

Article

Regulation of Agronomic Traits, Nutrient Uptake, Osmolytes and Antioxidants of Maize as Influenced by Exogenous Potassium Silicate under Deficit Irrigation and Semiarid Conditions

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Abstract: Understanding the link between the protective role of potassium silicate (K_2SiO_3) against water shortage and the eventual grain yield of maize plants is still limited under semiarid conditions. Therefore, in this study, we provide insights into the underlying metabolic responses, mineral nutrients uptake and some nonenzymatic and enzymatic antioxidants that may differ in maize plants as influenced by the foliar application of K_2SiO_3 (0, 1 and 2 mM) under three drip irrigation regimes (100, 75 and 50% of water requirements). Our results indicated that, generally, plants were affected by both moderate and severe deficit irrigation levels. Deficit irrigation decreased shoot dry weight, root dry weight, leaf area index (LAI), relative water content (RWC), N, P, K, Ca, Fe, Zn, carotenoids, grain yield and its parameters, while root/shoot ratio, malondialdehyde (MDA), proline, soluble sugars, ascorbic acid, soluble phenols, peroxidase (POD), catalase (CAT), polyphenol oxidase (PPO), and ascorbate peroxidase (APX) were improved. The foliar applications of K_2SiO_3 relatively alleviated water stress-induced damage. In this respect, the treatment of 2 mM K_2SiO_3 was more effective than others and could be recommended to mitigate the effect of deficit irrigation on maize plants. Moreover, correlation analysis revealed a close link between yield and the most studied traits.

Keywords: drip irrigation; silicon; mineral nutrients; oxidative stress; osmolytes; yield; *Zea mays*

1. Introduction

Semiarid regions are considered a pattern of drylands where the annual precipitation is not sufficient to meet the needs to grow vegetation all year. Generally, the rainfall in these regions ranges from 200 to 750 mm/year. This means the ratio between the total annual rainfall/the potential evapotranspiration reaches approximately 0.20 to 0.50 [1,2]. Currently, water scarcity is predicted to become the most severe environmental challenge that affects the agricultural sector and multiple socio-economic activities in many regions worldwide, especially with frequent climatic changes [3]. The harmful effects of drought stress on plants are usually associated with several events at cellular, biochemical, physiological and molecular levels that may enable the plants to adapt or tolerate such conditions [4–6]. These responses include the rapid generation of reactive oxygen species (ROS) [7], development of an array of complex antioxidant (nonenzymatic and enzymatic) systems [8], regulation of the expression of tolerance related genes [9] and alternation of nutrient uptake [10].

Maize (*Zea mays*) represents the third most important cereal crops cultivated worldwide after wheat and rice [11]. It has a high nutritional value for both human and animals; it contains approximately 72% starch, 10% protein and 4% fat, supplying an energy density of 365 Kcal/100 g [12]. Furthermore, maize provides suitable raw materials for several industries such as starch, fodder, silage and biofuels [13–15]. It is well documented that maize is highly sensitive to drought stress during any period of its growth cycle [16]. Water stress can cause considerable loss in the grain yield ranging from approximately 40–65% according to the genotype, stage of plant growth (the reproductive stage is more sensitive than the vegetative stage) and both the intensity and duration of exposure [17].

Potassium (K) is an essential macronutrient with broad effects on higher plants. In maize, K alleviates the harmful effects of drought stress by different strategies, including the improvement of net carbon assimilation and phloem transport of sugars from leaves to roots [18]. Moreover, K can enhance leaf area, total yield, grain filling and water use efficiency (WUE) in the stressed plants by decreasing leaf evapotranspiration [19]. In addition, K could play a key role in preventing oxidative damage of the maize plants by maintaining ROS homeostasis and enhancing antioxidant capacity [20].

Although silicon (Si) is not considered an essential mineral nutrient, several lines of evidence confirmed its benefits for plants, particularly under biotic and abiotic stresses [21]. It can promote photosynthesis by increasing the concentration of chlorophyll [22], and affect the activities of RuBisCO and PEP-carboxylase that are required for CO₂ fixation [23]. Furthermore, Si regulates antioxidant enzyme systems under diverse stress conditions [21]. Under drought stress, Si deposits in the cell walls of xylem vessels could prevent their compression caused by the high rate of transpiration [24], and it can improve the hydraulic conductivity of the roots in the radial direction leading to enhance uptake of water [25] and several essential nutrients [26]. Moreover, many previous reports indicated that Si could alleviate water deficit stress by improving osmotic adjustment and compatible solutes accumulation, i.e., proline, soluble sugars, free amino acids and polyamines, in several plant species [25,27].

Potassium silicate (K₂SiO₃) is a soluble source of potassium and silicon; it can be used as a fertilizer to maximize the benefits of both elements on plant growth and productivity. In this study, we provide insights into the underlying metabolic changes, uptake of mineral nutrients and some nonenzymatic and enzymatic antioxidants that may differ in maize plants as influenced by the foliar application of K₂SiO₃ under three irrigation regimes. These results may help to understand the link between the protective role of K₂SiO₃ against drought stress and the eventual yield of grains, especially under semiarid conditions.

2. Materials and Methods

2.1. Experimental Layout and Growth Conditions

Two field experiments were carried out during the seasons of 2018 and 2019 on a private farm, Ahmed Orabi Association, Cairo-Ismailia desert road, Qalyubia Governorate, Egypt. To investigate the effect of foliar application of potassium silicate (K₂SiO₃) at 0, 1 and 2 mM on growth, yield and some physiological and biochemical attributes of maize plants grown under three different levels of

drip irrigation (100, 75 and 50% water requirements). Before the establishment of the experiments, samples of soil were collected by an Auger T-Handle at depth 30–60 cm for physical and chemical analyses (Table 1). Climatic data were recorded by an agrometeorological station, Ismailia, to monitor the environmental conditions during the experiment (Table 2).

Table 1. Physical and chemical analysis of the experimental soil before cultivation in the seasons of 2018 and 2019.

Season	pH	EC $\mu\text{S cm}^{-1}$	$\text{CaCO}_3\%$	Cation meq/L			Anion meq/L		
				Ca^{++}	Mg^{++}	Na^+	HCO_3^-	Cl^-	SO_4^{--2}
2018	7.84	0.41	2.87	5.52	0.38	1.03	1.59	1.20	1.74
2019	7.61	0.47	3.13	7.04	0.50	0.80	2.14	1.38	1.62
N, P, K	N	P	K	Sand%	Silt%	Clay%	Soil texture		
	(ppm)								
2018	2.88	6.38	1.17	91.95	4.81	3.24	Sandy		
2019	2.03	6.22	0.91						

EC: Electrical conductivity.

Maize seeds of white single cross hybrid (Hytech 2030) produced by Misr Hytech Seed Int., Egypt was sown on 17th of May 2018 and 2019, respectively. The experiment was arranged in a split plot design with three replicates. A surface drip irrigation system with three levels (100, 75, and 50% of water requirements) was implemented in the main plots, and the foliar applications of K_2SiO_3 treatments (0, 1, and 2 mM) were randomly distributed in the subplots. The experimental unit area was 60 m^2 (15 m length \times 4 m width) consisting of 5 rows with 0.8 m distance between rows. The plant distance was 30 cm apart on one side. Maize plants were irrigated using drippers of 4 L h^{-1} capacity and 0.3 m distance between drippers. A flow meter was installed for each irrigation level treatment, and three rows were left without irrigation as a border between different irrigation levels.

