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Exogenous silicon nutrition mitigates salt-induced stress by modulating germination and biometrics markers in durum wheat cultivars

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Abstract:
Background*: Silicon (Si) has been recently considered as an important micronutrient in alleviating the negative impact of abiotic stress, including salt stress, on several crops especially durum wheat.*
Materials and Methods*: This study highlights the effect of Si supply (15 mg L^{-1}) on seed priming on germination characteristics of eight durum wheat varieties (‘Karim’, ‘Rezzak’, ‘Khiar,’‘Nasr’, ‘Maali’, Salim’,‘INRAT 100’ and ‘Dhahbi’) under salt stress (200 mmol NaCl) compared to control. In addition, a pot experiment was contemplated to assess the foliar supply benefits of this element on root, shoot and leaf physiological attributes of durum wheat, using the same concentration under stressed and unstressed conditions.*
Results*: Our results depict that salt stress inflicted marked reductions in germination characteristics and phenotypic performances. However, these drastic effects were modulated through seed priming and foliar supply of Si. This nutrient stimulated the elongation of shoots better than that of roots. In addition, cultivar-specific effects of Si were obtained. Intriguingly, Khiar and Karim, were most receptive to Si unlike Salim and Maali. This analysis also allowed the identification of cultivars exhibiting various levels of tolerance to NaCl with Si addition under salt conditions. In fact, among the eight cultivars, Salim, Dhahbi, Maali, INRAT 100 and Rezzak were the most performed ones. Based on Stress Tolerance Index (STI), varieties showed a higher STI under Si treatment. Thus, Si foliar supply mitigated the deleterious effects of salt stress on all biometric attributes (root and shoot length, dry and fresh weight shoot and root, chlorophyll index and leaf area) but with less level on germination characteristics.*
Conclusion: *These findings recommend potential exogenous Si application, in the future, as mitigating prospective approach to salt stress by eliciting germination and seedling attributes, in turn, sustain plant growth and productivity under these conditions.*
Key Word*: Germination; salt stress; silicon; foliar supply; durum wheat*

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I. Introduction

Soil salinity is one of the serious threats that prohibit crop growth and productivity worldwide and influences around 20% of arable land [1,2]. The salt-affected areas are increasing at a rate of 10% annually for various reasons, including scarcity of precipitation, high surface evaporation, poor cultural management, and use of saline water irrigation [3]. This issue has been further aggravated by climatic changes. As a result, serious morphological, physiological, and biochemical changes in plant processes occur, leading to deterioration in plant growth and yield [4] in many crops. Yield depress was estimated by 55% in maize and 28% in wheat [5]. Increasing the efficiency of screening for salt-tolerant cultivars requires an understanding of the impact of salt stress at specific critical growth stages, such as germination and seedling establishment stages. Root and shoot length, as well as fresh shoot and root weight are biometrics traits that have been shown to influence the adaptive response of crops to salt stress. Thereby, these traits might be considered as potentially useful traits for cultivar screening under salt conditions as well as important contributors to grain yield [6,7]. There is also an increasing interest in the selection of root and shoot to promote the salty water use efficiency in arid and semi-arid regions. Furthermore, the plant responses to salt stress involve physiological modifications; e.g., the measurement of chlorophyll content and chlorophyll fluorescence might be excellent indicators to quantify salt-induced destruction in the photosynthetic apparatus [8-10].

On the other hand, several studies reported that salt stress causes biochemical changes including ionic toxicity, water use insufficiency, and altered nutrient balance [11,14]. Furthermore, salinity accelerates the production of harmful reactive oxygen species (ROS) that cause oxidative damage to proteins, lipids, and nucleic acids by affecting normal cellular metabolism [15].

To overcome the negative effects of salinity in plants, the exogenous Silicon (Si) supply can be considered as an optional approach [16]. Si is the second most abundant element after oxygen in soil (28%), but most of its sources are not available to the plant [17]. Si exists in soil solution as monosilicic acid (H_4SiO_4) at concentrations ranging from 0.1 to 0.6 mM SiO_2 [18]. It is taken up by plants in this form in amounts ranging from 0.1% to 12% dry weight basis. This depends on the species and genotypes [19]. Under salinity conditions, Si seed priming improved germination attributes of wheat cultivars such as germination rate, vigor index, and seedling growth by decreasing Na^+ in favor of K^+ concentration [20]. In addition, Si had a crucial role in wheat mineral nutrition [21].

Otherwise, the studies of the interaction between Si and salinity in adult stage suggested that Si deposition in leaves could inhibit water loss *via* transpiration and hence improve the water status in cells for better plant metabolism [22,23]. In addition, Si could mitigate the salinity hazard by decreasing salt ions uptake and/or their transport to the shoot, *via* the formation of some sort of Na/Si complex in roots [24] or through direct deposition in root cells, causing a partial blockage of the transpiration bypass flow [25,26] and enhancing antioxidant defense [27]. Therefore, this nutriment enhanced total phenolic compounds, enzyme activities, protein contents, Chlorophyll a and b contents, CO_2 assimilation, and stomatal conductance [12,14]. This beneficial role of Si on tolerance to the hazardous effect of salinity has been extensively demonstrated in different species, including both low silicon-accumulating plants such tomato, potato, canola, and lentil [28,29] and silicon-accumulating plants like rice [30], maize [31], barley [32], soybean [33] and wheat [34,35]. Among these crops, durum wheat is the most cultivated cereal crop in Tunisia [36] and its production is limited by salt stress. In this context, we investigated i) the exogenous Si foliar application effect on germination and biometrics performances in germination and pot trials under salt stress conditions, and ii) the genetic durum wheat response to Si supply.

