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Effect of Potassium Silicate and Irrigation on Grain Nutrient Uptake and Water Use Efficiency of Wheat Under Calcareous Soils

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Abstract

In calcareous soil, two field experiments were conducted to investigate the effects of two potassium silicate treatments (with and without) and three irrigation levels (100, 80 and 60%, of crop evapotranspiration, abbreviated as IW100, IW80 and IW60, respectively) on wheat yield and nutrient uptake and water use efficiency (WUE). The experimental design was a strip plots design in randomized complete block arrangement with three replicates. Findings reveal that potassium silicate improved grain weight spike^{-1} by about 1.06 times whether with IW80 or IW60. Also, seed index increased by 1.03, 1.06 and 1.04 times owing to potassium silicate in the 1st season under IW100, IW80 and IW60 treatments, respectively. Application of potassium silicate surpassed the control treatment by about 1.05, 1.4 and 1.07 times for biological straw and grain yields under IW80. The interaction of IW80 × potassium silicate significantly equaled IW100 × potassium silicate for P, S Mg and Mn uptake in both seasons as well as N, K and Zn uptake in the 1st season and Fe uptake in the 2nd season. IW80 or IW60 with potassium silicate application were the efficient combinations for improving WUE in both growing seasons.

Keywords Drought · Grain nutrient content · Potassium · Silicon · Wheat productivity

Introduction

Due to its contribution as the major staple food crop universally, wheat is ranked at the first position among cereals (Iqbal et al. 2021). However, crop yield potential is limited because of climate change impacts, especially abiotic stresses, including heat, salinity and drought (Saudy et al. 2020a; Yadav et al. 2020; Saudy et al. 2021a, c; El-Bially et al. 2022a, b).

In numerous field crops, deficit irrigation tactic is one of the practical strategies in crop irrigation programs to save water, however, crop productivity is negatively affected (El–Bially et al. 2018; Saudy et al. 2020a; El–Metwally et al. 2021, 2022). Water scarcity or deficit irrigation reduces plant growth and yield (Abd El–Mageed et al. 2021; Salem et al. 2021) due to production of reactive oxygen species (ROS), causing lipid peroxidation of membrane and interaction with other macromolecules (Bistgani et al. 2017). Under moderate or severe drought stress, plants close stomata and leaf pigments reduced causing reduction in photosynthesis rate and nutrient uptake (Yan et al. 2016; El–Metwally and Saudy 2021a; Saudy et al. 2021a).

Mineral nutrition plays a beneficial role in developing environmental stress tolerance in crop plants (Saudy 2014, 2015; Jan et al. 2017). Potassium (K^+) is a phyto-beneficial macro-element that performs a pivotal role in organizing physio-biochemical processes to support plant survival against abiotic stresses, including salinity (Merwad 2016; Abd El-Mageed et al. 2022). Adequate K^+ nutrition has been shown to mediate PM H^+-ATPase activation to increase protons extrusion under abiotic stresses (Weng et al. 2020).

In several plant species, as wheat, the potentiality of silicon (Si) to reinforce the environmental stresses tolerance was obtained (Rodrigues et al. 2015). Si could enhance plant growth under normal and stress conditions (Saudy and Mubarak 2015). Application of Si increased water and osmotic potential in roots and leaves as well as alleviated water stress partially (Ming et al. 2012).

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Therefore, the current study aimed to investigate the potentiality of potassium silicate (as a source of K and Si) for alleviating the adverse impacts of drought stress in wheat through enhancing water use efficiency under calcareous soil conditions.

Materials and Methods

Study Site and Experimental Procedures

Two field experiments were implemented during winter seasons of 2019/20 and 2020/21 at Maryout experimental station, Desert Research Centre, Alexandria, Egypt. The soil was a calcareous and sandy loam in texture containing 92.0% sand, 2.1% silt, 5.9 clay, and 24.1% calcium carbonate with pH of 8.1 and 0.72 dS m^{-1} electrical conductivity. Sorghum (*Sorghum bicolar* L.) was the preceding crop in both seasons.