Table 2. Monthly averages of solar radiation, precipitation, wind speed, air temperature and relative humidity during the period of cultivation (May–September) in the season 2018 and 2019.

Date	Solar Radiation Dgt [MJ/m^2]	Precipitation [mm]	Wind Speed [m/s]		Air Temperature [$^{\circ}\text{C}$]			Relative Humidity [%]
	Average		Sum	Average	Max	Average	Min	Max
2018								
May	671.29	0.0	1.4	8.9	23.9	11.8	38.5	62.5
June	654.76	0.0	1.3	5.6	26.6	13.4	38.2	67.4
July	616.47	0.0	0.9	4.8	27.7	16.9	37.4	75.5
August	542.00	0.0	0.5	3.7	27.5	17.4	38.0	75.0
September	424.92	0.0	0.7	3.8	25.2	14.7	36.2	73.5
2019								
May	689.12	0.0	1.3	6.5	23.9	12.7	36.1	58.1
June	535.47	0.0	1.3	5.2	27.6	15.7	39.6	65.6
July	472.97	0.0	1.1	5.0	27.5	17.8	37.2	71.0
August	415.72	0.0	1.0	4.6	27.3	17.0	37.5	73.4
September	327.05	0.0	1.0	5.3	25.8	14.6	41.2	69.8

2.2. Calculations of Water Regimes

Data of class A pan (Epan) for the experimental site expressed in mm/day were obtained from an agrometeorological station located close to the site. Water requirements (Table 3) for different irrigation levels were calculated for 105 days, and then irrigation was stopped for 11 days before the harvesting date (117 days after sowing). The calculation was made according to Doorenbos [28].

Table 3. Average amounts of the water requirements for the maize plants in the seasons of 2018 and 2019.

Days	Date	Stage	KC*	Irrigation Level (m ³ ·ha ⁻¹)		
				100%	75%	50%
10 days	17/5:26/5	initial	0.3	299.52	299.52	299.52
10 days	27/5:5/6		0.6	694.08	694.08	694.08
Starting date of different irrigation regimes						
15 days	6/6:20/6	development	0.9	953.28	714.96	476.64
20 days	21/6:10/7		1.0	1114.56	835.92	557.28
20 days	11/7:30/7	Mid-season	1.2	1319.04	989.28	659.52
20 days	31/7:19/8		1.0	1085.76	814.32	542.88
10 days	20/8:29/8	Last season	0.9	1097.28	822.96	548.64
11 days	30/8:11/9				Not irrigated before harvest	
				Total amount (m ³ ha ⁻¹)		
116 Days				6563.52	5171.04	3778.56

KC*: Crop coefficient.

2.3. Foliar Application and Sampling

Maize plants were subjected to the foliar application of distilled water as a control and K₂SiO₃ (1 or 2 mM) four times: first at 24 days after sowing (DAS) then the subsequent applications were applied every 15 days. Tween 20 at 0.05 mL L⁻¹ was used as a wetting agent for all foliar treatments (K₂SiO₃-treated and control plants). To determine plant growth and physiological and biochemical changes in response to applications, plants samples were collected twice, first after 10 days of the last foliar application. Four plants were randomly collected from the inner rows to determine the vegetative growth (shoots and roots) in each experimental unit. Biochemical analyses were conducted using the 4th fully expanded leaf from the top, which was randomly collected from 3 plants of each experimental plot. In addition, two plants were randomly selected to collect the 4th fully expanded leaf from the top to determine mineral nutrients after drying in an oven at 105 °C. At the end of the experiment (117 DAS), grain yield per plant and its related traits were estimated, while the grain yield per hectare was determined from one inner row that was left for this purpose (12 m²/experimental unit).

2.4. Studied Parameters

2.4.1. Vegetative Growth

Shoot and root dry weights were determined by drying four plants from each experimental unit in an air-forced ventilated oven at 105 °C. The dry weight ratio of root/shoot ratio was calculated. Leaf area index (LAI) was calculated as described by Iqbal and Hidayat [29].

2.4.2. Leaf Relative Water Content (RWC)

Leaf relative water content was determined according to Ünayyar et al. [30]. Leaf discs (1.8 cm diameter) from 10 fully expanded young leaves (ear leaf) were taken from 6–8 plants at the mid-canopy position before irrigation. Then the discs were weighed (FW) and placed immediately in distilled water for 2 h at 25 °C then their turgid weights (TW) were recorded. The samples were dried in an oven at 110 °C for 24 h (DW). Relative water content (RWC) was calculated using the following formula: $RWC = (FW - DW)/(TW - DW) \times 100$.

2.4.3. Membranes Lipid Peroxidation

Lipid peroxidation was measured by the determination of malondialdehyde (MDA) as described by Heath and Packer [31]. Frozen leaf tissues were homogenized in 0.1% (w/v) trichloroacetic acid (TCA).

The absorbance (A) of the supernatant was measured at 535 nm and corrected for nonspecific turbidity at 600 nm using a spectrophotometer (Chrom Tech CT-2200, Taiwan). The MDA concentration (nmol g^{-1} FW) was calculated using ΔOD (A532-A600) and the extinction coefficient ($\epsilon = 155 \text{ mM}^{-1} \text{ cm}^{-1}$).

2.4.4. Proline and Soluble Sugars

Proline levels were determined using the method of acid-ninhydrin reagent as described by Bates et al. [32]. Soluble sugars were determined by anthrone-sulfuric acid reagent as described by Plummer [33].

2.4.5. Determination of Mineral Nutrients

Dry leaves were ground and digested using sulfuric acid and hydrogen peroxide. Leaf mineral concentrations of N, P, K, Ca, Fe and Zn were determined according to Cottenie et al. [34]. Nitrogen (N) was determined by the Kjeldahl method (Velp Scientifica, Europe). The colorimetric method by UV/VIS spectrophotometer was used to determine P; potassium (K) was determined by a Flamephotometer (Jenway, UK). Meanwhile, Ca, Fe and Zn were determined by atomic absorption spectrophotometry (AAS-Hitachi, Tokyo, Japan).

2.4.6. Determination of Carotenoids, Ascorbic Acid and Total Soluble Phenols

Carotenoids were determined using the acetone and petroleum ether method as described by de Carvalho et al. [35]. Ascorbic acid (AsA) was determined using the 2, 6-Dichloroindophenol titrimetric method according to Association of Official Analytical Chemists (A.O.A.C) [36]. Total soluble phenols were determined according to the method of Folin-Denis as described by Skalindi and Naczka [37].

2.4.7. Quantification of Antioxidant Enzymes

Leaf tissue of maize plants (0.5 g) was homogenized in 4 mL 0.1 M K-phosphate buffer (pH 7.0) containing 1% (*w/v*) polyvinylpyrrolidone (PVP) and 0.1mM Ethylenediaminetetraacetic acid (EDTA). The homogenate was centrifuged at 10,000 rpm for 15 min and the supernatant was used as a crude enzyme extract. All the preparation steps of the enzyme extract were carried out at 0–4 °C. Total soluble protein was determined according to Bradford [38].

