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ORIGINAL PAPER

Effect of Silicon (Si) Seed Priming on Germination and Effectiveness of its Foliar Supplies on Durum Wheat (*Triticum turgidum* L. ssp. *durum*) Genotypes under Semi-Arid Environment

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Abstract

Silicon (Si), a nutrient that currently arousing more and more interest from researchers, particularly in relation to water deficit resistance for durum wheat (*Triticum turgidum* L. ssp. *Durum*). The present study aimed to explore the effectiveness of Si seed priming and foliar application on durum wheat performances. Thus, a seed bioassay was conducted to assess the effect of three Si levels (15 and 20 mg/l from $Na_2SiO_3H_2O$ (sodium metasilicate powder extra pure) on the germination of 25 durum wheat genotypes under osmotic stress (150 g/l of PEG_{6000}). Under field conditions in semi-arid environment, we evaluated the Si foliar application potential benefits on the physiological and agro-morphological traits. Results showed that Si application, in particular using 15 mg/l, increased significantly the germination percentage (23.96 and 22.37%) the germination index (24.67 and 25.69%), the length of shoot (23.58 and 21.65%) and roots (22.40 and 20.81%), the seedling fresh weight (35.82% and 27.80%), and the seedling vigor index (41.58% and 38.95%) under non-stressed and stressed conditions, respectively. L6 showed the highest value of germination percentage, shoot and root length, and seedling vigor index for all treatments. In semi-arid conditions, Si foliar application enhanced the relative water content (11.66%) and the chlorophyll index (13.60%). In addition, Si increased spike length (8.47%), seed number/spike (19.01%) and grain yield (19.90%) of all durum wheat genotypes. Differential genotypic responses to Si application were observed at both seedling and adult stages.

Keywords Durum wheat · Seed priming · Semi-arid environment · Silicon

1 Introduction

Water deficit increased due to the serious and quick climate change in the world [1, 2]. In arid and semi-arid areas (i.e., Mediterranean regions), water stress is a major limiting factor of durum wheat production. The inter-annual variations of precipitation, affects the growth and development of this species [3–5] and leads to substantial yield losses reaching 35% [6]. To overcome this constraint, it is a challenge to develop varieties that are both water deficit tolerant and high yielding. Another approach to mitigate the effect of water scarcity on durum wheat production is the use of bio stimulants or beneficial elements to ensure grain yield stability. Particularly, silicon (Si), which has paradoxically been considered since 2005 as quasi essential element [7], is currently rarely used to balance nutritional calendar of crops in order to strengthen the cereal yields stability. In fact, after the oxygen, Si is the second most abundant element in the earth's crust. It is a mineral element such as nitrogen, phosphorus and potassium. Si concentration in plants depends on species and it varies from 0.1% to 10% dry weight basis [8]. Neu et al. [9] reported that Si concentration in wheat straw is up to 4%, which is similar to macronutrients. Recently, it is recognized as biostimulants in

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EU regulations [10]. Si has beneficial effects on plant growth and it improves tolerance to biotic and abiotic stresses [11, 12] due to its physiological, metabolic, antioxidant, and molecular roles in plant [13–15]. Its benefits were particularly treated in relation to water deficit statute [16–20].

Si is used for seed priming, soil fertilization or foliar application which has recently attracted the attention of several researchers [21–24]. Seed priming, which is an interesting method to ameliorate not only seed germination, early seedling growth and yield but also to ensure extensive survivability under different biotic and abiotic stresses [25–28]. It is a pre-sowing treatment which leads to more efficient germination. It involves seed imbibition and the occurrence of physicochemical changes previous to radical emergence and thus seeds are dehydrated before sowing [29]. Si stimulates physiological plant state and increase water uptake and cell elasticity [30]. The impact of Si on seed germination under water deficit stress is little studied [31]. Hameed et al. [32] showed that Si seed priming increase germination percentage and decrease mean germination time of wheat under drought stress. Also, Si can be used as a fertilizer, as a useful tool to improve wheat drought tolerance and thus increase grain yield [26, 33, 34]. Although previous studies have shown that Si application through the roots ameliorated drought tolerance in different species such as wheat [35], rice [36], and soybean [37], but little work has studied its effects as foliar application [38, 39]. This method ameliorates wheat survival capacity by developing its agro-morphological and physiological traits [40]. Si foliar application promotes wheat tolerance to drought by high relative water and chlorophyll content in wheat cultivars, especially at tillering and anthesis stages [41]. In fact, Si is an essential component in photosynthetic activity, leaf development and xylemic vessel structure at high transpiration rates [42]. Thereby, this element could improve water status, stomatal conductance, root hydraulic conductance, increasing the root/shoot ratio, root water uptake and water use efficiency in plants [43, 44]. In addition, Si enhances water transport by stimulating accumulation of osmolyte like soluble sugars, proline and inorganic ions in both leaves and roots which increased cells osmotic potential [14, 45, 46]. Therefore, commercial pressure to make products available based on silicon support its positive effect in crops, but experimental results to support its effectiveness in durum wheat are few.