In a strip plots design based on randomized complete block arrangement using 3 replicates, two potassium silicate containing 0.05% Si (0 and 500 ml L^{-1}) and three irrigation levels, were applied as ratio of crop evapotranspiration (100, 80 and 60%, abbreviated as IW100, IW80 and IW60, respectively) were tested. The experimental unit size was 10.5 m^2 (3 m × 3.5 m). On 19 November in 2019 and 2 December in 2020, wheat grains (cv. Giza–171) were sown in lines, 10 cm distance, at a rate of 150 kg grains ha^{-1}. During land preparation, single super phosphate (15.5% P_2O_5), at a rate of 240 kg ha^{-1}, and gypsum, as a soil conditioner, at a rate of 2.4 t ha^{-1}, were incorporated. At 30 days after sowing (DAS), ammonium nitrates fertilizer (33.5% N) at a rate of 450 kg ha^{-1} was applied.

Potassium silicate treatment was applied as foliar applications twice, 65 and 80 DAS. Irrigation water was applied equally to all irrigation treatments to increase the soil moisture up to field capacity until the 4–6 leaf growth stage (25 DAS); then, the irrigation treatments were started. Based on the meteorological data of the study area, reference evapotranspiration was calculated using FAO 56–Penman–Monteith method (formula 1) given by Allen et al. (1998). Using the formula 2 (Allen et al. 1998), wheat crop evapotranspiration was estimated. The irrigation water quantity (m^3 ha^{-1}) received by wheat plants under different irrigation levels are illustrated in Fig. 1. Gated pipe irrigation system was exploited for crop irrigation. The PVC gated pipes were installed in irrigation channel against the upper end of the furrows, which convey the water based on the required flow rate (one gate per furrow). The temporary dam was used to keep a constant hydraulic head, to realize adequate inflow rate during irrigation events. The inflow rate was 90 lpm $furrow^{-1}$, which predetermined according to the technique of Merriam et al. (1983). The amount of water applied was estimated by a flow meter installed on the delivery line of the irrigation system. Soil surface slope was 0.20%. Irrigation cutoff was at 90% of furrow length and runoff was negligible, which the furrows were closed–ends. The water amount applied during each irrigation event was appropriate to the crop's growth stage as described by Dorrenbos and Pruitt (1977). Soil water content was measured by gravimetric method (Merriam et al. 1983) before and after irrigation events along furrow length to a depth of 1.0 m in depth increments of 0.2 m to evaluate the soil moisture distribution and irrigation performance.

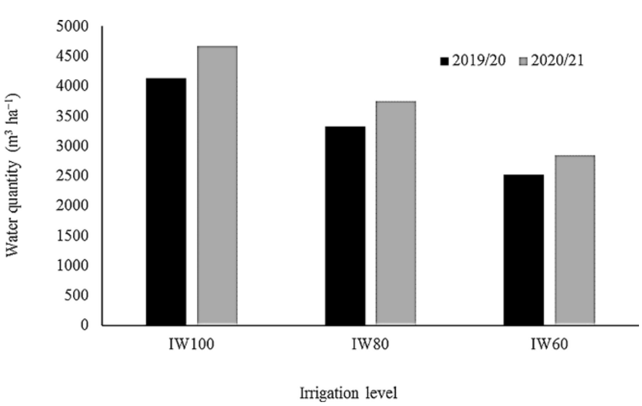

Fig. 1 Irrigation water amount applied under different irrigation levels in wheat during 2019/20 and 2020/21 seasons. IW100, IW80 and IW60: Irrigation at 100, 80 and 60% of crop evapotranspiration, respectively

Assessments

Yield and Yield Components

At harvest (15th and 21st of April in 2020 and 2021 seasons, respectively), spike number m^{-2} was measured. Moreover, ten plants were randomly obtained from each plot to measure grains number $spike^{-1}$, grains weight $spike^{-1}$ and seed index. Furthermore, whole plants of each plot were collected to estimate biological, straw and grain yields ha^{-1}.