Peroxidase (EC1.11.1.7) activity was quantified by the method of Hammerschmidt et al. [39]. The absorbance was recorded every 30 s for 3 min at 470 nm using a spectrophotometer (Chrom Tech CT-2200). Catalase (CAT) (EC 1.11.1.6) activity was determined according to the method of Cakmak et al. [40]. Polyphenol oxidase (PPO) (EC 1.14.18.1) activity was measured according to Oktay et al. [41]. The reaction mixture consisted of 100 μL crude enzyme, 600 μL catechol and 2.3 mL phosphate buffer (0.1 M, pH 6.5). The absorbance at 420 nm was recorded at zero time and after 1 min. Ascorbate peroxidase (APX) (EC 1.11.1.11) activity was measured according to the method of Nakano and Asada [42] by monitoring the decrease of absorbance at 290 nm following the ascorbate oxidation for 3 min. The reaction was initiated by the addition of H_2O_2 . All enzyme activities were expressed as $\Delta\text{OD min}^{-1} \text{ mg}^{-1}$ protein.

2.4.8. Determination of Yield Parameters

Maize ears were harvested at 117 DAS and averages of ear length, ear diameter, number of grains-ear⁻¹, weight of grains-ear⁻¹, weight of grains-plant⁻¹ were estimated from 10 random plants per each experimental unit. Eventually, total grain yield (t ha^{-1}) was calculated using the average yield of grains/12 m² (one inner row was left for this purpose in each experimental unit).

2.4.9. Statistical Analysis

Data of the two seasons were subjected to combined analysis following the two way ANOVA procedure as described by Snedecor and Cochran [43] using MSTAT-C software (Michigan State University, USA). Duncan's test based on a probability of $p \leq 0.05$ was used to determine the significant differences between means.

All data were expressed as means \pm standard deviation (SD). The correlation coefficient between the grain yield (t ha^{-1}) and different physiological and biochemical aspects was also estimated.

3. Results

3.1. The Main Effects of the Irrigation Levels and K_2SiO_3 Foliar Applications

Reduction of irrigation (moderate or severe level) caused significant ($p \leq 0.05$) decreases in shoot dry weight and root dry weight. Furthermore, a substantial reduction in the LAI, RWC, N, P, K, Ca, Fe, carotenoids, ear length, ear diameter, number of grains/ear, weight of grains/plant and grain yield (ton/ha) was observed when compared to the well-irrigated plants (Table 4), while, Zn was only decreased when plants were exposed to the irrigation level of 50% WR. In contrast, root/shoot ratio, MDA, proline, soluble sugars, ascorbic acid and soluble phenols, as well as the activities of peroxidase (POD), catalase (CAT), polyphenol oxidase (PPO), and ascorbate peroxidase (APX) were significantly increased (Table 4). The foliar applications of K_2SiO_3 at 1 or 2 mM significantly increased all studied variables except root/shoot ratio, MDA, proline and Zn. The treatment of 2 mM K_2SiO_3 was more effective in enhancing yield and its parameters than the lower concentration (1 mM).

Table 4. Mean comparison shows the main effects of the irrigation levels (100, 75, and 50 % of water requirements) and the foliar applications of K_2SiO_3 (0, 1, and 2 mM). KSi 0: K_2SiO_3 -untreated plants, KSi 1: K_2SiO_3 (1 mM) and KSi 2: K_2SiO_3 (2 mM). On the vegetative growth, water status, lipid peroxidation, osmolytes, mineral nutrients, non-enzymatic antioxidants, antioxidant enzymes, yield and its parameters of maize plants.

Variables	Irrigation Level			Foliar Application		
	100%	75%	50%	KSi 0	KSi 1	KSi 2
Shoot dry weight (g.plant^{-1})	318.4 ^A	242.1 ^B	208.1 ^C	232.6 ^C	260.3 ^B	275.7 ^A
Root dry weight (g.plant^{-1})	45.32 ^A	38.20 ^B	33.01 ^C	36.52 ^B	39.43 ^A	40.58 ^A
Root/shoot ratio	0.144 ^B	0.158 ^A	0.159 ^A	0.157 ^A	0.153 ^A	0.150 ^A
LAI	7.15 ^A	5.19 ^B	4.08 ^C	4.62 ^C	5.44 ^B	6.35 ^A
RWC (%)	88.11 ^A	73.13 ^B	67.79 ^C	75.52 ^B	77.17 ^A	76.34 ^{AB}
MDA (nmol.g^{-1} FW)	5.82 ^C	11.99 ^B	13.62 ^A	11.08 ^A	10.27 ^B	10.09 ^B
Proline ($\mu\text{g.g}^{-1}$ FW)	183.3 ^C	314.0 ^A	241.6 ^B	285.0 ^A	241.5 ^B	212.2 ^C
Soluble sugars (mg.g^{-1} DW)	24.50 ^B	45.54 ^A	44.53 ^A	35.13 ^C	37.99 ^B	41.44 ^A
N (mg.g^{-1} DW)	85.29 ^A	71.00 ^B	62.14 ^C	70.39 ^B	71.31 ^B	76.72 ^A
P (mg.g^{-1} DW)	2.24 ^A	1.91 ^B	1.50 ^C	1.77 ^B	1.93 ^A	1.96 ^A
K (mg.g^{-1} DW)	11.74 ^A	9.90 ^B	8.81 ^C	8.02 ^C	10.65 ^B	11.79 ^A
Ca (mg.g^{-1} DW)	7.25 ^A	6.52 ^B	5.22 ^C	6.07 ^B	6.31 ^{AB}	6.61 ^A
Fe ($\mu\text{g.g}^{-1}$ DW)	203.9 ^A	180.5 ^B	161.7 ^C	169.7 ^C	180.7 ^B	195.6 ^A
Zn ($\mu\text{g.g}^{-1}$ DW)	46.3 ^A	47.0 ^A	41.0 ^B	48.6 ^A	42.9 ^B	42.8 ^B
Carotenoids (mg.g^{-1} FW)	0.332 ^A	0.308 ^B	0.288 ^C	0.277 ^C	0.317 ^B	0.334 ^A
Ascorbic acid ($\mu\text{mol.g}^{-1}$ FW)	1.36 ^C	1.78 ^A	1.67 ^B	1.57 ^B	1.61 ^{AB}	1.64 ^{AB}
Soluble phenols ($\mu\text{g.g}^{-1}$ FW)	13.97 ^C	16.39 ^B	17.29 ^A	15.27 ^C	15.87 ^B	16.49 ^A
POD (Δ O.D. min^{-1} .mg protein)	14.3 ^C	33.6 ^B	35.6 ^A	25.92 ^B	28.90 ^A	28.67 ^A
CAT (Δ O.D. min^{-1} .mg protein)	2.64 ^C	4.17 ^A	3.57 ^B	3.19 ^B	3.58 ^A	3.60 ^A
PPO (Δ O.D. min^{-1} .mg protein)	6.95 ^C	8.59 ^B	9.69 ^A	7.97 ^B	8.57 ^A	8.67 ^A
APX (Δ O.D. min^{-1} .mg protein)	2.83 ^C	4.36 ^A	4.01 ^B	3.40 ^B	3.85 ^A	3.94 ^A
Ear length (cm)	23.3 ^A	19.1 ^B	15.7 ^C	18.2 ^C	19.4 ^B	20.5 ^A
Ear diameter (cm)	4.7 ^A	4.4 ^B	3.3 ^C	4.00 ^C	4.17 ^B	4.30 ^A
Number of grains/ear	332.4 ^A	271.8 ^B	226.3 ^C	264.7 ^B	281.2 ^A	284.6 ^A
Weight of grains/ear (g)	109.7 ^A	84.5 ^B	66.2 ^C	79.5 ^C	88.8 ^B	92.2 ^A
Weight of grains/plant (g)	172.8 ^A	127.6 ^B	95.0 ^C	118.1 ^C	135.0 ^B	142.4 ^A
Grain yield (ton.ha^{-1})	7.94 ^A	5.82 ^B	4.39 ^C	5.33 ^C	6.14 ^B	6.68 ^A

Data of the two seasons of 2018 and 2019 were subjected to combined analysis with 3 replicates in each season. The different superscript capital letters within a row indicate significantly different values according to Duncan's multiple range tests ($p < 0.05$). LAI, leaf area index; RWC, relative water content; MDA, malondialdehyde; POD, peroxidase; CAT, catalase; PPO, polyphenol oxidase; APX, ascorbate peroxidase.