II. Material And Methods

Germplasm collection

In order to assess the effect of Silicon (Si) application on durum wheat (*Triticum turgidum* L. ssp. *durum* [Desf.] Husn.) performances under salinity stress, eight Tunisian modern varieties (Karim, Rezzak, Khiar, Nasr, Maali, Salim, INRAT 100, and Dhahbi) were used. Karim and Maali, the most cultivated varieties, were used respectively as the most tolerant and sensitive control to salt stress. Nevertheless, INRAT 100 and Dhahbi are two new varieties that will be marketed for farmers during 2021-22 cropping season.

Experimental Layout

Germination bioassay

All the durum wheat seeds were surface-sterilized with 10% sodium hypochlorite for 5 min and rinsed with distilled water. Thereafter, seeds were thoroughly primed for 12 h [37] with Si (0 and 15 mg/l) using sodium metasilicate ($Na_2SiO_3H_2O$, sodium meta-silicate powder extra pure >98.0%, Sigma-Aldrich) as a source. After priming treatments, seeds were washed three times (5 min) with sterile distilled water. Then seeds were labeled and air-dried on blotting paper at room temperature (24°C) overnight. For each $Na_2SiO_3H_2O$ concentrations, two NaCl treatments were applied, 0 and 200 mmol/l. Ten sterilized and priming seeds of each variety were placed on sterile filter paper (12–15 µm, sterilized at 120°C for 1 h) in a 90 mm diameter Petri dish moistened with 4 ml of the following treatment: Treatment 1: Control (distilled water); Treatment 2: 0 mmol/l NaCl + Si (15 mg/l); Treatment 3: 100 mmol/l NaCl + Si (0 mg/l), and Treatment 4: 100 mmol/l NaCl + Si (15 mg/l).

Pot trial

The experiment was conducted in a semi-closed environment. The minimum and the maximum air temperature and relative humidity recorded during durum wheat growing season ranged between 10-35°C and 60-70%, respectively. Studied wheat varieties were sown in soil filled plastic pots (21 cm diameter and 25 cm height) with an outlet at the bottom for free drainage. The soil is classified as sandy-loam with 98 ppm N, 16.53 ppm P, 510 ppm K, 1.41% organic matter. Seeds were sterilized with 10% sodium hypochlorite solution for 5 min and then washed three times with distilled water. Ten seeds were sown in each pot maintained under unstressed (control) and stressed (200 mmol NaCl) conditions. Upon uniformity of germination, plants were thinned to maintain five plants in each pot. Si was applied using Sodium Silicate Powder (Meta) Extra Pure ($Na_2SiO_3.9H_2O$) as source, as an aqueous Na_2SeO_4 solution which was uniformly mixed with water. Si (15 mg/l) treatment was applied at the beginning and at the end of tillering stage (Z21 and Z29, respectively) using foliar supply method. The experiment was conducted in randomized completed block (RCB) design with Si and NaCl treatments, and variety as main factors (three replications per treatment, n=3).

Germination characteristics and biometrics measurements

At germination stage and after 10 days of treatment, four germination characteristics were assessed: germination percentage (GP), mean daily germination (MDG; i.e., the mean number of seeds that germinated each day), daily germination speed (DGS), and germination rate (GR). These parameters were calculated as follows:

GP = (total number of germinated seeds / total number of observed seeds) × 100

MDG = final emergence/10 [38]

DGS = 1/MDG [39]

GR = $(n_1 \times t_1) + (n_2 \times t_2) + (n_3 \times t_3) + \ldots (n_i \times t_i)/T$ [40]

where n = number of days in which seeds germinated; t = number of germinated seeds in each counting day; T = total number of germinated seeds.

At Z39 stage [40], the length of shoot (SL, cm) and roots (RL, cm) of five plants was taken by using a meter rod and averaged for each variety under non-stressed and stressed conditions. These samples were cleaned and washed with distilled water, and root and shoot were separated by a pair of scissors. After cleaning, the fresh weight of shoot (SFW, g) and root (RFW, g) was taken. These samples were oven-dried at 70°C for 72 h and subsequently, the shoot (SDW, g) and root dry weight (RDW, g) was determined using a digital balance. Chlorophyll index (Chl index, Chlorophyll meter SPAD 502, Konnica Minolta, Osaka, Japan), and leaf area (LA, mm^2, Electronic planimetre AM300, Soil Mesures, France) were also measured.

In order to study the salt stress sensitivity of different germination characteristics and growth parameters (SL, RL, SFW, RFW, SDW, RDW, Chl index, and LA), stress tolerance index (STI) was calculated according to the following formula:

STI (%) = [(PGT under saline conditions)/ PGT under control conditions] × 100

where, PGT was the mean values of plant growth trait under non-stressed and stressed conditions [41,42].

Statistical analysis

ANOVA test was used to determine the significance of different factors (salinity, Si treatments, and variety) impacts and their interaction followed by the Turkey's multiple range test ($p \leq 0.05$) for means comparison. Statistical analysis of obtained results was carried out using SPSS software ver. 16.0 (IBM SPSS Statistics SPSS for Windows, Version 16.0. Chicago, SPSS Inc., 2007). Otherwise, to describe the relationship between 'cultivar-treatment' combinations, the principal component analysis (PCA) was performed using R statistical software version 4.0 (The R Foundation for Statistical Computing).