Grain Nutrients Uptake

At Central Laboratory, Soil and Water Unit, Faculty of Agriculture, Ain Shams University, representative samples of grains were obtained to estimate the chemical analysis. Total nitrogen (N) was determined by micro Kjeldahl using 5% boric acid and 40% NaOH as described by Chapman and Pratt (1961). Total phosphorus (P) was estimated using Spectrophotometer according to the method described by Watanabe and Olsen (1965). Total potassium (K) was measured using Flame photometer (Chapman and Pratt 1961). Sulphur (S), magnesium (Mg), iron (Fe), zinc

(Zn), and manganese (Mn) were determined using ICP Mass Spectrometry (Benton 2001). After that, nutrient uptake was computed by multiplying the element concentration by grain yield ha^{-1}.

Water Use Efficiency

Based on the calculated applied irrigation water quantities for IW100, IW80 and IW60 in 2019/20 and 2020/21 seasons (Fig. 1), water use efficiency (WUE) was estimated according to Jensen (1983) (Eq. 1).

$$WUE = \frac{\text{Yield}\,(\text{kg ha}^{-1})}{\text{Water applied}\,(\text{m}^3\text{ha}^{-1})}(\text{kg m}^{-3}) \quad (1)$$

Statistical Analysis

Data of the two seasons was subjected to analysis of variance (ANOVA) according to Casella (2008). Costat software program, Version 6.303 (2004) was used for carrying out ANOVA. Means were separated using Duncan's multiple range test only when the F–test indicated significant ($p \leq 0.05$) differences among the treatments.

Results

Wheat Yield Components

Potassium silicate significantly influenced grain weight $spike^{-1}$ in 2019/20 and 2020/21 seasons and seed index in 2019/20 season (Table 1). Application of potassium silicate (500 ml L^{-1}) enhanced grain weight $spike^{-1}$ by 4.7 and 5.1% in 1st and 2nd seasons, respectively, and seed index by 4.2% in 1st season.

Full irrigation (IW100) achieved the maximum values of yield components in wheat in both growing seasons. While, reducing water amount by 40% (IW60) caused the maximum reductions. Moderate water deficit (IW80) caused 4.4, 4.9, 11.4 and 7.1% decreases (averages of the two seasons) in spike number m^{-2}, grains number $spile^{-1}$, grain weight $spile^{-1}$ and seed index, respectively, compared to no deficit water.

Interaction effect of potassium silicate and irrigation water revealed that potassium silicate applied in full irrigated plots showed the highest values of all yield parameters (Table 1). However, under each irrigation level, no noticeable differences between potassium silicate and tap water were obtained for all yield components in both seasons, except grain weight $spike^{-1}$ and seed index in the 1st season. Herein, potassium silicate improved grain weight $spike^{-1}$ by about 1.06 times whether with IW80 or IW60. Also, seed index was increased by 1.03, 1.06 and 1.04 times owing to potassium silicate in the 1st season under IW100, IW80 and IW60 treatments, respectively.

Wheat Yields

Wheat yields markedly responded to potassium silicate application in both growing seasons, except biological and straw yields in the 2nd season (Table 2). In the first season, increases in biological and straw yields due to potassium silicate were 5.7 and 6.1%, respectively. Moreover, increases

Table 1 Effect of potassium silicate and irrigation on wheat yield components in 2019/20 (I) and 2020/21 (II) seasons