3.2. Changes in Plant Growth

The progressive reduction in the irrigation level significantly ($p \leq 0.05$) inhibited plant growth in terms of shoot dry weight, root dry weight and LAI. In contrast, root/shoot ratio was not affected compared to the well-irrigated control (Figure 1). When plants were treated with K_2SiO_3 (1 or 2 mM), a significant increase was observed in shoot dry weight and LAI either under nonstressed or stressed conditions. Meanwhile, this trend was just obvious in root dry weight under water shortage conditions. Root/shoot ratio revealed a significant decrease in the K_2SiO_3 -treated plants under well-irrigated conditions. Generally, the highest concentration of the K_2SiO_3 treatments (2 mM) was more effective in this respect (Figure 1).

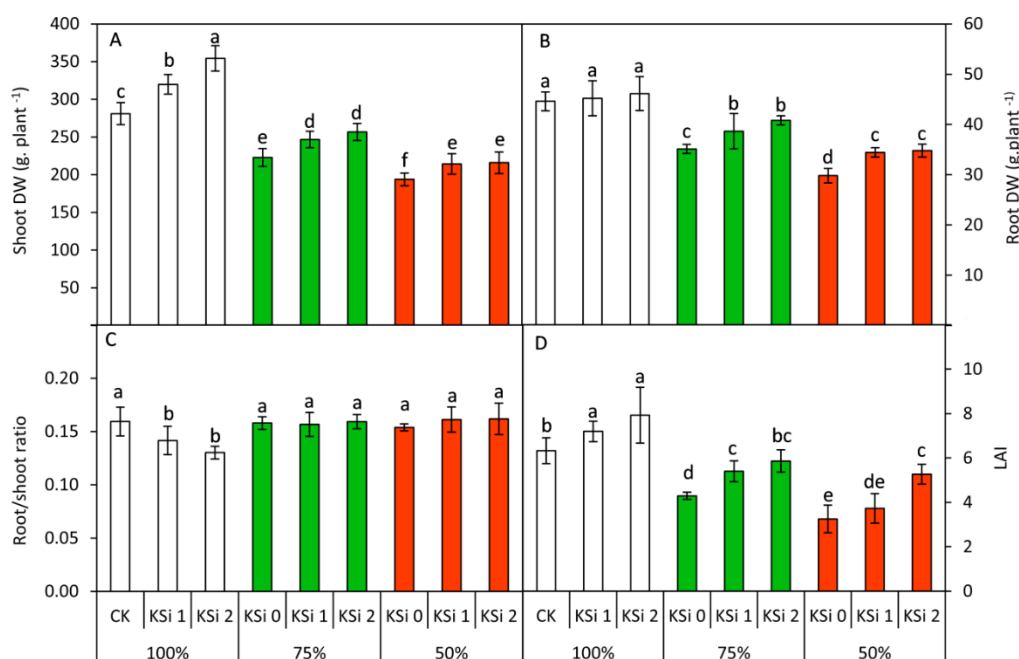


Figure 1. Shoot dry weight (A), root dry weight (B), root/shoot ratio (C) and leaf area index (LAI) (D) of the maize plants at 80 days after sowing (DAS) as influenced by the foliar application of K_2SiO_3 (0, 1 and 2 mM) under three irrigation regimes: 100% (white), 75% (green) and 50% (orange) of water requirements. CK: well-watered control, KSi 0: K_2SiO_3 -untreated plants, KSi 1: K_2SiO_3 (1 mM) and KSi 2: K_2SiO_3 (2 mM). Data of the two seasons of 2018 and 2019 were subjected to combined analysis. Means were presented \pm SD. Different letters are significant differences, according to Duncan's multiple range tests ($p < 0.05$).

3.3. Changes in RWC, MDA, Proline and Soluble Sugars

Plants that were exposed to deficit irrigation demonstrated a significant ($p \leq 0.05$) increase in MDA, proline and soluble sugars, whereas RWC was diminished compared to the well-irrigated conditions (Figure 2). The foliar applications of K_2SiO_3 significantly enhanced RWC under both investigated deficit-irrigation levels, while this tendency was conspicuous in soluble sugars under moderate level of deficit irrigation. Conversely, MDA and proline generally exhibited a significant decrease in K_2SiO_3 -treated plants compared to the untreated ones under stressed conditions. Overall, the treatment of 2 mM K_2SiO_3 was more efficient than the other treatments.

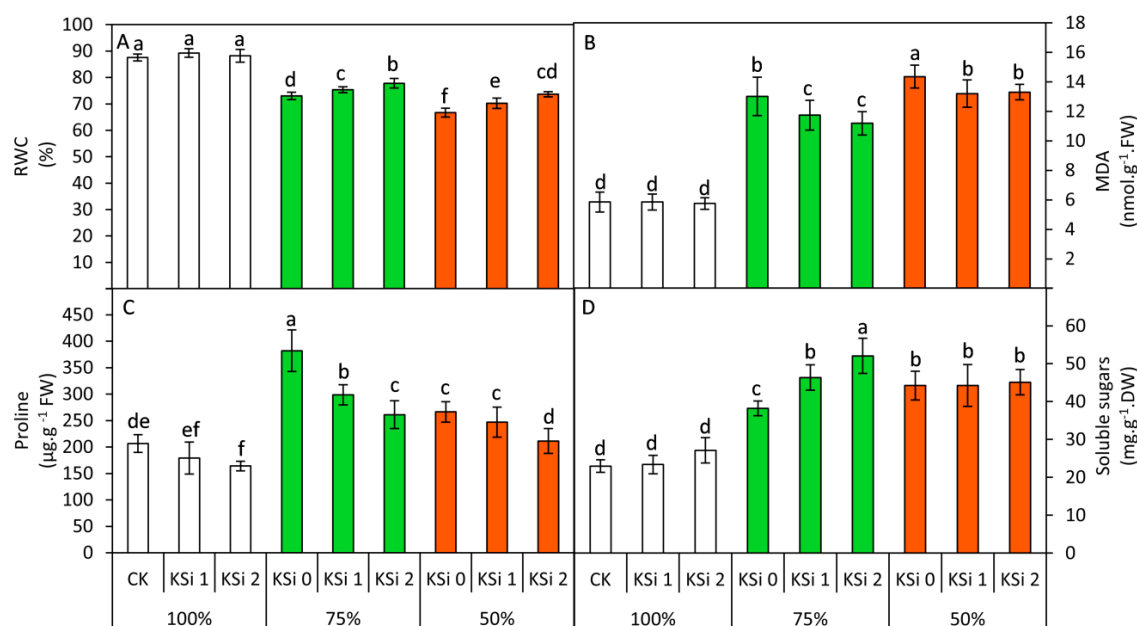


Figure 2. Leaf relative water content (RWC) (A), membranes lipid peroxidation as indicated by malondialdehyde (MDA) (B), proline (C) and soluble sugars (D) of t maize plants at 80 DAS as influenced by the foliar application of K_2SiO_3 (0, 1 and 2 mM) under three irrigation regimes: 100% (white), 75% (green) and 50% (orange) of water requirements. CK: well-watered control, KSi 0: K_2SiO_3 -untreated plants, KSi 1: K_2SiO_3 (1 mM) and KSi 2: K_2SiO_3 (2 mM). Data of the two seasons of 2018 and 2019 were subjected to combined analysis. Means were presented \pm SD. Different letters are significant differences, according to Duncan's multiple range tests ($p < 0.05$).