III. Results

Effect of Si supply on germination characteristics under salt conditions

Analysis of variance revealed significant differences ($p \leq 0.05$ and $p \leq 0.001$) among salt and Si treatments and varieties for all germination attributes (Table 1). Double interaction 'treatment × cultivar' was only significant for these traits ($p \leq 0.05$). Results displayed a significant effect of salt on PG, MDG, DGS and GR. Based on mean values, PG, MDG and GR were significantly reduced under salt stress by 4.12, 8.00 and 12.26%. In contrast, salinity caused an increase in DGS of 5.41%. There was also considerable variation in PG, MDG, DGS and GR between cultivars. Salim, Maali, INRAT 100 had significantly higher PG, MDG, GR and lower DGS compared to other varieties under stressed and unstressed conditions (Tables 1 and 2). The results depicted also the effect of Si seed priming application on germination characteristics of durum wheat seeds exposed to salt stress treatment. Overall, seed priming with Si significantly improved the germination characteristics by 2.02, 4.08, 19.25% for PG, MDG, and GR, whereas, it decreased the DGS by 8.51% under both conditions. Salim, Maali, INRAT 100 performed better for the germination attributes with Si addition and exhibited the best values for PG, MDG, and GR under stressed and non-stressed conditions.

Table 1. Analysis of variance (*F* value) of germination attributes.

Sources of variance	df	PG	MDG	DGS	GR
Salt treatment (ST)	1	22.3**	13.54**	3.34*	8.14*
Si supply (SiS)	1	4.26*	6.23**	7.4*	6.86*
Varieties (V)	7	5.76**	10.51**	7.23**	13.67**
ST x SiS	1	7.32	1.12ns	3.65ns	2.34
ST x V	7	5.33**	6.51**	4.3*	9.45**
SiS x V	7	7.12*	4.93*	5.2*	8.45**
ST x V x SiS	7	7.81*	1.42ns	1.98ns	1.12ns
Salt treatment					
Control		84.99a1)	0.50a	1.85a	1.55a
100 mmol		81.49b	0.46b	1.75b	1.36b
% of decrease		4.12	8.00	5.41	12.26
Si supply					
Control		82.39b	0.47b	1.72b	1.30b
15mg/l		84.09a	0.49a	1.88a	1.61a
% of increase		2.02	4.08	8.51	19.25
Varieties					
Karim		77.65c	0.53ab	1.74b	1.29b
Rezzak		80.64b	0.32b	2.17a	0.72c
Khiar		82.40b	0.35b	1.79b	0.81c
Nasr		81.73b	0.15c	2.19a	1.02ab
Maali		86.24a	0.62a	1.63bc	1.41
Salim		87.06a	0.70a	1.44c	1.97ab
INRAT 100		85.66a	0.53ab	1.81ab	2.21a
Dhahbi		84.58ab	0.63a	1.62bc	2.22a
Mean		83.05ab	0.46b	1.82ab	1.35b

GP: mean germination percentage, MDG: mean daily germination, DGS: daily germination speed, GR: germination rate. [1)]Different letters indicate significant differences according to Tukey's multiple range test ($p \leq 0.05$)

Table 2. Mean of germination attributes of the eight tested varieties within and without Si supply under salt and control conditions.

Traits	PG				MDG				DGS				GR			
Salt treatment	$NaCl^-$		$NaCl^+$		$NaCl^-$		$NaCl^+$		$NaCl^-$		$NaCl^+$		$NaCl^-$		$NaCl^+$	
Si supply	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+
Varieties																
Karim	79.33a [1)]	80.33c	77.63b	79.30b	0.54ab	0.63a	0.44ab	0.50a	1.85b	1.59b	2.27ab	2.00b	1.23b	1.57b	1.11bc	1.22b
Rezzak	80.67b	83.60bc	78.67ab	79.60b	0.37b	0.45b	0.35b	0.31b	2.70a	2.22ab	2.86a	3.23a	0.71b	0.85c	0.67c	0.69c
Khiar	83.33ab	86.33b	78.63ab	81.30b	0.39b	0.41b	0.36b	0.31b	2.56a	2.44a	2.78a	3.23a	0.82b	0.98c	0.64c	0.69c
Nasr	83.33 ab	84.67bc	78.33ab	80.60b	0.41b	0.35b	0.36b	0.31b	2.4a	2.86a	2.78a	3.23a	1.00b	1.24c	0.84bc	0.89c
Maali	86.67a	90.33ab	84.37a	85.60a	0.65a	0.69a	0.54b	0.59a	1.5c	1.45bc	1.85b	1.69c	1.17b	1.37c	0.97bc	1.05b
Salim	86.67a	93.30a	83.67a	84.60a	0.71a	0.78a	0.62a	0.68a	1.41c	1.28c	1.61b	1.47c	1.94a	2.13a	1.86b	2.01a
INRAT 100	87.00a	89.33ab	84.00a	86.30a	0.54ab	0.61a	0.46ab	0.51ab	1.85b	1.64b	2.17a	1.96b	2.20a	2.34a	2.18a	2.25a
Dhahbi	85.00a	90.00ab	80.00b	83.30b	0.62a	0.72a	0.56b	0.60a	1.6c	1.39c	1.79b	1.67c	2.19a	2.09a	1.79b	2.01a
Mean	84.00	87.24	80.66	82.58	0.53	0.58	0.46	0.48	2.00	1.86	2.26	2.31	1.41	1.57	1.26	1.35

