in drought tolerance due to its ability to detoxificate the produced destructive free radical species(Tatar and Gevrek 2008; Jaleel et al. 2009). Exogenous foliar application of zinc and iron was previously reported increasing proline content and enhancing tolerance against adverse impacts of drought stress (Hossain et al. 2014; Ali et al. 2020; Batista et al. 2020; Grangah et al. 2020).

Relative water content (RWC) implies the water status in plant leaves (Kabiri et al. 2014). The results displayed that RWC significantly declined due to drought stress while drought-stressed plants exhibited a significant increase in WSD and WUC relative to non-stressed ones (Fig. 2).

However, the foliar and soil applications of zinc sulfate and iron sulfate enhanced RWC and reduced WSD and WUC under water deficit conditions compared with untreated plants. The highest enhancement was exhibited by the foliar spray of combined both compounds, followed by applied foliar of iron sulfate solely and foliar application of zinc sulfate. Zinc has a vital role in the maintenance of potassium in stomata guard cells and increases leaf relative water content by reducing leaves' water loss. Likewise, iron increases the concentrations of the osmoregulators in plant cells causing higher osmotic alteration, higher relative water content, and greater membrane stability (Mozafari et al. 2018; Semida et al. 2021). Maintaining plant water status at a healthy status improves metabolic activities and osmotic adjustments under drought stress (Slabbert and Krüger 2014). In this respect, Batista et al. (2020) elucidated that zinc exhibited a valuable role in adjusting the stomatal opening and enhancing water status in soybean under drought stress. Similarly, Ali et al. (2020) disclosed that the foliar iron application considerably enhanced the water status of sunflower plants under water deficit conditions.

Severe drought stress reduced leaf characters; number of leaves per plant and leaf area which could be attributed to the reduction of chlorophylls content, dropping RWC, degenerating membrane structures, overproduction of ROS, and early leaf senescence in leaves (Griffiths et al. 2014). The application of zinc sulfate and iron sulfate mitigated the detrimental impacts of water shortage and increased leaf characters relative to untreated plants with superiority of combined foliar application of both elements. Similarly, Ma et al. (2017) and Sattar et al. (2021) demonstrated positive impacts of zinc on morphological and agronomic traits of wheat plants under water deficit conditions. Likewise, Ali et al. (2020) inferred that foliar application of iron enhanced morpho-physiological and yield traits in sunflower under drought stress.

Zinc and iron are essential elements in the biosynthesis of photosynthetic pigments and several important enzymes as catalase, superoxide dismutase, peroxidase, and glutamate dehydrogenase as well as enhancing membrane integrity (Babaei et al. 2017; Semida et al. 2021). Consequently, the soil and foliar applications of zinc sulfate and iron sulfate appreciably elevated proline accumulation resulted in better RWC and water status in wheat plants. Furthermore, their applications were associated with boosting chlorophylls content thus improving plant performance under drought stress. Accordingly, these positive impacts reflected positively on the leaf characters (number and area), yield components, grain yield, and biological yield with superiority of combined foliar application of zinc sulfate with iron sulfate. Likewise, Ma et al. (2017) and Sharifi et al. (2020) disclosed that zinc alleviated the destructive effects of drought stress and remarkably improved wheat growth and productivity. Furthermore, Jeshni et al. (2017) deduced that zinc sulfate increased number of grains and the productivity of *Matricaria recutita* under drought stress conditions. Besides, Maleki et al. (2014) depicted that zinc sulfate can reduce the drastic impacts of water shortage on maize grain yield and its contributing traits. In addition, previous reports elucidated that iron application mitigated the adverse impacts owing to water deficit conditions in sunflower (Babaeian et al. 2011; Ali et al. 2020), maize (Deswal and Pandurangam, 2018; Weisany et al. 2021), soybean (Rotaru and Sinclair, 2009; Gheshlaghi et al. 2019), and sesame (Heidari et al. 2011). Hence, it seems that the foliar applications of zinc sulfate and iron sulfate are effective in alleviating the adverse impacts of drought stress.

Finally, we conclude that drought stress significantly reduced all evaluated physiological, morphological, and agronomic traits in wheat plants relative to well-watered ones. On other hand, the soil and foliar applications of zinc sulfate and iron sulfate mitigated the detrimental impact of water deficit. Among the applied treatments, exogenous foliar application of combined zinc sulfate with iron sulfate was more effective in reducing oxidative stress by enhancing chlorophyll content, water status, and proline content under water deficit conditions. These influences reflected positively on the leaf characters (number and area), yield components, grain yield, and biological yield. Accordingly, the obtained results proposed that the exogenous foliar application of combined iron sulfate with zinc sulfate could be recommended to mitigate the devastating impacts of drought stress on wheat particularly in arid environments.

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## Declarations

**Conflict of interest** The authors declare no conflict of interest.

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