3.4. Changes in Mineral Nutrients

To evaluate the nutritional status of plants under continuous deficit irrigation and K_2SiO_3 foliar applications, N, P, K, Ca, Fe and Zn were quantified (Figure 3). The general tendency was that deficit irrigation obviously and significantly ($p \leq 0.05$) decreased N, K, Ca and Fe in K_2SiO_3 nontreated plants under both examined deficit levels of irrigation (75% and 50%). In comparison, P and Zn were only affected under the severe level of deficit irrigation (50%). Applied K_2SiO_3 , specifically at 2 mM, significantly improved the concentration of N, P, K, Ca and Fe under unstressed conditions. In contrast, a significant reduction in Zn was manifested in K_2SiO_3 -treated plants under well-irrigated conditions. When plants were subjected to continuous deficit irrigation, the treatment of 2 mM K_2SiO_3 exhibited the highest significant increases in N, K and Fe under both investigated levels of deficit irrigation. A similar trend was only observed in P under a moderate level of irrigation.

On the other hand, no significant differences were detected in Ca between K_2SiO_3 nontreated and the treated plants under both deficit irrigation levels (75% and 50%). Meanwhile, Zn was significantly decreased by the treatments of K_2SiO_3 under the moderate level of irrigation. This effect did not occur under the lower level of irrigation (50%).

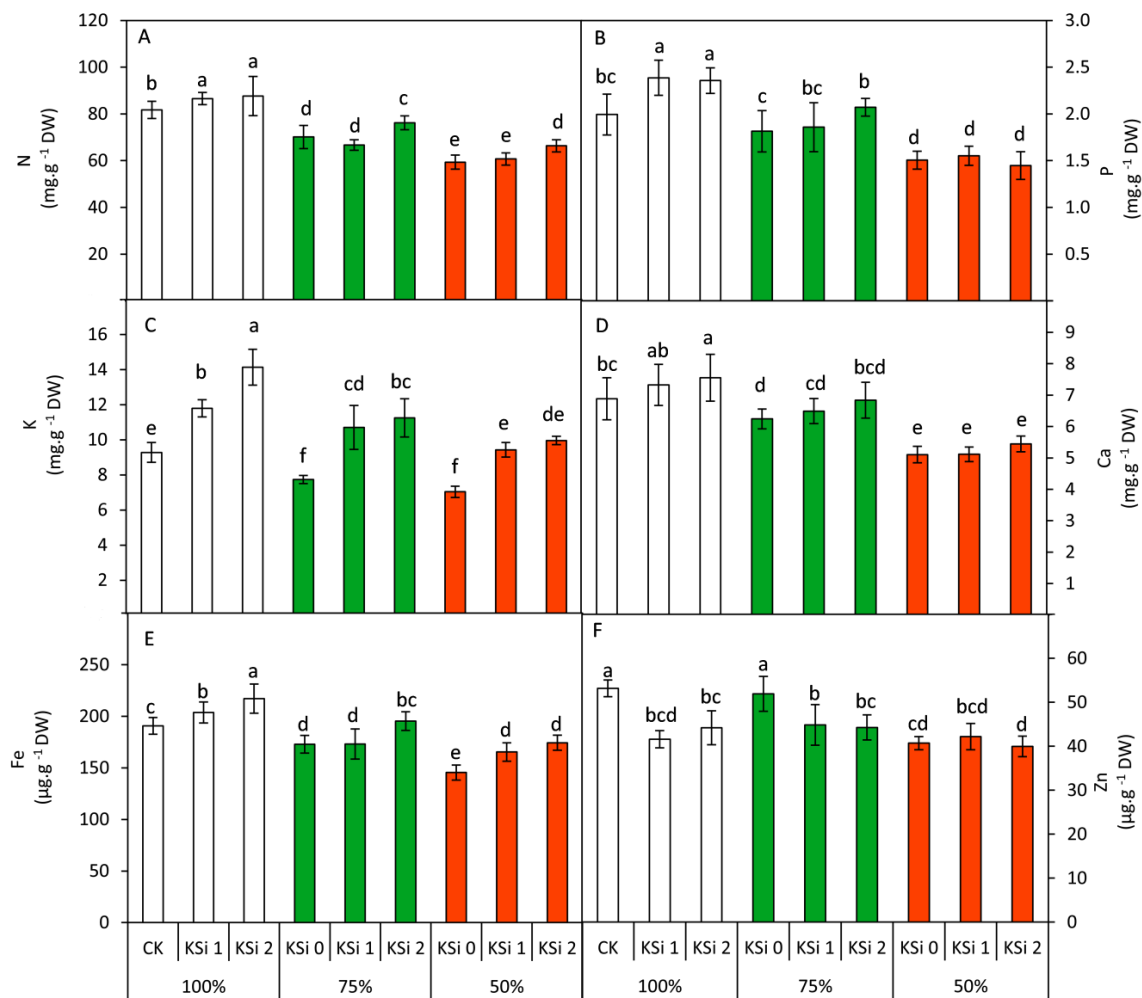


Figure 3. Leaf mineral content including N (A), P (B), K (C) Ca (D), Fe (E) and Zn (F) of the maize plants at 80 DAS as influenced by the foliar application of K₂SiO₃ (0, 1 and 2 mM) under three irrigation regimes: 100% (white), 75% (green) and 50% (orange) of water requirements. CK: well-watered control, KSi 0: K₂SiO₃-untreated plants, KSi 1: K₂SiO₃ (1 mM) and KSi 2: K₂SiO₃ (2 mM). Data of the two seasons of 2018 and 2019 were subjected to combined analysis. Means were presented ± SD. Different letters are significant differences, according to Duncan's multiple range tests ($p < 0.05$).

3.5. Changes in Nonenzymatic Antioxidants

Nonenzymatic antioxidant capacity of plants was investigated by the determination of carotenoids, ascorbic acid and soluble phenols (Figure 4). Plants that were not applied by K₂SiO₃ and exposed to continuous deficit irrigation demonstrated a significant ($p \leq 0.05$) increase in ascorbic acid and soluble phenols compared to the well-watered conditions, whereas carotenoids did not show any significant differences in this respect. Applied K₂SiO₃ (1 or 2 mM) significantly enhanced carotenoids and ascorbic acid, while soluble phenols were not changed under well-irrigated conditions. Similarly, K₂SiO₃ applications, in particular at the highest concentration (2 mM), exhibited the highest significant increases in carotenoids and soluble phenols under both investigated levels of deficit irrigation (75 and 50%). On the other hand, ascorbic acid revealed an opposite trend by the treatment of 2 mM K₂SiO₃ under the moderate (75%) and lower (50%) levels of irrigation.

