Influence of Silicon Forms on Nutrients Accumulation and Grain Yield of Wheat Under Water Deficit Conditions

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Abstract

Wheat productivity is severely hampered by drought, owing to its negative impacts on crop growth and development. For obtaining better yield, the impacts of drought should be ameliorated. Therefore, the current study scrutinizes the potential of different silicon (Si) forms to minify the drought-associated reduction in yield and the changes in nutrients accumulation. In a strip plots design based on randomized complete block arrangement using 3 replicates, two field experiments were carried out in 2019/20 and 2020/21 seasons. Three silicon (Si) forms (potassium silicate, calcium silicate, and aluminum silicate), in addition to the control (tap water) were sprayed. Also, three irrigation regimes were applied as ratio of crop evapotranspiration (60, 80 and 100%, denoted Irr60, Irr80 and Irr100, respectively). Findings clarified that application of aluminum silicate in both seasons, in addition to calcium silicate in the second season recorded the maximum accumulation of Si in wheat plants. Supplying wheat plants with different forms of Si reduced zinc (Zn) and manganese (Mn) and increased Si compared to the control (no Si application). Irr100 possessed increase in accumulation of Si in plant tissues greater than Irr80 or Irr60. Significant increases in all agronomic traits of wheat were obtained owing to spraying any Si form compared to the control. The differences between potassium silicate, calcium silicate, and aluminum silicate were not significant in flag leaf greenness (SPAD value), grains weight spike⁻¹, weight of 1000 grains, and grain yield ha⁻¹ in 2020/21 season. Irr100 was the effective treatment for enhancing SPAD value, spike length, grains weight spike⁻¹, weight of 1000 grains, and grain yield ha⁻¹. When irrigation water was reduced by 20% (Irr80), the lowest reduction in grain yield was obtained with potassium silicate compared to other forms of Si. It could be concluded that since lower accumulation of Si in plant tissues under water deficit than well-watered was recorded, the spraying of Si is great of importance to be applied under drought stress.

Keywords Nutrient uptake · Oxidative stress · Silicate compounds · Water requirement · Wheat yield potential

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Einfluss von Siliziumformen auf die Nährstoffakkumulation und den Kornertrag von Weizen unter Wassermangelbedingungen

Zusammenfassung

Die Weizenproduktivität wird aufgrund der nachteiligen Auswirkungen auf das Wachstum und die Entwicklung der Pflanzen durch Dürre stark eingeschränkt. Um einen besseren Ertrag zu erzielen, sollten die Auswirkungen von Trockenheit gemildert werden. Daher untersucht die aktuelle Studie das Potenzial verschiedener Silizium (Si)-Formen, die dürrebedingte Ertragsminderung und die Veränderungen der Nährstoffakkumulation zu minimieren. In einem Strip-Plot-Design auf Basis eines randomisierten vollständigen Blockdesigns mit 3 Wiederholungen wurden in den Saisons 2019/20 und 2020/21 zwei Feldversuche durchgeführt. Drei Si-Formen (Kaliumsilikat, Kalziumsilikat und Aluminiumsilikat) wurden zusätzlich zur Kontrolle (Leitungswasser) gesprüht. Außerdem wurden drei Bewässerungsregime im Verhältnis zur Evapotranspiration der Pflanzen angewandt (60, 80 und 100 %, bezeichnet als Irr60, Irr80 bzw. Irr100). Die Ergebnisse verdeutlichten, dass die Anwendung von Aluminiumsilikat in beiden Saisons zusätzlich zu Kalziumsilikat in der zweiten Saison die maximale Anreicherung von Si in Weizenpflanzen verzeichnete. Die Versorgung von Weizenpflanzen mit verschiedenen Si-Formen reduzierte Zn und Mn und erhöhte Si im Vergleich zur Kontrolle (keine Si-Anwendung). Bei Irr100 war die Si-Akkumulation in den Pflanzengeweben stärker als bei Irr80 oder Irr60. Bei allen agronomischen Merkmalen von Weizen wurden im Vergleich zur Kontrolle signifikante Steigerungen durch das Sprühen jeglicher Si-Form erzielt. Die Unterschiede zwischen Kaliumsilikat, Kalziumsilikat und Aluminiumsilikat waren in der Saison 2020/21 bzgl. des SPAD-Werts, dem Korngewicht pro Ähre, dem 1000-Korn-Gewicht und dem Kornertrag pro ha nicht signifikant. Irr100 war die wirksamste Behandlung zur Verbesserung des SPAD-Werts, der Ährenlänge, des Korngewichts pro Ähre, des 1000-Korn-Gewichts und des Kornertrags pro ha. Bei einer Reduzierung des Bewässerungswassers um 20 % (Irr80) wurde mit Kaliumsilikat im Vergleich zu anderen Si-Formen die geringste Verringerung des Kornertrags erzielt. Da eine geringere Anreicherung von Si im Pflanzengewebe bei Wasserdefizit als bei guter Bewässerung festgestellt wurde, könnte man zu dem Schluss kommen, dass das Besprühen mit Si bei Trockenstress von großer Bedeutung ist.