GP: mean germination percentage, MDG: mean daily germination, DGS: daily germination speed, GR: germination rate. [1)] Different letters indicate significant differences according to Tukey's multiple range test ($p \leq 0.05$)

Effect of Si supply on biometric attributes under salt conditions

ANOVA performed on eight traits measured during the vegetative growth stage in order to evaluate Si impacts and genetic varieties responses under salt stressed and unstressed conditions. Globally, significant ($p < 0.001$) differences among varieties (V), salt treatment (ST) and Si foliar supply (SiS) for all measured traits were displayed (Table 3). Overall, salt stress declined all parameters as compared with the control. Results revealed also significant variation among wheat varieties in response to Si supply in all parameters for both conditions. In most cases, the double interactions (ST × SiS) and (ST × V) were significant ($p < 0.05$), while (T × V) and the triple interaction (ST × SiS × V) were not significant. Therefore, ANOVA results indicated that Si effect and variety responses to these elements depend on the salt treatment. Otherwise, the response of varieties seems to be stable against stimulator treatments.

Mean comparisons indicated that salt stress significantly affected all biometrics attributes measured; it reduced RL, SL, RDW, SFW, RFW, SDW, Chl index, and LA respectively by 15.55%, 12.32%, 13.23%, 10.40%, 11.48%, 20.30%, 9.43%, 4.69%, and 4.31 % (Table 4). In addition, results revealed that varieties responded differently to salt stress. Among all studied cultivars, Karim (16.90, 23.06, 14.90, and 13.26%), Rezzak (19.92, 24.21, 14.30, and 13.54%), and Khiar (20.93, 22.11, 16.39, and 14.23%) showed the highest decrease rates under salt conditions for respectively SL, RL, SFW and SDW. The effect of salt treatment is less pronounced for LA (3.08, 4.29 and 2.14%) and Chl index (4.71, 5.92 and 11.24%). Maali and INRAT100 showed the lowest rate of decrease under stress conditions for SL (8.69, 10.04%), RL (5.01, 11.42%), SFW (5.45 and 8.64%) and SDW (3.33 and 7.75%). This suggests that the magnitude of differences between cultivars was sufficient to provide some scope for selecting cultivars to improve salt tolerance. In this study, root characters were reliable markers for identifying different categories of cultivars tested and could be used as a preliminary screening technique for detecting salt tolerance in early stage.

Table 3. Variance analysis of Si foliar supply on eight measured traits for eight durum wheat varieties under both conditions (0 and 200 mmol/l NaCl).

	df	RL	SL	RFW	RDW	SFW	SDW	Chl index	LA
Salt treatment (ST)	1	779.2***	489.12**	611.52**	1502.7**	74.41**	971.67***	34.11**	175.45***
Si supply (SiS)	1	172.48***	507.57***	237.01***	573.11***	154.92***	457.82***	65.17**	192.43***
Varieties (V)	8	11.95**	21.94**	93.56**	65.73**	16.42**	30.03**	9.25*	37.48**
ST x SiS	1	11.95**	21.94**	91.56**	65.73**	16.42**	20.03**	9.25*	31.48**
ST x V	8	1.56^{ns}	11.75*	16.14**	22.01**	8.79*	10.02*	2.55^{ns}	4.48^{ns}
SiS x V	8	1.55^{ns}	11.66*	16.14**	21.01**	8.79$_{*}$	10.01*	2.54^{ns}	4.47^{ns}
ST x V x SiS	8	1.24^{ns}	8.01^{ns}	5.3^{ns}	12.72**	4.1^{ns}	1.1^{ns}	1.14^{ns}	11.03*
Salt treatment									
Control		10.25a$^{1)}$	31.77a	1.05a	0.11a	9.33a	1.36a	52.92a	2550.13a
200 mmol/l NaCl		8.41b	26.78b	0.97b	0.10b	8.17b	1.19b	51.23a	2521.81b
Si treatment									
Control		8.81b	26.37b	0.87b	0.10b	8.11b	1.12b	48.87b	2370.65b
15 mg/l Si		9.43a	29.27a	0.95a	0.11a	8.96a	1.22a	53.24a	2553.14a
Varieties									
Karim		8.30b	26.75ab	0.56b	0.09c	8.50b	0.98d	39.72bc	1701.61c
Rezzak		9.15ab	26.75ab	0.89ab	0.10b	8.86ab	1.20b	40.13ab	1849.25bc
Khiar		8.93ab	24.97c	0.87ab	0.10b	7.32c	1.03d	43.03a	1724.34c
Nasr		8.84ab	25.67bc	0.91a	0.10b	8.05	1.11c	39.51bc	1952.84b
Maali		9.38a	28.24a	0.94a	0.10b	8.23bc	1.21b	41.24a	1974.06b
Salim		8.55a	28.45a	0.98a	0.10b	9.34a	1.23b	40.85ab	2046.39a
INRAT 100		9.33a	25.94bc	1.00a	0.12a	7.95bc	1.33a	41.71a	1964.10b
Dhahbi		9.16ab	28.47a	0.98a	0.10b	8.54b	1.27a	42.10a	1913.53b