Thus, main objectives of the present study were to assess (i) the effect of seed priming by different Si concentrations on germination attributes and early seedling growth under osmotic stress induced by PEG_{6000}, (ii) the effect of Si foliar application on physiological and agro-morphological performances of 25 durum wheat genotypes at field conditions under semi-arid environment.

2 Material and Methods

2.1 Plant Materials

To evaluate the effect of Si seed priming and foliar application on durum wheat (*Triticum turgidum* L. ssp. *durum* [Desf.] Husn.), twenty-four promising lines were used. These lines, resulting from ICARDA breeding program, were chosen based on information available about their drought stress and foliar diseases performances across several African countries. Tunisian improved variety, named ‘Salim’ characterized by a good resistance to septoria and rusts [24], was tested as control (Table 1).

2.2 Si Seed Priming Experiment in Petri Dishes

2.2.1 Experimental Design and Plant Growth Conditions

All the durum wheat seeds were surface-sterilized with 10% sodium hypochlorite solution for 5 min and rinsed two times (5 min) with sterile distilled water. Seeds were then thoroughly primed for 12 h [47] with Si (0, 15, and 20 mg/l) using sodium metasilicate ($Na_2SiO_3H_2O$, sodium metasilicate 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 water treatments were applied, 0 and 150 g/l PEG_{6000} (0 and − 3.0 Mpa, respectively). The osmotic stress treatment was induced by polyethylene glycol (PEG_{6000}, molecular weight 6000 g/mol, > 99.0% purity, Sigma-Aldrich St. Louis, USA). Ten sterilized and priming seeds of each genotype 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 g/l PEG_{6000} + Si (15 mg/l),
Treatment 3: 0 g/l PEG_{6000} + Si (20 mg/l),
Treatment 4: 150 g/l PEG_{6000} + Si (0 mg/l),
Treatment 5: 150 g/l PEG_{6000} + Si (15 mg/l),
Treatment 6: 150 g/l PEG_{6000} + Si (20 mg/l).

The experiment was arranged in completely randomized block with three replicates per treatment ($n = 3$). Seeds were germinated in dark growth chamber, at 50% relative humidity and an average day/night temperature of 22 ± 2 °C [48]. The germination was considered to have occurred when the root length was ≥5 mm [49].

Table 1 Name and pedigree of advanced lines

Line	Pedigree
L1	Younes/TdicoAlpCol//Korifla
L2	Korifla/AegSpeltoidesSyr//Amedakul
L3	F413J.S/3/Arthur71/Lahn//Blk2/Lahn/4/Quarmal
L4	Amedakul1/TdicoSyrCol//Loukos
L5	Korifla/AegSpeltoidesSyr//Heider
L6	Korifla/AegSpeltoidesSyr//Mrb5
L7	Waha
L8	Amedakul1/TdicoSyrCol//Cham1
L9	Geromtel-1/Icasyr-1=Icakassem1
L10	Korifla/AegSpeltoidesSyr//Loukos
L11	Korifla/AegSpeltoidesSyr//Mrb5
L12	Stj3//Bcr/Lks4/3/Ter-3/4/Bcr/Gro1//Mgnl1=Secondroue
L13	Korifla/AegSpeltoidesSyr/Amedakul
L14	Amedakul1/TdicoJCol//Cham1
L15	Younes/TdicoAlpCol//Korifla
L16	Tomouh
L17	Heider/TAraticumMA//Mrb5
L18	Jori c69/Hau
L19	Icasyr1/3/Gcn//Stj/Mrb3
L20	Ouasloukos1/5/Azn1/4/BEZAIZSHF//SD19539/ Waha/3/Gdr2
L21	Mgnl3/Ainzen1//Mgnl3/Ainzen1
L22	Mgnl3/Ainzen1//Mgnl3/Aghrass2
L23	Azeghar1/4/IcamorTA0462/3/Maamouri3
L24	ICAMORTA0472/Ammar7
Salim	Tunisian improved variety resulting from a local crossing and released in 2009

2.2.2 Germination and Seedling Growth Parameters

After seven days of growth, the germination percentage (GP, %), the germination index (GI), and the seedling vigor index (SVI) were determined as follows:

$$\mathrm{GP}\ (\%) = (\text{Number of germinated seeds}/\text{Total number of tested seeds}) \times 100$$

$$\mathrm{GI} = \left(\frac{\text{Number of germinated seeds}}{\text{Day of first count}}\right) + \ldots + \left(\frac{\text{Number of germinated seeds}}{\text{Day of final count}}\right)$$

$$\mathrm{SVI} = \text{Seedling lenght} \times \text{Germination percentage}$$

Shoot (ShL, cm) and root length (RL, cm), and seedling fresh weight (SFW, g) were measured from five uniform seedlings from each replicate.