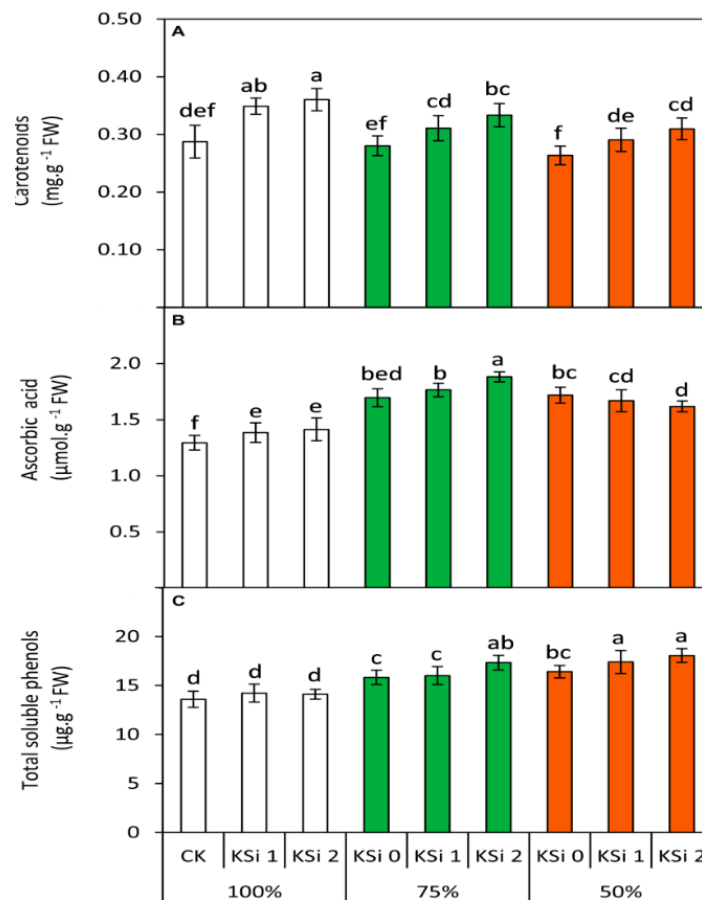


Figure 4. Nonenzymatic antioxidants including carotenoids (A), ascorbic acid (AsA) (B) and total soluble phenols (C) in the leaves of the maize plants at 80 DAS as influenced by the foliar application of K_2SiO_3 (0, 1 and 2 mM) under three irrigation regimes: 100% (white), 75% (green) and 50% (orange) of water requirements. CK: well-watered control, KSi 0: K_2SiO_3 -untreated plants, KSi 1: K_2SiO_3 (1 mM) and KSi 2: K_2SiO_3 (2 mM). Data of the two seasons of 2018 and 2019 were subjected to combined analysis. Means were presented \pm SD. Different letters are significant differences, according to Duncan's multiple range tests ($p < 0.05$).

3.6. Changes in Antioxidant Enzymes

The activities of antioxidant enzymes (POD, CAT, PPO, and APX) were determined in this study under deficit irrigation conditions and the exogenous application of K_2SiO_3 (Figure 5). No significant differences were observed between K_2SiO_3 -treated, and nontreated plants in the activity of all studied antioxidant enzymes under well-irrigated conditions. Reducing irrigation levels significantly ($p \leq 0.05$) increased the activity of these enzymes compared to the well-irrigated conditions. Applied- K_2SiO_3 significantly enhanced the activity of CAT, PPO and APX under the moderate level of irrigation (75%), whereas POD was not affected. When plants were exposed to severe deficit irrigation (50%), POD exhibited a significant increase by the treatment of 1 mM K_2SiO_3 . At the same time, the highest activity of CAT and PPO were obtained by the treatment of 2 mM K_2SiO_3 . On the contrary, APX did not reveal any significant differences between K_2SiO_3 -treated and nontreated plants under the lower level of irrigation.

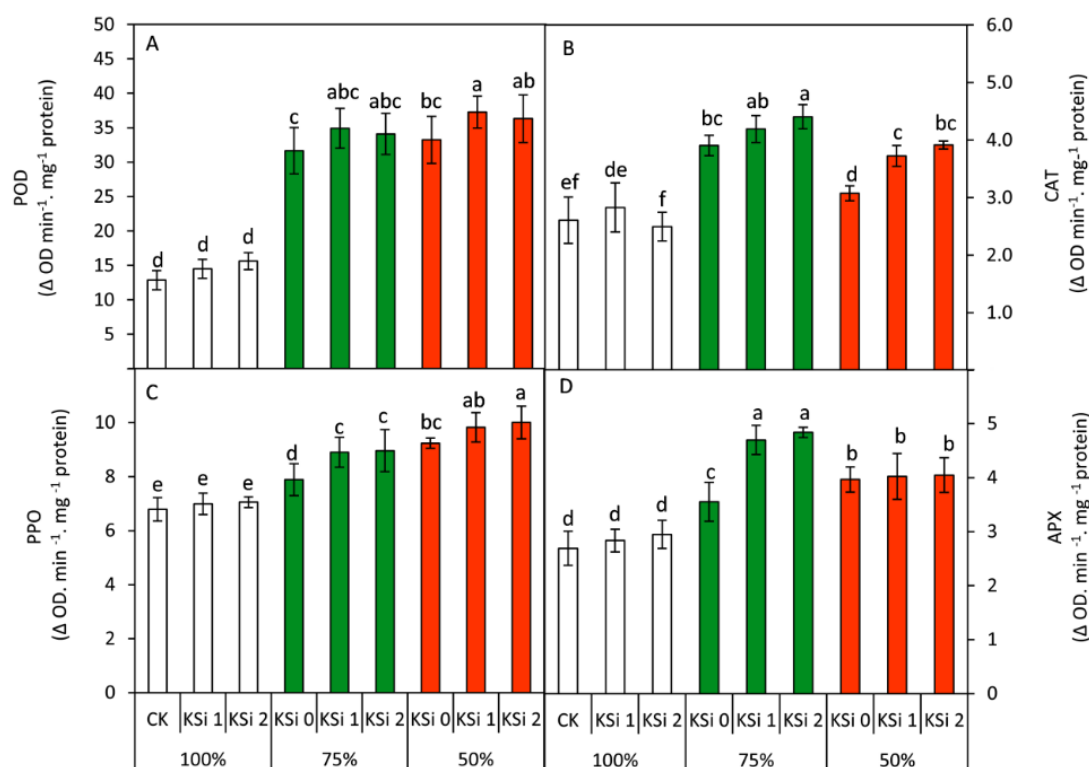


Figure 5. Activities of antioxidant enzymes including POD (A), CAT (B), PPO (C) and APX (D) in the leaves of maize plants at 80 DAS as influenced by the foliar application of K_2SiO_3 (0, 1 and 2 mM) under three irrigation regimes: 100% (white), 75% (green) and 50% (orange) of water requirements. CK: well-watered control, KSi 0: K_2SiO_3 -untreated plants, KSi 1: K_2SiO_3 (1 mM) and KSi 2: K_2SiO_3 (2 mM). Data of the two seasons of 2018 and 2019 were subjected to combined analysis. Means were presented \pm SD. Different letters are significant differences, according to Duncan's multiple range tests ($p < 0.05$).