Schlüsselwörter Nährstoffaufnahme · Oxidativer Stress · Silikatverbindungen · Wasserbedarf · Weizenерtragspotenzial

Introduction

Wheat (*Triticum aestivum* L.) occupies a pivotal position among cereals around the world and contributes a significant part of daily calories and protein intake (Kizilgeci et al. 2021). Beneficial components to human health such as proteins, minerals, vitamins, phytochemicals, and dietary fibers could be provided from wheat (Shewry and Hey 2015). Owing to its contribution as the major staple food crop universally, wheat is ranked at the first position among cereals (Iqbal et al. 2021). Nevertheless, yield potential of wheat is limited due to climate change effects, especially abiotic stresses, including heat, salinity, and drought (Yadav et al. 2020).

It is well known that water is one of the most significant factors affecting growth and development of crop plants. It has been proved the critical role of water in physiological processes especially photosynthesis and nutrient uptake. Accordingly, deficiency or unavailability of water will cause imbalance in all plant biological pathways. In this respect, drought as an environmental factor mutates the pathway stability of water and nutrients to become out of balance (Meena et al. 2017; Saudy and El-Metwally 2019), hence, reductions in plant growth and yield owing to low water supply were obtained (El-Metwally et al. 2022; Saudy et al.

2021; Abd-Elrahman et al. 2022). While, in arid and semi-arid conditions, farmers are forced to irrigate the crops with less water than required, due to lack of irrigation water, although the shortage in yield is realized. In this concern, applying practices that mitigate the adverse effect of water deficit is a crucial action. 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). The induction of plant resistance by Si to stress might be attributed to formation of phytoliths and polymerization of insoluble Si in cell walls and around the vascular bundle, reducing water loss, by controlling transpiration (Mecfel et al. 2007). Also, Si activates the antioxidant mechanisms to quench the reactive oxygen species (ROS) production, hence, reduce lipid peroxidation (Ye et al. 2013; Rodrigues et al. 2015; Abdel-Halim et al. 2017). Application of Si increased water and osmotic potential in roots and leaves as well as alleviated water stress partially (Ming et al. 2012). Since Si has a vital role in enhancing growth and yield (Salim 2014), in the future, its application will become a sustainable strategy and mitigate the adverse impacts under abiotic stress (Etesami and Ryong Jeong 2018).

The effect of cation associated Si in the used compounds should not be neglected. There are several forms of Si could be used as fertilizers like aluminum silicate, calcium silicate and potassium silicate. Although potassium silicate has received great attentions, very little information is available about aluminum silicate and calcium silicate. The harmful impacts of low water supply were reduced by application of potassium silicate (Abu-Muriefah 2015).