2.3 Si Foliar Application under Field Conditions

2.3.1 Site Description, Experimental Design, and Field Management

The field trial was conducted in Boulifa/Kef research station of the National Agricultural Research Institute of Tunisia (36° 7.998’ N 08° 42′ E, altitude 518 m) during the growing season 2017/2018. The studied region has a typically Mediterranean semi-arid climate with a 30-year average rainfall of 300–450 mm per year and 30-year average temperature of 14.6 °C. The soil was identified as clay-loam (50% clay and 30% loam) [50]. Seeds were sown on December 14, 2017 with a density of 350 grains/m^2. Six blocs (243 m^2) subdivided each into 25 plots of 9 m^2 (in total 100) containing six rows of 6 m length, with 0.2 m inter-row spacing and 0.5 m inter-plot spacing. Nitrogen (N) was supplied as ammonium nitrate (33.5% N), split into three doses of 100 kg/ha each, at

Table 2 Mean rainfall (mm) and temperature (°C) in Boulifa/Kef site during 2017/2018 cropping season

Meteorological data	October	November	December	January	February	March	April	May	June
Rainfall (mm)	16.8	15.5	10.0	10.8	10.3	15.7	18.0	23.0	28.7
Temperature (°C)	27.0	96.2	23.2	32.4	31.6	41.4	39.7	8.2	40.4

3-leaf (Z13), at tillering (Z26), and at heading growth stage (Z32) [51]. Two Si treatments were adopted in this study:

Treatment 1: Control (without Si),
Treatment 2: Si applied at tillering (Z26, 2 l/ha) and heading (Z32, 2 l/ha) stages.

The experimental design was arranged as a completely randomized block design with three replicates per treatment ($n = 3$). Meteorological data (precipitation and temperature average) during vegetative and reproductive stages of the growing season 2017/2018 were recorded in Table 2.

2.3.2 Physiological and Agro-Morphological Parameters

The relative water content (RWC) was calculated on three plants according to Clark and Mac Caig [52], using the following equation:

$$\mathrm{RWC}\ (\%) = ((\mathrm{FW}-\mathrm{DW})/(\mathrm{TW}-\mathrm{DW})) \times 100$$

Variables include: Fw, fresh weight of harvested leaves; TW: weight of soaked leaves in distilled water for 4 h at room temperature; Dw, weight of leaf dried at 80 °C for 24 h.

A chlorophyll meter SPAD 502 Plus (Minolta, Japan) was used to estimate chlorophyll (Chl) content. At heading stage, the ‘SPAD value’ was determined on flag leaves of five randomly selected plants per replicate. Four SPAD readings were taken per leaf and averaged to produce a single observation.

At maturity, the two agro-morphological parameters, spike length (SL, cm) and seed number/spike (SN/S) were measured on six plants of each genotype per treatment, while the grain yield (GY, kg) was recorded for each plot.

2.4 Data Analysis

Analysis of variance (ANOVA) was performed using General Linear Model (GLM) to assess the effect of Si treatment, water stress, and durum wheat genotypes, and their respective interactions on germination and seedling growth parameters. For physiological and agro-morphological traits, a two-way ANOVA model was performed, with Si treatment and genotypes as main factors. Means were compared by Duncan’s multiple range test at 5% significance level. All statistical analyses were realized using SAS software (version 9.4).

3 Results

3.1 Effect of Si Seed Priming on Germination and Seedling Growth Attributes

In most cases, the three-way ANOVA model revealed significant variations among the osmotic stress, Si treatment, and genotypes ($P < 0.01$), and their interaction ($P < 0.05$) for all germination and seedling growth parameters (Table S1). Compared to the control (0 g/l PEG_{6000}), all tested traits were significantly altered by water stress (150 g/l PEG_{6000}) (Table S1; Fig. S1). The addition of Si enhanced, however, the germination and the growth of seedlings grown under non-stressed (0 g/l PEG_{6000}) and stressed (150 g/l PEG_{6000}) conditions.