RL: root length (cm), SL: shoot length (cm), RFW: root fresh weight (g), RDW: root dry weight (g), SFW: shoot fresh weight (g), SDW: shoot dry weight (g), Chl index: chlorophyll index, LA: leaf area (mm^2), df: degrees of freedom, Level of significance: $p > 0.05 = ^{ns}$, $p \leq 0.05 = ^{*}$, $p < 0.01 = ^{**}$, $p < 0.001 = ^{***}$. $^{1)}$, For each trait, different letters indicate significant differences according to Tukey's multiple range test ($p \leq 0.05$)

Similarly, Si treatment was effective in increasing plant growth (shoots and roots length). Its effect was visibly clear under both stressed and non-stressed conditions. In fact, Si application displayed a considerable increase for RL, SL, RFW, RDW, SFW, SDW, Chl index and LA respectively for stressed (7.01, 12.94, 8.64, 7.15, 12.20, 10.71, 8.53 and 7.07%) and non-stressed conditions (6.28, 7.03, 7.04, 4.86, 8.7, 7.95, 7.94 and 7.23%) compared to control (Figure 1). Overall, the beneficial effect of Si application was markedly more pronounced under salt stress conditions compared to the control. The highest increase observed for SL and SFW. Furthermore, results revealed that durum wheat varieties responded differently ($p < 0.001$) to Si application under stressed and unstressed conditions for different plant growth attributes. Based on RL, SDW and SFW, Khiar responded better to Si application under unstressed (9.87%, 8.03, and 12.99, respectively) and stressed conditions (18.93, 14.81, and 23.01%, respectively) unlike Maali and Salim. Thus, obtained results revealed that Si effectively promoted seedlings growth, particularly, shoots and roots traits with reducing the undesirable impact of salt stress.

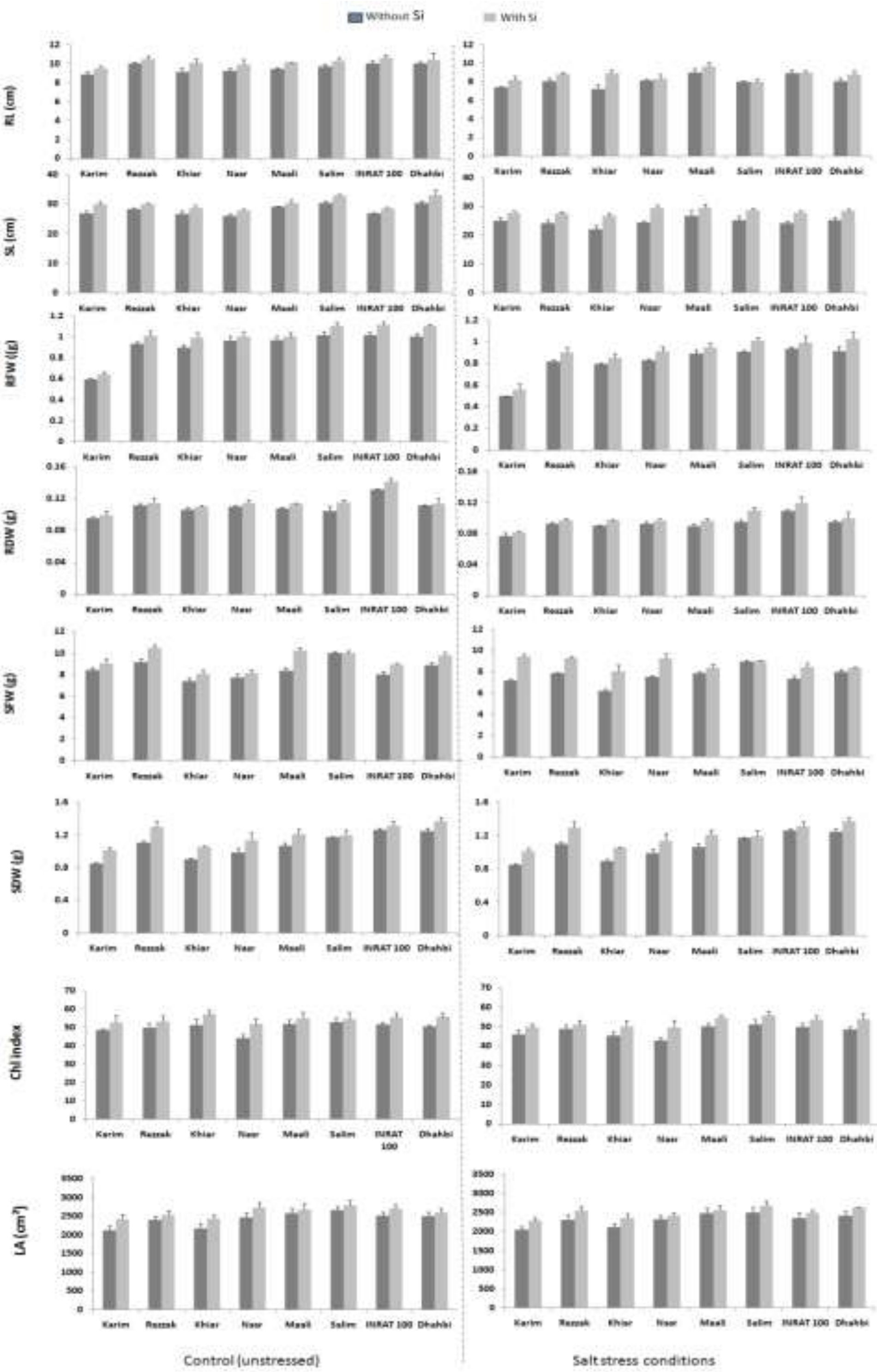

Figure 1. Effect of Si foliar supply on eight measured traits for eight durum wheat varieties under both treatments (0 and 200 mmol/l NaCl). RL: root length, SL: shoot length, RFW: root fresh weight, RDW: root dry weight, SFW: shoot fresh weight, SDW: shoot dry weight, Chl index: chlorophyll index, LA: leaf area.