The most favorite form of Si for plant growth, especially under stresses, is still unclear. In the current work we hypothesized that the different forms of Si supply have different impacts toward the plant response to water stress. Thus, the aim was to compare the potentialities of aluminum, calcium, and potassium silicates for alleviating the water deficit impacts on wheat.

Materials and Methods

Study area Description

At Maryout experimental station, Desert Research Centre (latitude 31° 00' 21" N, longitude 29° 47' 26" E), adjacent to the Mediterranean coast, Alexandria, two field experiments were carried out in winter seasons of 2019/20 and 2020/21. The soil was a calcareous of sandy loam texture and its properties and water status are presented in Table 1. According to soil taxonomy (IUSS Working Group WRB 2015), the soil is order Entisols and suborder psamments. As an average of the two seasons, the mean values of daily

air temperature, wind speed, relative humidity, precipitation, and solar radiation were 17.3 °C, 2.73 m sec⁻¹, 60.4%, 0.57 mm, and 16.7 MJ m⁻² day⁻¹, respectively. The preceding cultivated crop was sorghum (*Sorghum bicolor* L.) in both seasons.

Experimental Treatments

The experiment was implemented in a strip plots design based on randomized complete block arrangement using 3 replicates. In the vertical plots, three silicon (Si) forms (potassium silicate, calcium silicate, and aluminum silicate each of them containing 0.05% Si), in addition to the control (tap water) were sprayed. While, three irrigation regimes, were applied as ratio of crop evapotranspiration (60, 80 and 100%, denoted Irr60, Irr80 and Irr100, respectively), occupied the horizontal plots. Silicon treatments were applied as foliar applications twice, 65 and 80 days after sowing (DAS), at a rate of 500 ml L⁻¹. 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) as follow:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma[900/(T + 273)]U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

where: ET_o is reference evapotranspiration (mm day⁻¹), R_n is net radiation at the crop surface (MJ m⁻² day⁻¹), G is soil heat flux density (MJ m⁻² day⁻¹), T is mean daily air temperature at 2 m height (°C), U_2 is wind speed at 2 m height (m sec⁻¹), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), $e_s - e_a$ is saturation vapor pressure deficit (kPa), Δ is slope of vapor pressure curve (kPa °C⁻¹) and γ is psychrometric constant (kPa °C⁻¹).

Using the formula 2 (Allen et al. 1998), wheat crop evapotranspiration was estimated

$$ET_c = K_c \times ET_o \quad (2)$$

where ET_c is daily crop evapotranspiration (mm); K_c is daily crop coefficient; ET_o is grass reference evapotranspiration (mm).

Accordingly, the irrigation water amount (m³ ha⁻¹) received by wheat plants was approximately 2519.2 and 2838.9 with Irr60; 3325.6 and 3751.8 with Irr80 as well as 4132.0 and 4664.8 with Irr100 treatments in the first and second seasons, respectively.

Table 1 Initial physico-chemical traits and water status of soil at the experimental research station of Maryout, Egypt

Parameter	Unit	Value
<i>Mechanical analysis</i>		
Sand	%	92.0
Silt	%	2.10
Clay	%	5.90
<i>Chemical analysis</i>		
pH (1:2.5)	–	8.10
Electrical conductivity (EC)	dS m ⁻¹	0.72
Calcium cations (Ca ²⁺)	Meq L ⁻¹	1.91
Magnesium cations (Mg ²⁺)	Meq L ⁻¹	0.93
Sodium cations (Na ⁺)	Meq L ⁻¹	0.29
Potassium cations (K ⁺)	Meq L ⁻¹	3.01
Chloride anions (Cl ⁻)	Meq L ⁻¹	1.33
Bicarbonate anions (HCO ₃ ⁻)	Meq L ⁻¹	3.40
Sulphate anions (SO ₄ ²⁻)	Meq L ⁻¹	2.23
Calcium carbonate (CaCO ₃)	%	24.12
<i>Water status</i>		
Saturation percentage	%	29.52
Field capacity	%	20.20
Wilting point	%	9.21

Plants were irrigated through gated pipe irrigation system and the application irrigation efficiency was 80%. 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 adequately 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.