In the absence of Si treatment, water deficit significantly reduced the germination percentage (GP) of all genotypes by 14.97% compared to the control (Fig. 1a, b; Fig. S1). Si seed priming stimulated, however, the GP under control (0 g/l PEG_{6000}) and stress conditions (150 g/l PEG_{6000}). The application of 15 and 20 mg/l Si significantly alleviated the stress-induced reduction by 23.96 and 22.37%, respectively (Table S1). A genotypic variation was observed for GP. Under stress conditions, the increase rate of GP ranged between 12 and 36% and 9–36% for seeds treated with 15 and 20 mg/l Si, respectively. The L17 showed the best increase rate for both Si treatments (Table S1) and exhibited the highest value (93.33%) of GP with L16 and L19 (Fig. 1a, b).

Germination index (GI) of non-primed seeds was also significantly decreased by 11.29% under water deficit (Fig. 1c, d; Fig. S1). The addition of 15 and 20 mg/l Si improved clearly the GI of stressed seedlings by 24.67 and 25.69%, respectively (Table S1). The genotypes responded differently to water stress and Si treatments (Fig. 1c, d; Table S1). Overall, under stress conditions, the L24 (33.48% with 15 mg/l Si) and L15 (42.09% with 20 mg/l Si) responded best to Si application. Nonetheless, the L6 (12.81) and the L18 (12.80) showed the highest values of GI after adding 15 and 20 mg/l Si, respectively (Fig. 1c, d).

Similar to GP and GI, shoot (ShL) and root length (RL) were negatively affected (17.20 and 11.13%, respectively) when subjected to 150 mg/l PEG_{6000} (Fig. 1e-h; Fig. S1). However, seed priming with 15 and 20 mg/l of Si was an effective treatment to enhance the durum wheat growth of the above- (23.58 and 21.65%, respectively) and the below-