Principal component analysis (PCA) was conducted using as variables the different phenotypic traits, the 8 varieties and the 2 growth conditions including the control and the treatment with NaCl (Figure 2).The PCA was applied in order to evaluate the relation between cultivars and applied treatments (with or without Si) under control and salt conditions. The first and the second principal components (PC-1 and PC-2) accounted respectively for 64.8 and 14.7% of the total data variance; i.e., their mutual projections. In this study, the collection of eight durum wheat varieties was characterized by large diversity over the two PC axes. Seedlings traits varied among the eight Tunisian durum wheat varieties under stressed and non-stressed conditions. PCA could further classify the eight durum wheat cultivars and two groups might be discerned: the first group combined most of Si-treated cultivars in control and salt conditions, while the second group was mainly constituted by most untreated cultivars under both conditions. Therefore, the PCA results confirmed the noteworthy beneficial effect of Si on all traits since the Si-treated cultivars were correlated with the studied traits for unstressed and stressed conditions. Interestingly, Salim, Dhahbi, Maali, and Rezzak treated with Si treatment showed the highest value of Chl index, SL, SFW, and LA under control conditions. In these same conditions, INRAT 100, Nasr showed the highest values for RFW and RDW. Same trends of distribution of 'cultivar-treatment' combinations were observed for these varieties under salt conditions. Otherwise, Rezzak showed the best Chl index, SL, SFW, and LA under stressed conditions.

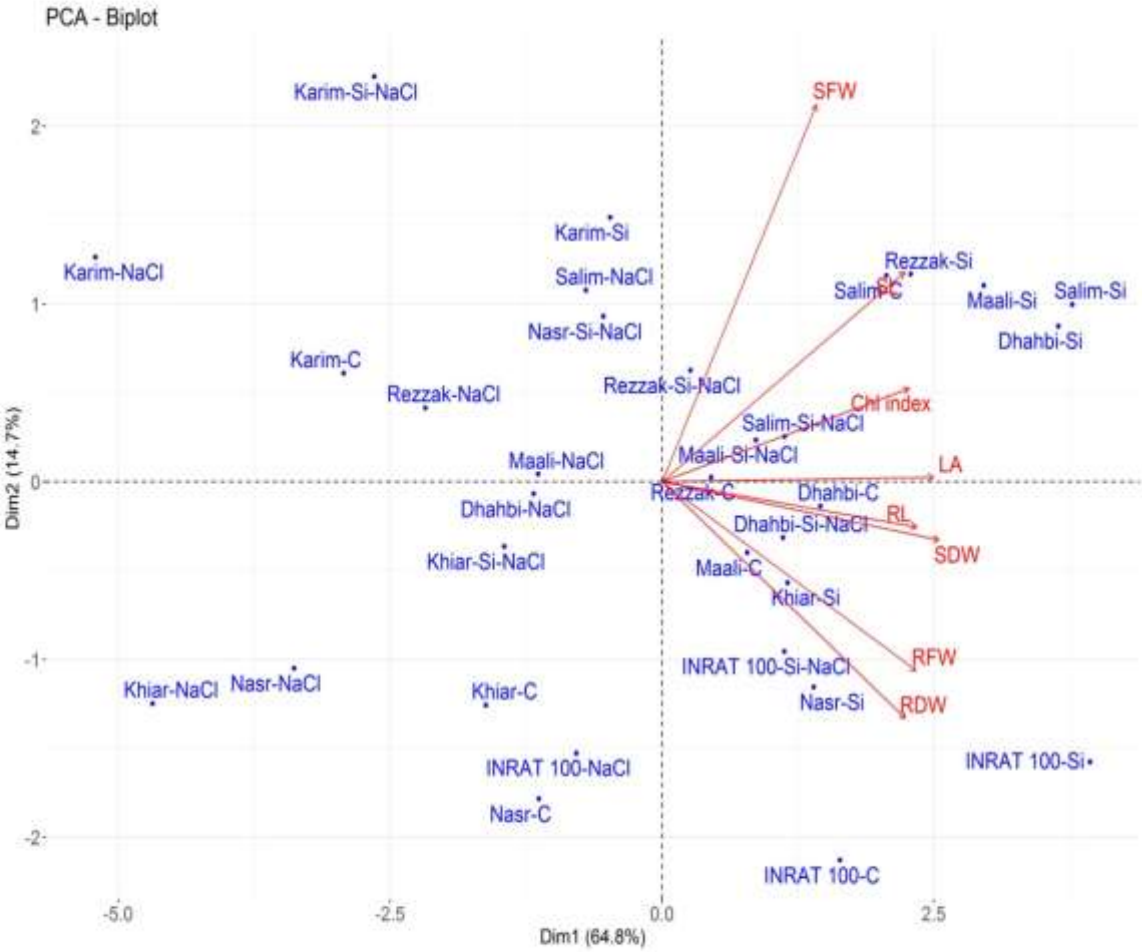

Figure 2. Principal component analysis showing the distribution of growth traits and the eight durum wheat varieties with and without Si foliar application, grown in non-stressed and stressed conditions.