The volume of water applied for each plot was calculated as follow by formula 3:

$$Q = q \times T \times n \quad (3)$$

where: Q is water volume (L plot⁻¹), q is irrigation water inflow rate furrow⁻¹ (L minute⁻¹), T is total irrigation time furrow⁻¹ min⁻¹ and n is number of furrows per plot⁻¹.

Crop Management

With land preparation, the ordinary single super phosphate (15.5% P₂O₅), 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. Soil divided into strips which separated by boarders (2.1 m land spacings) to minimize water superposition among irrigation treatments. The experimental unit size was 10.5 m² (3 m × 3.5 m). On 19 November in 2019 and 2 December in 2020, wheat grains (cv. Giza-171) were planted in lines, 10 cm distance, at a rate of 150 kg grains ha⁻¹. At 30 DAS, ammonium nitrates fertilizer (33.5% N) at a rate of 450 kg ha⁻¹ was applied.

Data Record

Plant Analysis

Representative plant samples were obtained at 105 DAS for carrying out the chemical analysis at Central Laboratory, Soil and Water Unit, Faculty of Agriculture, Ain Shams University. Total nitrogen (N) was determined by micro Kjeldahl using 5% boric acid and 40% NaOH as described by Chapman and Pratt (1961). Total phospho-

rus (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). Iron (Fe), zinc (Zn), manganese (Mn) and silicon (Si) were determined using ICP Mass Spectrometry (Benton 2001).

Crop Traits

Flag leaf greenness (SPAD value) was measured at 105 DAS by chlorophyll meter (SPAD-502Plus) according to Süß et al. (2015).

Wheat plants were harvested on 15 and 21 April in 2020 and 2021 seasons, respectively. Ten plants were randomly chosen from each plot to measure plant height, spike length, grains weight spike⁻¹ and weight of 1000 grains. Furthermore, whole plants of each plot were collected to estimate straw and grain yields ha⁻¹.

Statistical Analysis

A two-way analysis of variance (ANOVA) for the data of the two seasons was undertaken (Casella 2008), using Co-stat software program, Version 6.303 (2004). Based on Duncan's multiple range test, means separation were performed only when the F-test indicated significant ($p < 0.05$) differences among the treatments.

Results

Plant Analysis

Analysis of variance proved that neither Si form nor irrigation had significant effects on all estimated macronutrients in wheat in both growing seasons of 2019/20 and 2020/21 (Table 2). While, except for Fe, the other studied micronutrients affected significantly by Si form and irrigation (Table 3). Supplying wheat plants with different forms of Si reduced Zn and Mn and increased Si compared to the control (no Si application) in both seasons. However, potassium silicate in the first season and aluminum silicate in the second season showed similar Mn values as the control. Moreover, application of aluminum silicate in both seasons, in addition to calcium silicate in the second season recorded the maximum values of Si.

Except for Mn in 2020/21, all micronutrients responded significantly to irrigation regimes. Under Irr60, higher concentrations of Zn (in both seasons) and Mn (in the first season) were obtained (Table 3). On the contrary, the maximum concentration of Si was observed with Irr100 (in both seasons), in addition to Irr80 (in the second season).

Table 2 Influence of silicon form and irrigation regime on nitrogen (N), phosphorus (P), and potassium (K) content in wheat plants in 2019/20 (S1) and 2020/21 (S2) seasons

Variable	N%		P%		K%	
	S1	S2	S1	S2	S1	S2
<i>Silicon form</i>						
Potassium silicate	1.87a	2.23a	0.28a	0.28a	2.12a	1.80a
Calcium silicate	1.65a	1.87a	0.26a	0.29a	2.22a	1.87a
Aluminum silicate	1.76a	2.23a	0.25a	0.33a	1.81a	2.01a
Control	1.96a	1.78a	0.27a	0.28a	2.21a	1.86a
<i>Irrigation regime</i>						
Irr60	1.80a	2.25a	0.27a	0.28a	1.95a	1.88a
Irr80	1.86a	1.89a	0.26a	0.29a	1.94a	1.79a
Irr100	1.76a	1.93a	0.27a	0.31a	2.38a	1.98a