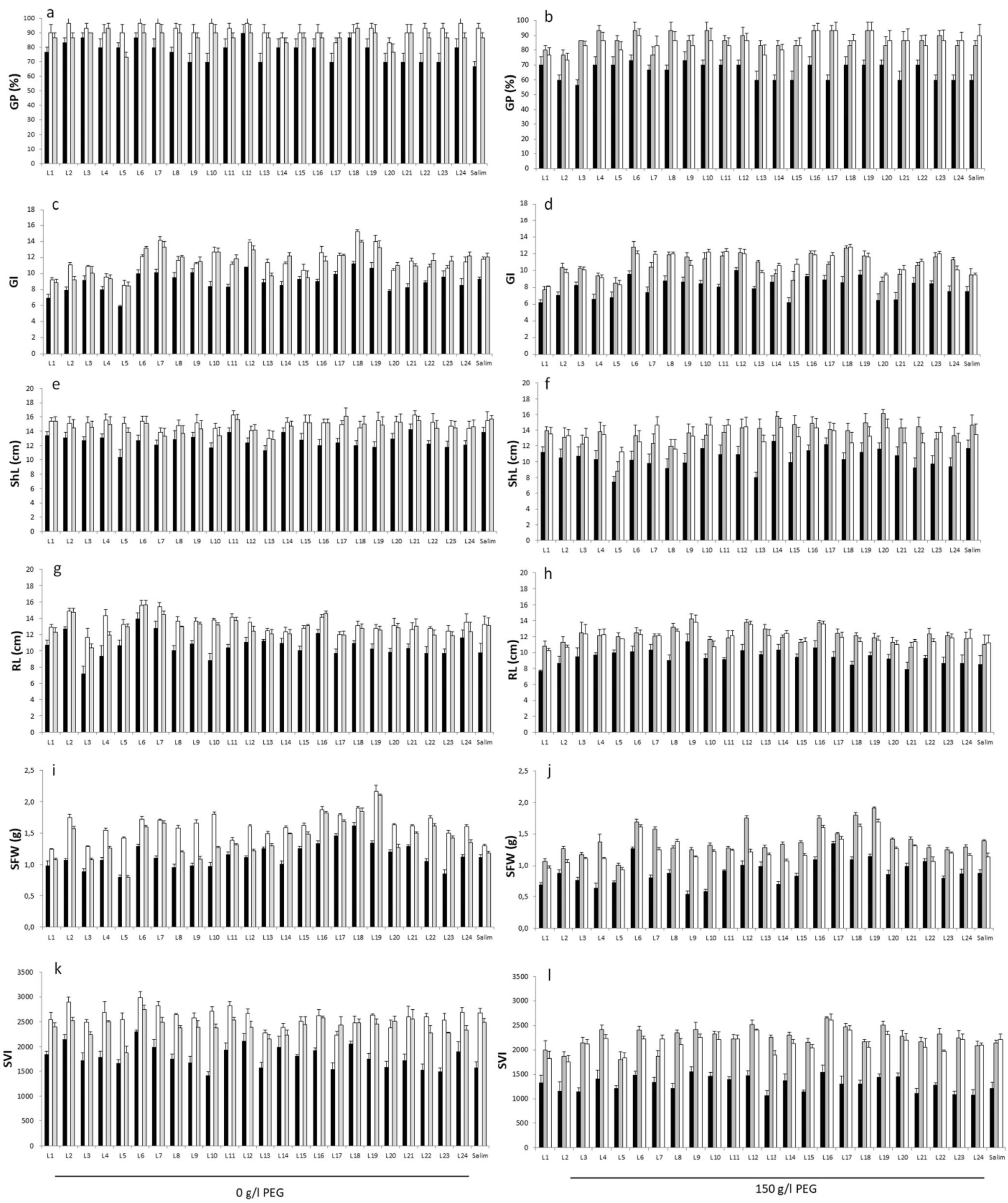

Fig. 1 Effect of silicon (Si) on germination percentage (GP, a, b), germination index (GI, c, d), shoot (ShL, e, f) and root length (RL, g, h), seedling fresh weight (SFW, i, j), and seedling vigor index (SVI, k, l) of 25 durum wheat genotypes, under non-stressed (0 g/l PEG_{6000}) and stressed conditions (150 g/l PEG_{6000}). Graph bars are means of three replicates ± SE

ground traits (22.40 and 20.81%, respectively) (Table S1). The data showed a divergent genotype pattern for ShL and RL according to water stress and Si treatment. The rate of increase ranged between 12 and 44% and 12–36% for ShL, and 13–32% and 13–30% for RL by adding 15 and 20 mg/l of Si, respectively. Interestingly, the highest lengths were obtained for L20 (16.11 cm) and L14 (15.80 cm) for shoots, and L9 (14.24 cm) and L16 (13.72 cm) for roots (Fig. 1e-h).

The use of PEG_{6000} impaired also the seedling fresh weight (SFW) by 21.74% (Fig. 1i, j; Fig. S1). By contrast, the adverse effect of PEG_{6000} treatment was alleviated by Si addition which considerably improved this parameter by 35.82 and 27.80% using 15 and 20 g/l of Si, respectively (Table S1). Considering the durum wheat genotypes, the increase rate of SFW after seed priming with 15 and 20 mg/l Si ranged from 17 to 57%, and from 0.2 to 52%, respectively. Notably, under water stress conditions, the L9 showed the best increase of SFW for both Si treatments. However, L19, L18, and L6 were the best performing genotypes when exposed to 15 mg/l Si, while L18, L6, and L16 were the best at 20 mg/l Si (Fig. 1i, j).

Furthermore, water stress significantly declined the seedling vigor index (SVI) by 27.27% compared to control plants (Fig.1k, l; Fig. S1). However, Si seed priming treatments markedly improved SVI of water-stressed seedlings by 41.58 and 38.95% using respectively 15 and 20 mg/l of Si (Table S1). Under the same conditions, the increase rate of SVI varied according to genotypes by 28–53% and 27–51%. L16 (2657.43 and 2607.83% with 15 and 20 mg/l Si, respectively) and L12 (2518.28 and 2411.77% with 15 and 20 mg/l Si, respectively) recorded the highest values of SVI under osmotic stress and for both Si treatments (Fig. 1k, l).

For all germination and seedling growth parameters, the beneficial role of Si was markedly higher in the presence of water stress with a slightly more pronounced effect using 15 mg/l Si (Fig. 1; Table S1).

3.2 Effect of Si Foliar Application on Physiological and Agro-Morphological Parameters under Field Conditions

The two-way ANOVA model with relative water content (RWC), chlorophyll content (Chl), spike length (SL), seed number/spike (SN/S), as well as grain yield (GY/plot) revealed significant Si treatment and genotype variations ($P < 0.01$), except the insignificant genotypic effect for RWC. Significant interaction ($P < 0.05$) between Si treatment and genotypes were also obtained for Chl, SL, and GY/plot.

For all durum wheat genotypes, Si foliar fertilization seems to be effective in the maintenance of plant water status. As compared to the control, RWC increased in plants received Si foliar spray by 11.66% (Fig. 2a; Fig. S2). Durum wheat lines responded positively and differently to Si foliar application. The increase rate of RWC varies among genotypes from 0.82 to 26.63% for L10 and L14, respectively (Table S2). L5 (57.46%) and L22 (43.71%) showed respectively the highest RWC with and without Si fertilization (Fig. 2a).