Variable		Spike number m^{-2}		Grains number $spile^{-1}$		Grain weight $spile^{-1}$ (g)		Seed index (g)	
		Season I	Season II	Season I	Season II	Season I	Season II	Season I	Season II
Potassium silicate, PS (mg L^{-1})									
With, 500		294.0a	298.6a	45.11a	45.33a	2.02a	2.06a	44.63a	45.38a
Without, 0		294.0a	295.7a	44.88a	44.77a	1.93b	1.96b	42.85b	43.75a
Irrigation, I									
IW100		311.0a	318.0a	47.66a	47.00a	2.22a	2.31a	46.73a	49.33a
IW80		303.0b	298.6b	44.83b	45.16ab	2.03b	1.98b	45.31b	43.86b
IW60		268.0c	275.0c	42.50c	43.00b	1.66c	1.74c	39.17c	40.50c
PSxI									
IW100	500	311.0a	318.6a	47.33a	47.00a	2.25a	2.38a	47.52a	50.75a
	0	311.0a	317.3a	48.00a	47.00a	2.21a	2.25a	45.95b	47.92b
IW80	500	303.0b	302.0b	45.00b	45.66ab	2.09b	2.01b	46.53b	44.23c
	0	303.0b	295.3b	44.66b	44.66ab	1.97c	1.94bc	44.10c	43.49cd
IW60	500	268.0c	275.3c	43.00c	43.33b	1.71d	1.78cd	39.86d	41.17de
	0	268.0c	274.6c	42.00c	42.66b	1.61e	1.69d	38.49e	39.83e

IW100, IW80 and IW60: Irrigation at 100, 80 and 60% of crop evapotranspiration, respectively; Different letters within columns indicate that there are significant differences by Duncan's Multiple Range Test at $p \leq 0.05$

Table 2 Effect of potassium silicate and irrigation on wheat yields (t ha^{-1}) in 2019/20 (I) and 2020/21 (II) seasons

Variable		Biological yield		Straw yield		Grain yield	
		Season I	Season II	Season I	Season II	Season I	Season II
Potassium silicate, PS (mg L^{-1})							
With, 500		12.98a	12.85a	7.34a	6.92a	5.64a	5.93a
Without, 0		12.28b	12.15a	6.92b	6.42a	5.36b	5.72b
Irrigation, I							
IW100		14.62a	14.35a	8.20a	7.37a	6.41a	6.98a
IW80		13.05b	12.78b	7.26b	6.86a	5.79b	5.92b
IW60		10.23c	10.36c	5.92c	5.79b	4.31c	4.57c
PSxI							
IW100	500	14.75a	14.58a	8.22a	7.48a	6.52a	7.05a
	0	14.48a	14.16a	8.18a	7.25a	6.29b	6.90a
IW80	500	13.42b	13.12b	7.43b	6.94a	5.98c	6.17b
	0	12.69c	12.45b	7.10c	6.78a	5.59d	5.67c
IW60	500	10.78d	10.90c	6.36d	6.33ab	4.41e	4.56d
	0	9.68e	9.83d	5.48e	5.25b	4.20f	4.58d

IW100, IW80 and IW60: Irrigation at 100, 80 and 60% of crop evapotranspiration, respectively; Different letters within columns indicate that there are significant differences by Duncan's Multiple Range Test at $p \leq 0.05$

Table 3 Effect of potassium silicate and irrigation on grain macronutrients uptake (kg ha^{-1}) of wheat in 2019/20 (I) and 2020/21 (II) seasons

Variable		N uptake		P uptake		K uptake		S uptake		Mg uptake	
		Season I	Season II	Season I	Season II	Season I	Season II	Season I	Season II	Season I	Season II
Potassium silicate, PS (mg L^{-1})											
With, 500		137.5a	127.9a	19.6a	22.3a	157.5a	174.5a	10.5a	9.4a	15.6a	14.3a
Without, 0		121.6a	126.5a	19.5a	21.6a	155.6a	163.2b	9.9a	11.2a	8.0b	14.8a
Irrigation, I											
IW100		156.4a	155.4a	22.0a	26.6a	178.0a	208.1a	15.2a	13.5a	12.8a	16.8a
IW80		136.3ab	127.0b	20.4ab	22.6b	168.7a	164.1b	9.3ab	9.5a	14.9a	16.7a
IW60		95.4b	99.2c	16.2b	16.6c	123.0b	134.4c	6.1b	7.9a	7.8a	10.2a
PSxI											
IW100	500	161.4a	155.3a	22.1a	26.5a	171.7a	208.3a	14.6ab	10.7a	17.7a	16.2a
	0	151.5ab	155.5a	21.9a	26.6a	184.3a	207.9a	15.7a	16.2a	7.9b	17.3a
IW80	500	154.7ab	129.0b	20.7ab	23.4ab	171.4a	179.4b	10.5abc	10.2a	20.5a	15.7a
	0	118.0bc	125.1b	20.1b	21.9b	166.0a	148.7c	8.2bc	8.9a	9.4b	17.7a
IW60	500	96.6c	99.4c	16.0c	16.9c	129.5b	135.9c	6.3c	7.2a	8.7b	10.8a
	0	95.2c	98.9c	16.4c	16.3c	116.6b	132.9c	5.8c	8.6a	6.8b	9.5a