Irr60, Irr80 and Irr100: irrigation at 60, 80 and 100% of crop evapotranspiration, respectively. Different letters within columns indicates that there are significant differences at 0.05 level of probability

Table 3 Influence of silicon form and irrigation regime on iron (Fe), zinc (Zn), manganese (Mn), and silicon (Si) content in wheat plants in 2019/20 (S1) and 2020/21 (S2) seasons

Variable	Fe (mg kg ⁻¹)		Zn (mg kg ⁻¹)		Mn (mg kg ⁻¹)		Si (mg kg ⁻¹)	
	S1	S2	S1	S2	S1	S2	S1	S2
<i>Silicon form</i>								
Potassium silicate	71.9a	54.7a	91.9b	130.0d	28.2ab	35.2c	0.54c	0.37b
Calcium silicate	131.4a	92.4a	76.9c	131.2c	23.7bc	41.2b	0.73b	0.83a
Aluminum silicate	83.4a	53.4a	60.7d	140.8b	18.9c	46.8a	0.81a	0.76a
Control	134.4a	107.2a	97.7a	153.4a	29.9a	51.5a	0.34d	0.32b
<i>Irrigation regime</i>								
Irr60	122.8a	76.6a	99.9a	156.5a	30.6a	55.4a	0.50c	0.51b
Irr80	107.5a	80.0a	71.3c	118.8c	22.9b	32.7a	0.59b	0.61a
Irr100	85.4a	73.9a	74.1b	141.3b	22.0b	42.9a	0.73a	0.58a

Irr60, Irr80 and Irr100: irrigation at 60, 80 and 100% of crop evapotranspiration, respectively. Different letters within columns indicates that there are significant differences at 0.05 level of probability

The interaction between irrigation regime and silicon form had significant effects only on Mn and Si content in wheat plants (Table 4). Irr60×potassium silicate and Irr80×control showed the maximum Mn values in 2019/20 season. In 2020/21 season, Irr60×calcium silicate, aluminum silicate or control as well as Irr100×aluminum silicate or control recorded the highest Mn content. Irr100×calcium silicate (in the first season) as well as Irr60 or Irr80×calcium silicate and Irr100×aluminum silicate (in the second season) were the distinctive combinations for increasing Si content in wheat plants.

Crop Parameters

All wheat crop traits significantly influenced by Si form in both growing seasons, except spike length (Table 5). Generally, noticeable enhancements in crop traits were obtained owing to spraying Si forms compared to the control. In this context, potassium silicate achieved the maximum values. However, in 2019/20 season, SPAD value (with calcium silicate or aluminum silicate) and grains weight spike⁻¹ (with

calcium silicate) statistically leveled that of potassium silicate. Also, the differences between potassium silicate, calcium silicate, and aluminum silicate were not significant for SPAD value, grains weight spike⁻¹, weight of 1000 grains, and grain yield ha⁻¹ in 2020/21 season.

Irrigation regime had remarkable impacts on all crop traits in both seasons (Table 5). Along the two seasons, Irr100 was the effective treatment for enhancing SPAD value, spike length, grains weight spike⁻¹, weight of 1000 grains, and grain yield ha⁻¹. Spike length of Irr80 was similar to that of Irr100 in 2020/21 season.