Furthermore, Si foliar spray enhanced significantly the Chl content by 13.60% compared to control plants (Fig. 2b; Fig. S2). Significant variation existed among genotypes for both Si treatments (i.e., with and without Si application). Considering durum wheat genotypes, the lowest and the highest increase rate of Chl amount were obtained respectively for L14 (1.59%) and L5 (20.85%) (Table S2). However, L2 and L14 showed respectively the best values of Chl when exposed or no to Si treatment (Fig. 2b).

Regarding agro-morphological traits, the beneficial effect of added Si was obvious for SL (8.47%), SN/S (19.01%), and GY/plot (19.90%) (Fig. 2c-e). For SL, the increase rate ranged between 1.45 and 16.98% for L8 and L12, respectively (Table S2). The highest values were recorded for L6 (7.85 cm) and L7 (7.05 cm) in the presence and absence of Si, respectively (Fig. 2c). Similarly, durum wheat genotypes differed significantly for SN/S. The increase rates ranged between 2.27 and 36.18% for L3 and L9, respectively (Table S2). L2 (41.17) and L1 (32.17) recorded, however, the maximum SN/S in Si treated and no treated plants, respectively (Fig. 2d). Finally, the Si foliar spray enhanced the GY from 1.38% for L9 to 61.20% for L6 (Table S2). Under control conditions, L16 was the best genotype (1839.67 kg/plot), while Si application depressed remarkably this genotype. With Si supply, L1 (1698.88 kg/plot) and L6 (1612.09 kg/plot) were consistently the best performing genotypes after the commercial variety, 'Salim' (1708.13 kg/plot) (Fig. 2e).

4 Discussion

4.1 Effect of Si Seed Priming on Germination and Seedling Growth Attributes

Germination is a key step of durum wheat establishment which is widely affected by abiotic stresses mainly early drought, in particular, in arid and semi-arid area. To the best of our knowledge, research focused on the durum wheat response to drought stress after Si seed priming still poorly documented [32, 53]. In the present investigation, Si seed priming improved germination percentage (GP) and germination index (GI) under both non-stressed (0 g/l PEG_{6000}) and stressed (150 g/l PEG_{6000}) conditions for all durum wheat genotypes. Similar findings were obtained for water-stressed durum wheat [22], bread wheat [32], maize [54], and borage crop [55]. Seed priming can repair the membrane damages caused by deterioration during seed storage or abiotic stresses [56]. In addition, Asgedom and Becker [57] and Ajouri et al. [58] reported that seed priming trigger the germination process by producing biochemical changes in the seed, including activation of enzymes that are involved in cellular metabolism, metabolism of inhibitors, dormancy breaking, and water imbibition.