3.7. Changes in Yield Parameters

Grain yield and its parameters, including ear length, ear diameter, number of grains-ear⁻¹, weight of grains-ear⁻¹, weight of grains-plant⁻¹ and total grain yield (t ha⁻¹) were estimated in this investigation (Figure 6). Concerning K_2SiO_3 -untreated plants, reducing irrigation level led to significant ($p \leq 0.05$), and gradual decreases in all yield parameters studied in parallel with the severity of deficit irrigation. Generally, except for the number of grains-ear⁻¹ under the lower level of irrigation, applied- K_2SiO_3 , specifically at 2 mM, significantly improved all studied traits regardless of the level of irrigation.

3.8. Relationships between Grain Yield and RWC, MDA, Osmolytes, Nutrients and Antioxidants

To elucidate the relationships between the grain yield of maize plants as influenced by the foliar applications of K_2SiO_3 under different irrigation regimes and RWC, MDA, osmolytes, nutrients and antioxidants, the correlation coefficient was analyzed (Figure 7). We observed that grain yield (t ha⁻¹) was significantly and positively correlated with leaf relative water content (RWC), carotenoids, N, P, K, Ca and Fe. Meanwhile, MDA, soluble sugars, soluble phenols, POD and PPO demonstrated a negative correlation. On the other hand, proline, ascorbic acid (AsA), CAT, APX and Zn did not reveal any significant correlation in this respect.

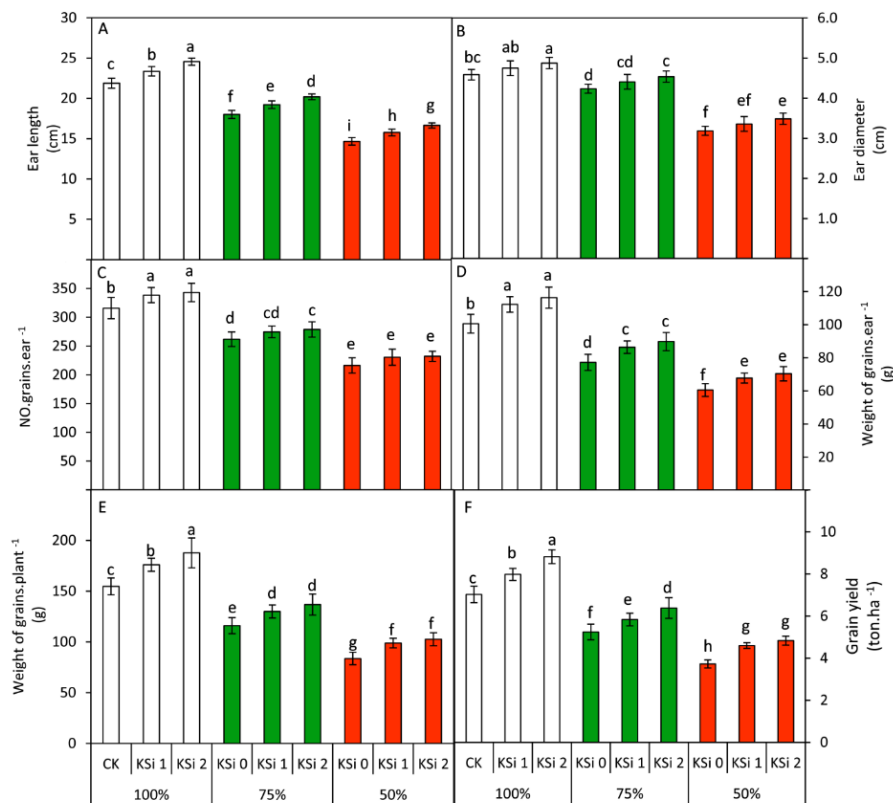


Figure 6. Yield and its parameters including averages of ear length (A), ear diameter (B), number of grains/ear (C) weight of grains/ear (D), weight of grains/plant (E) and grain yield (t ha⁻¹) (F) of the maize plants at 80 DAS as influenced by the foliar application of K₂SiO₃ (0, 1 and 2 mM) under three irrigation regimes: 100% (white), 75% (green) and 50% (orange) of water requirements. CK: well-watered control, KSi 0: K₂SiO₃-untreated plants, KSi 1: K₂SiO₃ (1 mM) and KSi 2: K₂SiO₃ (2 mM). Data of the two seasons of 2018 and 2019 were subjected to combined analysis. Means were presented ± SD. Different letters are significant differences, according to Duncan's multiple range tests (*p* < 0.05).

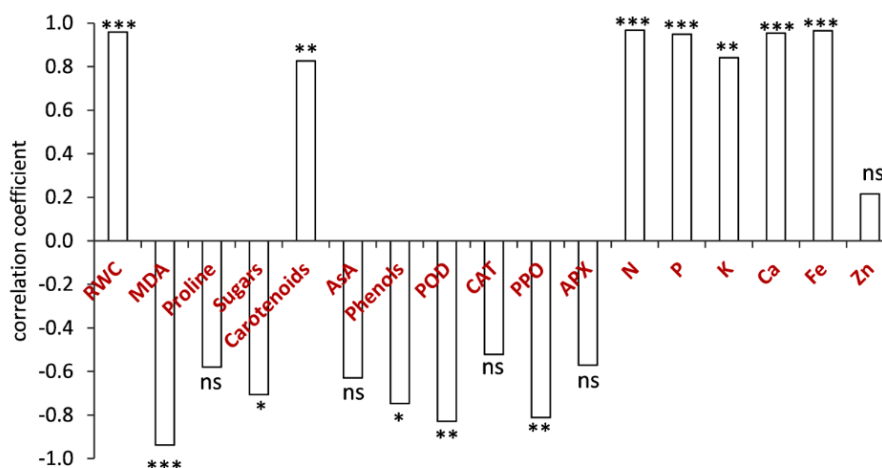


Figure 7. Relationship between the grain yield of maize crop and RWC, MDA, osmolytes, nonenzymatic antioxidants, antioxidant enzymes and mineral nutrients as influenced by the foliar application of K₂SiO₃ (0, 1 and 2 mM) under three different irrigation regimes (100, 75 and 50% of water requirements). Data of the two seasons of 2018 and 2019 were subjected to combined analysis. ns: not significant, * *p* ≤ 0.05, ** *p* ≤ 0.01 and *** *p* ≤ 0.001.

4. Discussion

Under semiarid conditions, deficit irrigation is thought to be one of the most limiting factors that can restrict plant growth and productivity. In this study, soil analysis and climatic data showed that maize was exposed to high solar radiation and air temperatures with no precipitation during the cultivation periods in the two seasons. All of these factors exhibited drought stress on the maize plants during this study. It is well documented that drought stress reduces the growth of many plant species due to the restriction of cell division and differentiation [44]. In this study, reducing irrigation level exhibited significant decreases in shoot dry weight, root dry weight and LAI of the water-stressed plants (Figure 1). These reductions could be attributed to the disruption that occurred in the photosynthetic process through the degradation of pigments, limitation of stomatal conductance and decreasing the photochemical quantum yield [8,45]. On the other hand, root/shoot ratio as dry weight was unaffected under deficit irrigation (Figure 1). These results were in agreement with those obtained by Ma et al. [46], and may imply that phloem transport and leaf carbon exportation were less sensitive to water deficit under the circumstances of this study.