Genotype-Dependent Response to Salinity and Si supply

For germination traits, Si application showed no increase of the stress tolerance index for varieties tested. However, for almost attributes, Si application improved the stress tolerance index of almost varieties, except Chl index and LA. In fact, with Si addition, the highest STI observed for RL, SL, RFW, RDW, SFW, SDW, Chl index and LA were respectively 94.72, 97.19, 94.75, 95.61, 96.06, 98.09 and 96.90%. Thus, the Si foliar supply mitigated the deleterious effects of salt stress on all biometric attributes (root and shoot length, dry and fresh weight shoot and root, chlorophyll index and leaf area). Compared to others varieties, Maali showed the highest STI for RL, RFW with and without Si addition. This variety showed also the highest SFW without Si supply.

Table 4. Stress tolerance index for eight durum wheat varieties on mean germination percentage (GP), mean daily germination (MDG), daily germination speed (DGS), and germination rate (GR).

Varieties	Stress tolerance Index (STI, %)							
	PG		MDG		DGS		GR	
	SiS-	SiS+	SiS-	SiS+	SiS-	SiS+	SiS-	SiS+
Karim	97.86a[1)]	98.72a	81.48c	79.37bc	122.73a	126.00bc	90.24b	77.71c
Rezzak	97.52a	95.22b	94.59a	68.89c	105.71b	145.16a	94.37ab	81.18b
Khiar	94.36b	94.17b	92.31a	75.61c	108.33b	132.26b	78.05d	70.41c
Nasr	94.00b	95.19b	87.80ab	88.57a	113.89ab	112.90c	84.00c	71.77c
Maali	97.35a	94.76b	83.08b	85.51ab	120.37a	116.95c	82.91c	76.64b
Salim	96.54a	90.68c	87.32ab	87.18a	114.52ab	114.71c	95.88a	94.37a
INRAT 100	96.55a	96.61ab	85.19b	83.61b	117.39ab	119.61c	99.09a	96.15a
Dhahbi	94.12b	92.56c	90.32b	83.33b	110.71ab	120.00c	81.74cd	96.17a
Mean	96.04	94.74	87.76	81.51	114.21	123.45	88.28	83.05

[1)]For each trait, different letters indicate significant differences according to Tukey's multiple range test ($p \leq 0.05$)

Table 5. Stress tolerance index (STI, %) for the eight tested durum wheat varieties on biometrics attributes measured

Varieties	Stress Tolerance Index (STI, %)															
	RL		SL		RFW		RDW		SFW		SDW		Chl index		LA	
	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+	SiS^-	SiS^+
Karim	83.10bc	85.49ab	93.26a	93.00b	83.23b	86.19c	81.05c	82.27c	85.10d	95.79b	86.73c	93.63ab	95.28a	94.78b	96.92a	94.65ab
Rezzak	80.07c	84.03b	85.03b	91.90bc	87.67ab	89.22ab	83.15c	84.78c	85.70d	88.91d	95.10a	95.72a	98.09a	96.18ab	95.70a	96.90a
Khiar	79.07c	87.90ab	82.70b	92.43b	88.19ab	85.64c	84.71bc	88.64b	83.61d	99.50a	89.76b	91.68b	88.75b	88.33c	97.86a	96.68a
Nasr	87.70b	84.09b	93.14a	94.84b	85.88b	90.65ab	84.09bc	84.35c	97.04a	87.91d	89.27b	92.67b	97.11a	95.71ab	94.04ab	88.57c
Maali	94.98a	94.72a	91.31a	97.05a	91.48a	94.75a	83.49c	84.43c	94.45b	81.87e	88.75bc	89.15b	97.07a	99.86a	96.53a	95.45a
Salim	81.67c	77.34c	83.13bc	87.04c	89.51ab	91.78ab	90.48a	95.61a	89.80c	90.02c	91.35b	88.28b	96.59a	97.83a	94.01ab	95.81a
INRAT 100	88.57b	84.54b	89.95a	97.19a	91.52a	89.17c	83.05c	84.97c	91.36c	94.71b	92.24b	89.27b	96.74a	97.00a	93.69b	91.72b
Dhahbi	80.42c	83.65b	82.84b	85.64c	90.66a	93.15a	85.39b	87.50b	89.82c	85.76d	96.06a	96.91a	96.82a	96.81ab	96.78a	93.23ab
Mean	84.45	85.22	87.67	92.39	88.52	90.07	84.43	86.57	89.61	90.56	91.16	93.41	95.81	96.44	95.69	94.13

RL: root length (cm), SL: shoot length (cm), RFW: root fresh weight (g), RDW: root dry weight (g), SFW: shoot fresh weight (g), SDW: shoot dry weight (g), Chl index: chlorophyll index, LA: leaf area (mm^2), [1)] For each trait, different letters indicate significant differences according to Tukey's multiple range test ($p \leq 0.05$)

IV. Discussion

Si supply alleviates the deleterious effects of salt stress on durum wheat germination performances