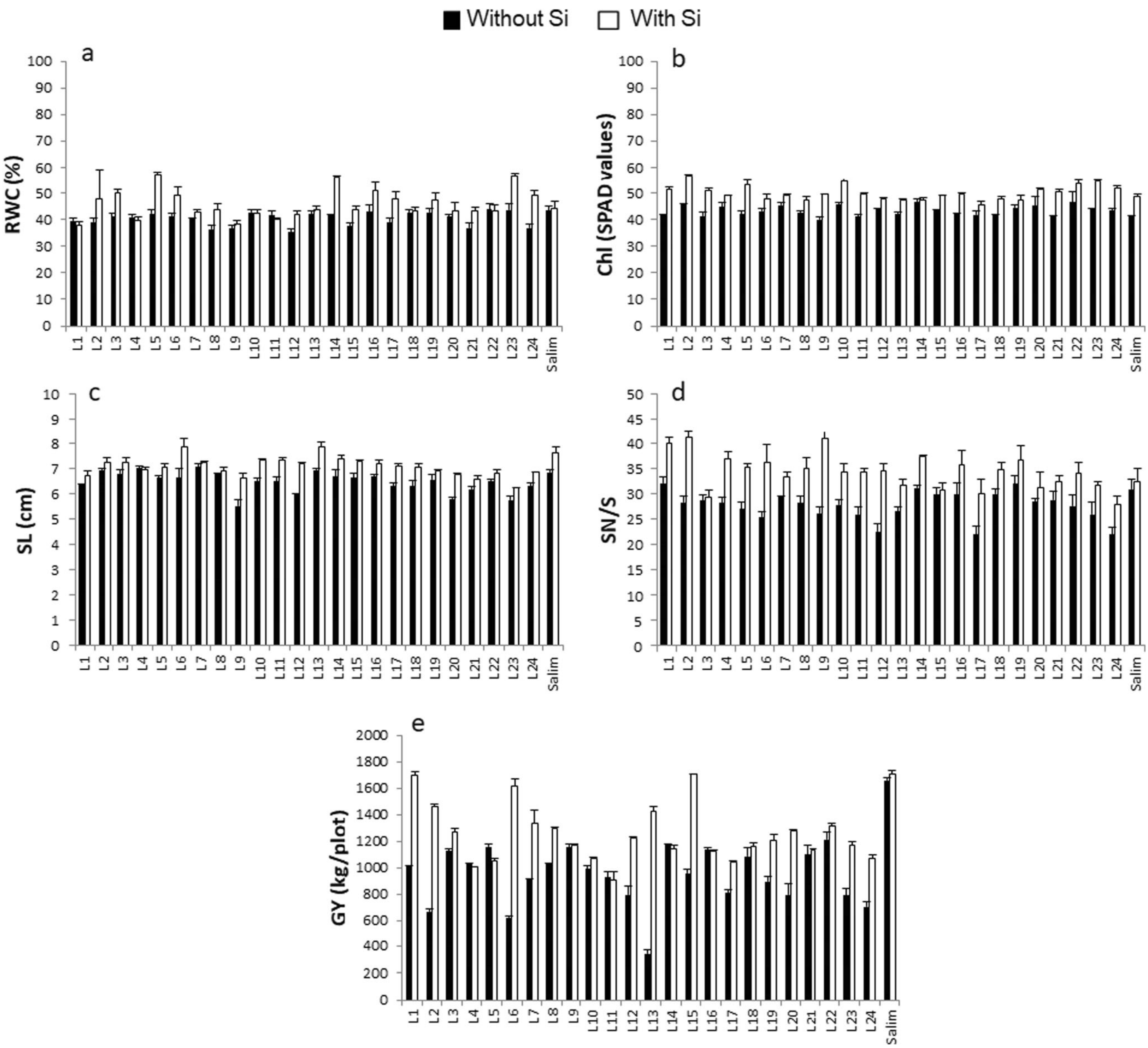

Fig. 2 Effect of silicon (Si) on relative water content (RWC, a), chlorophyll content (Chl, b), spike length (SL, c), seed number/spike (SN/S, d), and grain yield (GY, e) of 25 durum wheat genotypes under rainfed conditions. Graph bars are means of three replicates ± SE

Osmotic stress decreased seedling growth and vigor (i.e., ShL, RL, SFW, and SVI). These findings were confirmed by previous studies, reporting that increasing osmotic potential level resulted in decreased root length and vigor, and SVI in wheat and oats seedlings [46, 59, 60]. The deleterious effect of water stress might be explained by a decrease in turgor and dehydration of the protoplasm, which correlates with the reduction in cell expansion and prevention of mitosis [61]. Our results showed that Si seed priming promoted the seedling growth under normal conditions (0 g/l PEG_{6000}) and minimized the harmful effect of osmotic stress (150 g/l PEG_{6000}). As reported by several authors, Si promoted both the below- (e.g., diameter, area, volume, dry mass, and total length of roots) [20, 32, 62] and the above-ground traits [32, 53, 63, 64] under abiotic stress. The enhanced root length could be owing to Si accumulation in the endoderm and in the epidermis of roots which plays a mechanical role by protecting the plant against external aggressions [65]. Furthermore, Si treatments might induced anatomical changes in cell wall of leaves by the formation of silica cuticle, in the form of polymerized silicon dioxide (SiO_2) solid particles, alleviating the oxidative damage of functional molecules [15, 22, 35]. Recent research revealed that Si priming improved antioxidant enzymes activities (SOD, POD, and CAT) while it decreased the MDA and H_2O_2 contents in maize under stress conditions [65]. Some evidence has shown also that Si induces dehydration tolerance at tissue or cellular levels by maintaining water balance, avoids vessels compression and reduces water loss caused by transpiration [25]. In addition, Si element plays a relevant role in water uptake and mineral nutrients [62], and provides additional sites for ions absorption [66]. Under drought stress, Si application can adjust aquaporin gene and mitigate inhibition of their activity induced by ROS although, but it is exact role in these processes is still not well understood [44, 54, 63].

We noticed a distinct response of durum wheat genotypes to water stress and Si application for all germination and seedling growth aspects. This could be due to their sensitivity to water deficit and their variability in Si absorption capacity. As reported by Bukhari et al. [47], differences between genotypes may be attributed to their genetic composition for the accumulation of biochemical parameters. For SVI, L13 and L23 responded the best to the application of Si, but these genotypes did not present the best index. L16 and L12 recorded, however, the highest values of SVI under osmotic stress and for both Si treatments. In our case, the Si concentration of 15 mg/l was more effective as treatment under both optimal and adverse conditions. On the other hand, Si seed priming was found to be more successful under stressful environment, which suggests that Si is a vital element for proper growth and development under water shortage conditions.