The positive effect of K_2SiO_3 on the shoot, root dry weight and LAI in the water-deficit stressed plants could be attributed to the synergistic effect of both K and Si on photosynthesis and production of assimilates [20,47]. In the present study, deficit irrigation negatively affected RWC while the K_2SiO_3 applications significantly mitigated this effect (Figure 2). Applied K positively affected leaf water content under stress conditions by maintenance of turgor potential and enhancing the integrity of cell membranes [48]. Additionally, Si could improve RWC by decreasing the rate of transpiration [49]. Lipid peroxidation is considered a pervasive biochemical response to stress in plant species due to the uncontrolled release of ROS [8]. Applied K and/or Si can promote the antioxidant capacity of the stressed plants [20,21]. This response may explain the significant decrease of MDA in the treated plants with K_2SiO_3 under water-stressed conditions (Figure 2). Proline is considered a compatible osmolyte and one of the most contributing factors that maintain intracellular redox homeostasis under stress conditions [50]. Moreover, under drought stress, proline has a crucial role in protecting the integrity of cell membranes and osmotic adjustments that allow the plant to uptake water [50,51]. Soluble sugars are the second compatible osmolytes that were determined in this investigation. The accumulation of soluble sugars during water deficit irrigation could be due to the up-regulation of genes involved in the starch-sucrose pathway [52,53]. All of the above-mentioned responses may explain the dramatic accumulation of proline and soluble sugars in the water-stressed plants under the circumstances of this study (Figure 2). The exogenous application of K_2SiO_3 resulted in a notable decrease in proline and a visible increase in soluble sugars. These effects indicate that K and/or Si may enhance the osmotic potential of leaves by stimulating the conversion of starch into soluble sugars, particularly up to the moderate level of irrigation [54,55]. Furthermore, the decrease of proline in the K_2SiO_3 -treated plants may highlight the significance of K and/or Si in the protection of cell membranes and maintenance of RWC under deficit irrigation conditions (Figure 2).

Drought stress strongly affects the uptake of nutrients and it can restrict the translocation of some nutrients acropetally between plant organs [56]. Furthermore, it negatively affects active transport, permeability, and leaf transpiration [25,57]. In our study, plants exposed to moderate or severe stress exhibited a significant decline in N uptake (Figure 3A). This could be due to decreases in the activity of the N-uptake proteins (NRT1, NRT2) for inorganic nitrate (NO_3^-) and (AMT1) or ammonium (NH_4^+) [58]. Additionally, the availability of N could be reduced under the inadequate water supply [59]. The foliar application of K_2SiO_3 improved N-uptake under stressed and normal conditions. Applied-K can ameliorate the deleterious effects of drought through the regulation of stomatal movement, increasing root cell elongation, osmotic adjustment and detoxification of ROS [48]. Furthermore, silicon improves photosynthesis, antioxidant activities, and absorption of mineral nutrients of many crops [21,47]. These effects could explain the positive influence of K_2SiO_3 on N-uptake in our study. Concerning phosphorus (P), it was decreased under severe level of deficit irrigation (50%) (Figure 3B). This decrease may be attributed to reducing the concentration and/or

activity of the P-uptake protein (PHT1) [58]. Moreover, under drought stress, P may be quickly converted into an immobile or insoluble form [60]. On the other hand, the increase in P-uptake prior to K_2SiO_3 application was significantly under severe and moderate stress. These effects imply that P-uptake in maize is highly dependent on the intensity of drought stress. Similarly, water stress markedly exhibited K deficiency compared to all K_2SiO_3 untreated plants (Figure 3C). This effect could be due to reduction in absorption by the roots and transpiration rate, which consequently reduced water and nutrient transport via xylem [60]. Applied- K_2SiO_3 significantly increases K content compared to the untreated plants. These results are in agreement with Jiang et al. [61], who found that the application of K can significantly increase its concentration in the different parts of maize plants such as grains and straw. In this study, Ca uptake was also inhibited by reducing water supply (Figure 3D). This impact was clear under the lower level of stress. Furthermore, the foliar application of K_2SiO_3 had no significant effect on Ca uptake under both examined treatments. Maize plants could be severely affected by Ca deficiency under drought condition because Ca is relatively an immobile nutrient and its uptake may require sufficient water supply [62].

Deficit irrigation manifestly suppressed the uptake of Fe in K_2SiO_3 -untreated plants (Figure 3E). In contrast, applied K_2SiO_3 , specifically at the highest concentration (2 mM), improved Fe-uptake under both treatments. Silicon (Si) can mitigate the symptoms of Fe deficiency in different plant species including soybean, cucumber and rice [63,64]. It could play a crucial role in Fe uptake and its translocation from roots to the aerial parts of the plant [65,66]. This impact could be attributed to the fact that applied-Si can enhance citrate concentration, which acts as an Fe chelator and facilitates its movement through the xylem [67]. The translocation of Zn from roots to leaves may be inhibited by Si application. This effect may be due to the fact that Si precipitates with Zn as zinc silicate around the root epidermis [68], which may reduce Zn translocation via xylem [69].

Under drought stress, plants develop a wide array of complex antioxidant systems that integrated with each other simultaneously to reduce the accumulation of ROS and oxidative damages [70]. The foliar application of K_2SiO_3 induced dramatic improvement in the concentration of carotenoids under different investigated levels of irrigation. The increase of carotenoids under water stress due to K or Si supplementation could foster the antioxidant capacity of plants under deficit irrigation [71–74]. Under stress conditions, ascorbate (ASA) could be increased through the overexpression of its synthesis related-genes such as GMP, GME, GalUR, DHAR, and MDHAR [75]. In this study, ASA was substantially increased by reducing the irrigation level (Figure 4B). This response could help in scavenging ROS and inducing the ascorbate–glutathione cycle [8,76]. Phenolic compounds could also be involved in plant tolerance to drought stress and play a significant role as a sink for carbon under stress conditions [77,78]. These effects could explain the improvement in total soluble phenols by reducing the irrigation level in this study (Figure 4C). The increase in total soluble phenols by the treatments of K_2SiO_3 could be due to the effect of Si, which may induce several changes in the phenolic compounds under abiotic and biotic stresses [79,80].

In the present study, our results showed that deficit irrigation increased the activities of POD, CAT, PPO and APX in the leaves of maize plants (Figure 5). These findings could reflect the integrated regulation between these enzymes in the tolerance of maize plants to water stress. Exogenous applications of K_2SiO_3 induced a synergistic effect leading to an increase in the activities of all studied antioxidant enzymes under deficit irrigation levels. Previous reports showed that K and/or Si could enhance the antioxidant capacity of plants under stress conditions [20,21]. In this study, these effects were confirmed by the enhancement of RWC and reduction of MDA.

It is well documented that water stress has several deleterious influences on the productivity of maize plants [17,81]. It can affect different metabolic pathways, photosynthesis and translocation of many metabolites required for grain filling [81]. Furthermore, water stress can increase the potential for unsuccessful pollination and poor kernel setting of maize by affecting the anthesis and silking stages [82]. In this study, reducing irrigation levels reduced the yield of grains (Figure 6). Applications of K_2SiO_3 not only relatively reversed these adverse effects but also increased the ultimate yield of

grains under water stress. These findings could be correlated with corresponding changes in several biochemical and physiological aspects that were found during this work (Figure 7).

5. Conclusions

In this study, it was found that applied K_2SiO_3 , particularly at 2 mM as a foliar spray, may have several benefits on maize crops under limited irrigation supply. These effects were associated with several changes at physiological and biochemical levels, including adjustment of RWC and osmolytes, alleviation of oxidative damage and reduction of cell membrane dysfunction, as well as enhancement of nutrient uptake and regulation of several nonenzymatic and enzymatic antioxidant systems. These results could provide a link between the protective role of K_2SiO_3 against drought stress and the eventual yield of grains, especially under semiarid conditions.

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