Plant growth and development, as well as productivity, are predicted by seed germination. In the current study, salt stress induced by sodium chloride (NaCl), caused a pronounced inhibition of germination and its characteristics mainly PG, MDG, and GR for all durum wheat varieties tested. Meanwhile, this impact is modulated when $Na_2SiO_3.9H_2O$ was added as source of Si, with a satisfactory performance observed on PG, MDG, and GR. Thus, this result proved that the use of Si is able to produce a significant reduction in the deleterious effects of NaCl on seed germination characteristics as reported by Rizwan et al. [43]. This author reported that the beneficial effect of Si on various crops is far more evident under stressful conditions. In fact, this element was found to be directly linked to the physiological process of seed germination in wheat under saline conditions [44]. The positive role of Si is attributed also to improved water economy due to the deposition of Si that forms a silica body in the mesophyll cells. Thereby, Si acts as a wall of silica gel preventing water from escaping, reducing transpiration from the leaves, facilitating the transmission of light for photosynthesis which leads to increasing plant vegetative growth [45]. Additionally, Si application boosts the water, macro- (e.g., P, K, Ca, and Mg) and micronutrients (e.g., Fe, Cu, and Mn) uptake [46] and regulates the hormone balance [47]. Moreover, Si addition decreased the activities of superoxide dismutase, catalase, peroxidase and ascorbate peroxidase, and the concentrations of protein and proline in radicles of seedlings under salt stress, implying stress alleviation. Previous study showed that silicon might decrease ABA level, maintain high gibberellin level and increase α-amylase activity, therefore improving seed germination under salt stress [48]. Meaningful and consistent differences between durum wheat varieties were observed in their response to Si seed priming. Similar result was noticed by Ayed et al. [49] after Si seed priming and foliar application of twenty-four ICARDA promising lines of durum wheat. Genotype-specific Si responses were also noted by Othmani et al. [50], Sapre and Vakharia [51] and Thorne et al. [2]. This genotypic variability might be explained by differential Si accumulation. Thus, the improvement of stress tolerance is related to a better accumulation of Si.

Si foliar supply alleviates the deleterious effects of salt stress on durum wheat growth seedling performance

Similarly to germination study, results showed that salt stress caused also a significant reduction in the fresh and dry roots and shoots and physiological markers (chlorophyll content and leaf area) on durum wheat in early stage. According to Liu et al. [52], salinity stress hinders the growth potential of crop plants by influencing morphological and physiological changes and may be explained by the inhibition of cell division and elongation. Interestingly, in this study, the Si supply reduce the impact of salt stress on durum wheat fresh and dry matter content (shoots and roots), LA and Chl content. These finding are in agreement with several studies revealing that the addition of Si might protect the growth of many crops from the toxic effect of salt stress [47,53]. Si enhances growth performance directly, through blocking the transport of sodium to the shoots, increasing the leaf and root activity of oxidative stress enzymes, and enhancing antioxidant activity which cause the reduction in lipid peroxidation of the plasma membrane of plants under salt stress. Thus, Si promotes cell elongation and division, leading to elevated plant height [54,55]. Furthermore, Si acts indirectly through different physiological processes that alleviate the negative effects of salinity [37]. In fact, under salinity conditions, Si enhances photosynthetic activity by decreasing ion toxicity and ROS content, preserving the structure and function of the organelles responsible for photosynthesis [14], maintaining stomatal conductance, transpiration, membrane permeability, net photosynthesis, and chlorophyll levels [56]. Si decreases plant transpiration due to Si accumulation as external layers above cell walls of leaves and stems, leading to thicker leaves and stem cuticle. In addition, Si improves stem hydraulic conductance [45]. Si alters the osmotic pressure, which increases plant tolerance under salinity stress conditions [47]. Higher water content in Si-plants grown under saline conditions is mainly associated with salt dilution inside the plant, leading to plant growth improvements [51]. Numerous studies also indicated that Si could alleviate salinity stress of salt-stressed plants such as maize [57], barley [58], canola [59] and wheat [35].

On other hand, results showed that the exogenous Si application on durum wheat plants displayed a considerable increase of Chl content under stressed conditions. Thus, Si maintains chlorophyll content and photosynthetic rate in plants grown under saline conditions enhancing the photochemical efficiency of PS II [60,61]. Gassami-Golezani et al. [62] reported that salt-induced alterations in chlorophyll content may result from impaired chlorophyll biosynthesis or its accelerated degradation, whereas Si may limit these detrimental changes. Moreover, Si increases leaf flatness, allowing for increasing light interception and more photosynthetic pigments [61], and thus more carbohydrates and dry matter accumulation.

Thus, Si supply was effective in mitigating the deleterious effect of salt stress through enhancing germination and biometrics performances of durum wheat over the both treatments. Otherwise, in this study, basing on attributes measured and SSI, Si’s beneficial effect is more pronounced under stressed conditions with increasing tolerance of all varieties. Thus, although a beneficial micronutrient, Si exerts a dual effect in plants: It can stimulate plant growth and provide beneficial effects in stress conditions. Same results were obtained by Etesami and Jeong [63]. Meaningful and consistent differences between durum wheat varieties were observed in their response to Si seed foliar supply under both conditions. According to Ayman et al. [22] and EL Sabagh et al. [44], positive effects of Si depend on the chosen plant cultivar. A significant interaction between cultivars and Si treatment was noted. This genotypic variability might be explained by differential Si accumulation. Previous studies have shown that the improvement of stress tolerance is related to a better accumulation of Si. However, Segalin et al. [64], observed that cultivar x Si interaction was not significant showing that cultivar behavior is independent of Si treatment.

V. Conclusion

Si supply was effective in mitigating the deleterious effect of salt stress through enhancing germination characteristics and phenotypic performances. Otherwise, in this study, Si beneficial effect is more pronounced under stressed conditions (highest SSI) particularly on biometrics attributes. Meaningful and consistent differences between durum wheat varieties were observed in their response to Si seed foliar supply under both conditions.

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