4.2 Effect of Si Foliar Application on Physiological and Agro-Morphological Parameters under Field Conditions

Under semi-arid environment and rainfed conditions, the amount of precipitation (216.9 mm) recorded during 2017/2018 cropping season did not meet the needs of durum wheat. Thereby, this crop was subject to water deficit stress which significantly reduced crop growth and grain yield attributes. Our results showed that Si foliar spray increased RWC for all genotypes and thus maintained higher water status under field conditions. Several studies have found also that Si addition increase RWC for several species, such as wheat [67, 68], chickpea [69], and sunflower [70]. According to Ma [71] and Ahmed et al. [72], Si addition could improve the water status of the plant by reducing the osmotic effect of drought on water uptake and storage. Si might maintain high stomatal conductance of treated plants [73].

Chlorophyll content is an indicator of plant tolerance to environmental stresses, since it is associated to plants photosynthesis. The current study revealed also that Si application increased Chl content for all durum wheat genotypes. Similarly, foliar-applied Si increased photosynthetic pigments including chlorophyll a and b, and carotenoids in wheat [39, 41, 74], maize [75], sorghum [76], and chestnut (*Castanea* spp.) [77] leaves. Maghsoudi et al. [25] noticed that Si foliar spray (6 mM sodium silicate) at tillering and anthesis stages mediate wheat drought-stress tolerance by improving cellular membrane integrity and increasing relative water and chlorophyll content.

Better water status and better photosynthetic activity in treated plants will certainly have a positive feedback on the agro-morphological parameters and productivity. In fact, Si foliar spray increased the SL, SN/S, and GY/plot of the 25 durum wheat genotypes. The Si application increased the grain yield of wheat by stimulating physical characteristics, managed photosynthetic activity and enhanced growth by improving the stability of the cell membranes and cell Si concentration [29]. Our results are consistent with previous findings showing that Si increases the yield and its components (e.g., spike length, spike/m^2, seed number/spike, and 1000 grain weight) of wheat [12, 23, 77–79] or maize [80]. On the opposite hand, some authors mentioned that seed physiological quality and most yield components including seed number/spike, 1000 grain weight, and grain yield, did not respond to Si foliar application [81, 82]. A genotypic variation was observed under both Si treatments and a significant interaction between genotypes and Si treatment was noted. However, Segalin et al. [81], observed that cultivar x silicon interaction was not significant showing that cultivar behavior is independent of Si treatment. Similar to Petri diches bioassay, some genotypes was found to be more receptive to Si foliar application. Notably, Si supply enhanced greatly the GY of L6 (61%). However, 'Salim' followed by L1 and L6 were better able to withstand water stress after the Si application. The differential response to Si application could be due to the fact that the 25 genotypes have development cycles with variable precocity and therefore have widely varying degree-day requirements.

5 Conclusion

Our findings highlights the effectiveness of Si seed priming in moderating the adverse effects of water deficit on germination attributes and seedling growth of durum wheat genotypes. Si foliar spray was also effective to overcome drought constraints for durum wheat in semi-arid environments by maintaining better water status, chlorophyll content of plants, and better grain yield. Meaningful differences between genotypes were observed in responses to Si application. The most receptive genotypes to Si were not necessarily the best performing genotypes in term of seedling vigor or yield parameters.

Abbreviations GP, Germination percentage (%); GI, Germination index; ShL, Shoot length (cm); RL, Root length (cm); SFW, Seedling fresh weight (g); SVI, Seedling vigor index; RWC, Relative water content (%); Chl, Chlorophyll content; SL, Spike length (cm); SN/S, Seed number/spike; GY, Grain yield (kg/plot); L, Line; Si, Silicon; PEG, Polyethylene glycol

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12633-021-00963-2.

Author's Contributions Sourour Ayed, Afef Othmani, and Imen Bouhaouel conceived the project. Syrine Othmani performed the experiment. Neila Rassaa analyzed the data. Sourour Ayed, Afef Othmani, and Imen Bouhaouel wrote the paper. Hajer Slim Amara contributed reagents and materials and revised the paper. All authors read and approved the final manuscript.

Data Availability Applicable.

Code Availability No applicable.

Compliance with Ethical Standards

Applicable.

Conflict of Interest The authors declare that they have no conflict of interest.

Consent to Participate The authors give full consent to participate in this research work.

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