The statistical analysis revealed that spike length, weight of 1000 grains, and grain yield ha⁻¹ significantly responded to the interaction between Si form and irrigation regime in both seasons (Table 6). Commonly, silicate forms were more efficient for increasing spike length, weight of 1000 grains, and grain yield ha⁻¹ under well-watered plants (Irr100). Reducing irrigation water by 20% (Irr80) than Irr100 caused reductions in grain yield by 8.2, 13.1, 10.6% in the first season and 12.5, 17.4, 14.3% in the second sea-

Table 4 Influence of irrigation regime and silicon form interaction on manganese (Mn), and silicon (Si) content in wheat plants in 2019/20 (S1) and 2020/21 (S2) seasons

Variable		Mn (mg kg ⁻¹)		Si (mg kg ⁻¹)	
		S1	S2	S1	S2
Irr60	Potassium silicate	45.6a	34.3de	0.24l	0.40ef
	Calcium silicate	27.5 cd	65.8a	0.33j	0.88abc
	Aluminum silicate	27.5 cd	58.8a	1.02b	0.32ef
	Control	21.6cde	62.7a	0.40h	0.47de
Irr80	Potassium silicate	20.5de	35.7cde	0.86d	0.43def
	Calcium silicate	13.3e	28.3de	0.79e	0.96ab
	Aluminum silicate	16.6e	25.3e	0.46g	0.84bc
	Control	37.8ab	41.5bcd	0.26k	0.22f
Irr100	Potassium silicate	18.5de	35.6cde	0.53f	0.29ef
	Calcium silicate	30.3bc	29.4de	1.06a	0.66 cd
	Aluminum silicate	12.6e	56.4ab	0.96c	1.10a
	Control	30.3bc	50.4abc	0.36i	0.26ef

Irr60, Irr80 and Irr100: irrigation at 60, 80 and 100% of crop evapotranspiration, respectively. Different letters within columns indicates that there are significant differences at 0.05 level of probability

Table 5 Influence of silicon form and irrigation regime on agronomic traits of wheat in 2019/20 (S1) and 2020/21 (S2) seasons

Variable	Leaf greenness (SPAD value)		Spike length (cm)		Grains weight spike ⁻¹ (g)		Weight of 1000 grains (g)		Grain yield (t ha ⁻¹)	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
<i>Silicon form</i>										
Potassium silicate	44.0a	39.3a	10.1a	10.1a	2.02a	2.06a	44.6a	45.3a	5.69a	5.98a
Calcium silicate	43.6ab	39.6a	10.2a	10.1a	1.96b	2.02ab	43.7c	44.8a	5.53b	5.82a
Aluminum silicate	43.5ab	38.7a	10.2a	10.2a	1.99ab	2.02ab	44.1b	45.0a	5.59b	5.91a
Control	42.9b	38.4b	10.1a	10.0a	1.93c	1.96b	42.8d	43.7b	5.41c	5.77b
<i>Irrigation regime</i>										
Irr60	39.8c	37.5c	9.8c	9.6b	1.66c	1.74c	39.0c	40.5c	4.32c	4.55c
Irr80	44.0b	39.2b	10.2b	10.3a	2.02b	2.01b	45.3b	44.3b	5.82b	5.98b
Irr100	46.7a	40.3a	10.5a	10.3a	2.24a	2.30a	47.0a	49.3a	6.52a	7.08a

Irr60, Irr80 and Irr100: irrigation at 60, 80 and 100% of crop evapotranspiration, respectively. Different letters within columns indicates that there are significant differences at 0.05 level of probability

son with application of potassium silicate, calcium silicate and aluminum silicate, respectively.

Discussion

There is no doubt that the nutrients balance within plants is substantially correlated with water status of plant cells. In this regard, it has been reported that deficit irrigation reduces plant growth by affecting various physiological and biochemical processes, such as photosynthesis, respiration, translocation, ion uptake, carbohydrates, nutrient metabolism, and growth promoters (Farooq et al. 2008; Razmjoo et al. 2008; Salem et al. 2021). Also, reducing water supply caused severe depression in plant physio-

logical, anatomical, and agronomic traits (El-Bially et al. 2018; El-Metwally et al. 2021; Makhlof et al. 2022). In the stressed plants accumulation of abscisic acid is stimulated in leaves, which sets up ionic imbalance that compels potassium ion (K⁺) to leak out from guard cells and loss of guard cell turgor pressure. Thus, narrowing the aperture mostly would be due to reduced leaf relative water content and increased stomatal closure (Abd El-Mageed et al. 2021; Makhlof et al. 2022). Water deficit reduced the concentration of N and P in plant tissue (He and Dijkstra 2014) and decreased nutrient uptake from soil (Ge et al. 2012; Sardans and Peñuelas 2012). Decreases in nutrient uptake during drought could be attributed to the reduction of nutrient supply through mineralization process (Sanaullah et al. 2012; Saady et al. 2020), and by reducing nutrient diffusion