IW100, IW80 and IW60: Irrigation at 100, 80 and 60% of crop evapotranspiration, respectively; Different letters within columns indicate that there are significant differences by Duncan's Multiple Range Test at $p \leq 0.05$

in grain yield were 5.2 and 3.6% in the 1st and 2nd seasons, respectively.

As shown in Table 2, supplying wheat plants with IW100 recorded the highest yields, while, reductions associated lower water supply. Accordingly, as averages of the two seasons, reductions in biological, straw and grain yields were approximately 10.8, 9.2 and 12.4% with IW80 as well as 28.9, 24.6 and 33.6% with IW60, respectively.

The impact of potassium silicate on wheat yields was more pronounced under lowering water supply. In this respect, significant differences in biological straw and grain yields between addition or no addition of K2Si4 under IW60 or IW80. For instance, in the first season, application of potassium silicate surpassed the control treatment by about 1.05, 1.4 and 1.07 times for biological straw and grain yields under IW80. Moreover, with irrigation by IW60 the corresponding increases reached 1.11, 1.16 and 1.05, respectively (Table 2).

Grain Nutrient Uptake

There were insignificant variations between potassium silicate and control treatments for macronutrient (Table 3) and micronutrient (Table 4) uptake of wheat grains in both sea-

Table 4 Effect of potassium silicate and irrigation on grain micronutrients uptake (kg ha^{-1}) of wheat in 2019/20 (I) and 2020/21 (II) seasons

Variable		Fe uptake		Zn uptake		Mn uptake	
		Season I	Season II	Season I	Season II	Season I	Season II
Potassium silicate, PS (mg L^{-1})							
With, 500		154.2a	168.5a	52.8a	48.8a	21.2a	38.3a
Without, 0		146.1a	165.8a	37.4a	44.9a	19.7a	28.8a
Irrigation, I							
IW100		179.8a	194.8a	48.5a	76.8a	25.7a	38.0a
IW80		155.1b	173.3a	56.2a	43.5a	20.3ab	36.6a
IW60		115.4c	133.3b	30.7a	20.4a	15.3b	26.1b
PSxI							
IW100	500	178.9a	189.4ab	46.5a	105.7a	27.8a	44.5a
	0	180.6a	200.3a	50.6a	48.2bc	23.6ab	31.4b
IW80	500	164.7b	179.1ab	69.0a	25.4bc	19.6ab	42.0a
	0	145.5c	167.6b	43.3a	61.6b	21.1ab	31.1b
IW60	500	118.9d	137.1c	43.1a	15.8c	16.3b	28.3b
	0	112.0d	129.4c	18.3a	25.0bc	14.3b	23.8b

IW100, IW80 and IW60: Irrigation at 100, 80 and 60% of crop evapotranspiration, respectively; Different letters within columns indicate that there are significant differences by Duncan's Multiple Range Test at $p \leq 0.05$