Table 6 Influence of irrigation regime and silicon form interaction on agronomic traits of wheat in 2019/20 (S1) and 2020/21 (S2) seasons

Variable		Spike length (cm)		Weight of 1000 grains (g)		Grain yield (t ha ⁻¹)	
		S1	S2	S1	S2	S1	S2
Irr60	Potassium silicate	9.9d	9.7abc	39.8f	41.1de	4.45f	4.60c
	Calcium silicate	9.6e	9.3c	38.9g	41.0de	4.29g	4.44c
	Aluminum silicate	9.7e	9.5bc	39.0g	40.3e	4.32g	4.54c
	Control	10.0cd	9.9abc	38.4h	39.8e	4.24g	4.62c
Irr80	Potassium silicate	10.2bc	10.4a	46.5b	44.2bcd	6.04c	6.22b
	Calcium silicate	10.3b	10.5a	44.8d	44.3bcd	5.72e	5.89b
	Aluminum silicate	10.2bc	10.3ab	45.9c	45.3bc	5.88d	6.09b
	Control	10.1bcd	10.0abc	44.1e	43.4cde	5.64e	5.72b
Irr100	Potassium silicate	10.2bc	10.1abc	47.5a	50.7a	6.58a	7.11a
	Calcium silicate	10.7a	10.4a	47.4a	49.2a	6.58a	7.13a
	Aluminum silicate	10.7a	10.6a	47.4a	49.4a	6.58a	7.11a
	Control	10.2bc	10.3ab	45.9c	47.9ab	6.35b	6.96a

Irr60, Irr80 and Irr100: irrigation at 60, 80 and 100% of crop evapotranspiration, respectively. Different letters within columns indicates that there are significant differences at 0.05 level of probability

and mass flow in the soil (Lambers et al. 2008). Disturbing the kinetics of nutrient under drought could decrease nutrient uptake by plant roots (Christophe et al. 2011). On the contrast, our results showed that macronutrients concentration did not affect by low water supply (Table 2). Since the impact of drought depends on its intensity and duration during a plant's life cycle (Bradford and Hsiao 1982), irrigating wheat by 60 or 80% of crop evapotranspiration could not represent a significant issue for macronutrient uptake. However, Si concentration was the pronounced element that drastically reduced with water deficit (Table 4). Reductions in Si concentration with Irr60 were 31.5 and 13.7% in the first and second seasons, respectively.

Drought not only affects the plant nutrient balance but also plant growth and development. In this respect, the revealed results in Table 5 clarified that all yield traits were reduced with lowering water supply. As averages of the two seasons, the reductions owing to Irr60 and Irr80 compared to Irr100 were 11.1 and 4.4% in SPAD value, 6.7 and 1.4% in spike length, 25.1 and 11.2% in grains weight spike⁻¹, 17.4 and 7.0% in weight of 1000 grains, as well as 34.8 and 13.2% in grain yield ha⁻¹, respectively (Fig. 1). Under deficit irrigation at 80% of crop evapotranspiration, the growth and yield index of spring wheat were not influenced greatly and reached 5–13% lower than under full irrigation. While, under deficit irrigation at 60% crop evapotranspiration, the growth and yield index were greatly reduced by about 10–37% lower than under full irrigation (Zhou 2020). Water stress occurred decreases in water uptake by roots, leaf expansion and stomatal conductance, causing a decrease in carbon assimilation in photosynthesis process and yield (Christophe et al. 2011; Sharma et al. 2020a; El-Metwally and Saady 2021). Declined frequency of cell division and cell enlargement, root differentiation, shoot

Fig. 1 Reductions in leaf greenness (SPAD value), spike length (cm), grains weight spike⁻¹ (g) weight of 1000 grains (g), and grain yield (t ha⁻¹) of wheat owing to Irr60 and Irr80 compared to full irrigation (Irr100). Irr60, Irr80 and Irr100: irrigation at 60, 80 and 100% of crop evapotranspiration, respectively

length, altered stomatal movements, water and mineral nutrition association with decreased plant yield and water use efficiency are the major outcomes of drought (Kumawat and Sharma 2018; Mubarak et al. 2021). Photosynthesis activity is decreased primarily by closing of stomata, membrane injury and altered functioning of several enzymes, particularly those which are associated with ATP synthesis (Kumawat and Sharma 2018; Sharma et al. 2020a). Drought stress conditions also enhanced generation of reactive oxygen species (ROS) and reactive nitrogen species (RNS), which disturb the cell redox regulatory functioning (Laxa et al. 2019; Sharma et al. 2020b). Accordingly, water deficit, especially at elongation and heading stages would reduce the yield of wheat (Tari 2016).

To mitigate against the detrimental impacts of water deficit, new tactics are urgently needed to ensure future food security. Results of the current study showed the ben-

eficial effect of Si in enhancing leaf greenness (Table 5). Improvements in SPAD or chlorophyll content were noted with silicate fertilizer (Silva et al. 2012; Radkowski and Radkowska 2018). Moreover, Si fertilization had the potentiality to improve plant tolerance to drought (Debona et al. 2017; Luyckx et al. 2017). In this situation, Si can improve anti-oxidative both enzymatic and non-enzymatic defense mechanisms thus, avoid damage from ROS produced by various abiotic stresses (Maghsoudi et al. 2019; Sattar et al. 2019). Si influences water relations in drought-treated plants, since it induces the formation of a silica cuticle double layer under the leaf epidermis which reduces water losses through cuticular transpiration (Gong et al. 2003). Si also reduces stomatal conductance in relation to turgor loss of guard cells resulting from Si deposition and modified cell wall properties (Zhu and Gong 2014). The improvement of drought resistance due to Si application could be ascribed to its strong abilities to extract water from the soil because of Si-related promotion of root elongation (Hattori et al. 2005) and up-regulation of aquaporin genes (Liu et al. 2015). Si has been described to reduce many of the effects including the biological and abiotic stresses of plants at high evaporation rates, and maintain the water potential of plants, photosynthesis, stomatal conductivity, and leaf erection (Das et al. 2017). Si improves the plant growth by modulating the nutrient (Na, Mg and Si) uptake and phytohormone levels and alleviating plant stress levels (Gong et al. 2008). Enhancing the tolerance of the wheat plants against drought stress was achieved, since Si caused balance of endogenous hormones (Xu et al. 2017). Moreover, the associated cation with silicon could have a promotive role for enhancing drought tolerance. In this respect, osmotic adjustment is considered an effective component of drought resistance (Gomathi et al. 2010). Potassium affects the osmotic adjustment of the plant and increases drought resistance by enhancing the translocation of assimilates and maintaining osmotic charge (Marschner 1995; Mubarak et al. 2016). Accordingly, supplying wheat plants by potassium silicate, particularly under severe water deficit is regarded as a crucial action to enhance the tolerance of plants with reducing yield losses.

Conclusion

Since lower accumulation of Si in plant tissues under water deficit than well-watered was recorded, the significance of foliar application of Si when plants receive low water supply become more essential. Moreover, potassium, calcium, and aluminum silicates showing similar yield, farmers could choose any available Si form to fertilize wheat irrigated by water less than the full irrigation. However, under moderate water supply (irrigation by 80% of crop evapotranspi-

ration), potassium silicate could be the favorite Si form for obtaining better yield.

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