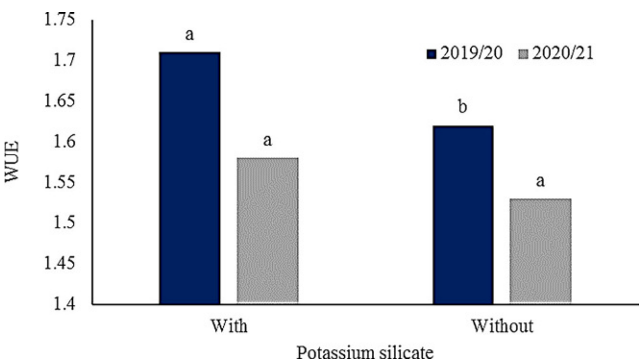

Fig. 2 Effect of potassium silicate on water use efficiency, WUE, (kg m^{-3}) of wheat in 2019/20 and 2020/21 seasons. Different letters within bars indicate that there are significant differences by Duncan's Multiple Range Test at $p \leq 0.05$

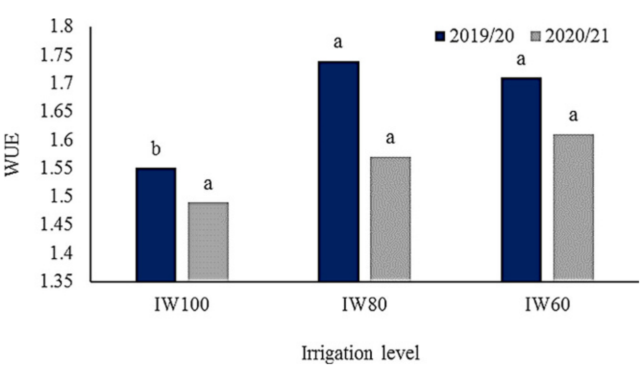

Fig. 3 Effect of irrigation on water use efficiency, WUE, (kg m^{-3}) of wheat in 2019/20 and 2020/21 seasons. IW100, IW80 and IW60: Irrigation at 100, 80 and 60% of crop evapotranspiration, respectively; Different letters within bars indicate that there are significant differences by Duncan's Multiple Range Test at $p \leq 0.05$

sons, except K uptake in the second season and Mg uptake in the first season. Due to application of potassium silicate grain K uptake increased by 6.9% in 2020/21 season and grain Mg uptake increased by 95.0% in 2019/20 season.

All nutrients uptake recorded with IW80 were similar to those measured with IW100 in both growing seasons, except N uptake in 2020/21 season and Fe uptake in 2019/20 season. Also, all irrigation treatments statistically equaled in S uptake in the 1st season as well as Mg uptake and Zn uptake in both seasons.

Macro- and micro-nutrients uptake significantly responded to the interaction between potassium silicate and irrigation in both seasons, except S and Mg uptake in the 2nd season (Table 3) and Zn uptake in the 1st season (Table 4). Superiority of full irrigation (IW100) still pronounced with potassium silicate for enhancing grain nutrients uptake of wheat. However, IW80 x potassium silicate significantly equaled IW100 x potassium silicate for P, S Mg and Mn uptake in both seasons as well as N, K and Zn uptake in the 1st season and Fe uptake in the 2nd season.

Water Use Efficiency

Potassium silicate surpassed the control for WUE in the first season causing 5.6% increase (Fig. 2). There was no significant difference among the studied irrigation treatments in WUE of wheat (Fig. 3). Concerning the interaction, Fig. 4 depicted that IW80 or IW60 with potassium silicate application were the efficient combinations for improving WUE in both growing seasons.

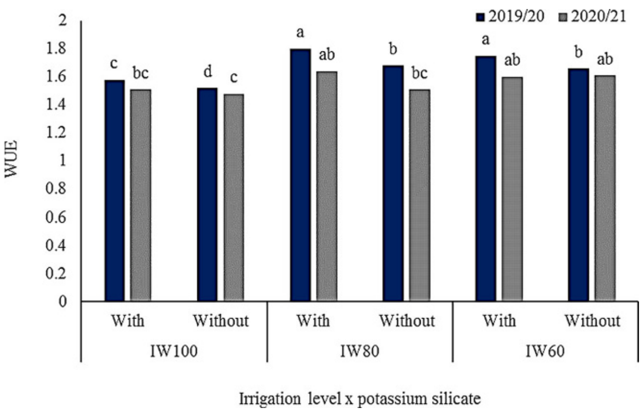

Fig. 4 Effect of potassium silicate and irrigation interaction on water use efficiency, WUE, (kg m^{-3}) of wheat in 2019/20 and 2020/21 seasons. IW100, IW80 and IW60: Irrigation at 100, 80 and 60% of crop evapotranspiration, respectively; Different letters within bars indicate that there are significant differences by Duncan's Multiple Range Test at $p \leq 0.05$

Discussion

Wheat productivity is severely hampered by drought, owing to its negative impacts on crop growth and development. Deficit water caused serious reduction in yield productivity and quality (Saudy and El-Bagoury 2014; Saudy and El–Metwally 2019). Owing to drought, reductions in stomatal conductance, photosynthesis and transpiration rates were observed, and consequently CO_2 assimilation rates declined (Farooq et al. 2012). Low water supply caused reduction in leaf pigments and soluble sugars, hence dry matter accumulation and nutrient uptake decreased (Saudy and El–Metwally 2019, 2022). The significant reduction in relative water content of leaves positively correlated with soil water availability under different irrigation treatments (Kalariya et al. 2015). Also, drought adversely influences the absorption and use of mineral nutrients shackling plant growth and production (Sun et al. 2012; Mubarak et al. 2021). Because of drought plant nutrient uptake capacity was reduced (Sanaullah et al. 2012; Abd–Elrahman et al. 2022). Low water supplies reduced plant growth and development by influencing uptake, transport, and partitioning of nutrients (Gessler et al. 2017; Saudy et al. 2020a). Also, reducing water supply caused severe depression in plant physiological, anatomical, and agronomic traits (El–Metwally et al. 2021; Makhlouf et al. 2022). Accordingly, in crop production management, all tools reduced water lost should be adopted.

Supplying of crop plants in appropriate quantities and forms of nutrients certainly promotes growth and development both under favorable and unfavorable conditions (Saudy et al. 2018, 2020b; El-Metwally and Saudy 2021b; Saudy et al. 2021b). The current study proved that potassium silicate alleviated, partially at least, the hazards of drought with enhancing yield traits (Tables 1 and 2), nutrients uptake (Tables 3 and 4) and water use efficiency (Fig. 3). In this respect, Debona et al. (2017) and Luyckx et al. (2017) stated that Si fertilization had can improve plant tolerance to drought. Si also can enhance the anti–oxidative defense mechanisms thus, avoid damage from reactive oxygen species produced by various abiotic stresses (Maghsoudi et al. 2019). Si promotes the plant growth by modulating the nutrient (Na, Mg and Si) uptake and phytohormone levels and alleviating plant stress levels (Gong et al. 2008). On the other hand, potassium is an essential nutrient for growth with maintaining cell turgor and regulating the water content plant cells (Rengel and Damon 2008). Moreover, potassium supply plays an important role in regulating osmotic potential, increasing water uptake ability and avoiding K^+ depletion (Zengin et al. 2009). Also, K may help in maintaining a normal balance between carbohydrates and proteins (Monreal et al. 2007). It is a major nutrient for photosynthesis and the transport of assimilates (Wang et al. 2015). Potassium affects the osmotic adjustment of the plant and by enhancing the translocation of assimilates and maintaining osmotic charge (Marschner 1995; Mubarak et al. 2016). Therefore, providing wheat plants with potassium silicate is regarded as a crucial action for keeping productivity particularly under adverse conditions as drought (Salem et al. 2022).

Conclusion

It could be concluded that in calcareous soils, providing potassium silicate to wheat plants is seen as a critical measure for maintaining productivity, commonly under suitable conditions, or particularly in adverse situations such as lack of irrigation water. Moreover, farmers can mitigate drought stress effects and improve water use efficiency by using judicious application of potassium silicate and a moderate irrigation level (80% of crop evapotranspiration) in their fields, thus saving the applied water by 20%.

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Conflict of interest H.S. Saudy, E.M.M. Salem and W.R. Abd El-Momen declare that they have no competing interests.

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