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EFFECT OF SILICON ON MAIZE UNDER WATER DEFICIT CONDITIONS AT FLOWERING STAGE

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SUMMARY

The use of silicon is an option for reducing the adverse effects of water deficit conditions. The recent study took place at the Agricultural Research and Experiment Station of the Faculty of Agriculture, Cairo University, Giza, Egypt (30°02′ N and 31°13′ E, with an altitude of 30 m) in two seasons of 2019 and 2020. The study's chief objective aimed to investigate the effect of water deficit at flowering on maize and its relation to silicon spraying. The study included two water treatments: non-stress (NS) and water stress (WS); three silicon treatments: (0, 3, and 6 mM L^{-1}); and five single-cross hybrids. A split-split plot design in a randomized complete block arrangement proceeded with three replications. Water deficit caused a significant reduction in grain yield ha^{-1} by 7.41%. Yield reduction resulted from substantial reductions in kernels row^{-1} (8.52%), 100-kernel weight (7.16%), carbohydrate % (4.79%), and carbohydrate yield ha^{-1} (11.88%). Silicon treatments caused notable increases in carbohydrate % by 0.57% and 0.71% and oil % by 7.69% and 19.49% due to the concentrations of 3 and 6 mM L^{-1} of sodium silicate, respectively. In addition, significant increases in kernels row^{-1} (3.01%), 100-kernel weight (3.12%), and oil yield ha^{-1} (18.12%) occurred under the concentration of 6 mM L^{-1}. The most interesting observation in the study showed the noteworthy increase in oil yield/ha for all studied hybrids, ranging from 13.33% (SC-3444) to 29.41% (SC-3433). It resulted from the application of the concentration of 6 mM L^{-1}. The hybrids SC-30N11, SC-3433, and SC-3444 proved the best hybrids, displaying tolerance to water.

Keywords: Maize (*Zea mays* L.), water stress, silicon, yield, carbohydrate, protein, oil, stress-tolerance index

Key findings: The water deficit condition at the flowering stage caused a significant reduction in yield and its components in maize. The silicon treatment 6 mM L^{-1} concentration notably enhanced the grain and oil yields and carbohydrates.

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INTRODUCTION

Maize (*Zea mays* L.) is one of the essential cereal crops worldwide. It is commonly used for human consumption, feeds for animals and poultry, and starch and oils production for cooking. Egypt could increase its maize production by horizontal expansion, growing

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maize in the newly reclaimed lands, mostly sandy soils with restricted water assets. However, using these lands exposes the maize plants to water deficit stress, which under such conditions, could result in low grain yields. Moreover, the expected future irrigation water shortages in Egypt require a great deal of attention from maize breeders to develop tolerant maize cultivars to fit these conditions, using some compounds to mitigate the impact of water stress. Under both water deficit and well-watered conditions, these cultivars could yield high grains. Maize is susceptible to water deficits during flowering stages (Westgate and Grant, 1989; Chapman *et al.,* 1996; Ribaut *et al.,* 1997; Salih *et al.,* 2014; Atta and Masri, 2015; Atta *et al.,* 2017; Al-Naggar *et al*., 2000 and 2018), but it becomes less sensitive as reproduction progresses (Classen and Shaw, 1970; Westgate and Boyer, 1985; Westgate and Grant, 1989; Atta *et al.,* 2017; Al-Naggar *et al.,* 2000 and 2018).

After 50% silking, the sensitive period of maize to drought stress ranged from about a week before to two weeks after (Classen and Shaw, 1970). Shaw (1977) added that yield losses per day of comparable pressure, before and after flowering, ranged from 45% and 60%, respectively, with peak yield losses at silking. Although yields were reduced by 70% most severely due to stress coinciding with silking, yields were reduced by 40%–50% from stresses occurring 10–31 days after mid-silk and reduced kernel numbers due to stresses occurring up to 22 days after silking (Grant *et al*., 1989). Nesmith and Ritchie (1992) also observed that kernel numbers per plant decreased by 8%–20%, and kernel weight declined by 21%–25% when the plants were stressed 18–31 days after silking.

The use of silicon (Si) is an option for reducing the adverse effects of water deficit, especially for plants belonging to the family Poaceae*,* such as, maize. Silicon belongs to the class of plant-friendly materials. Although it is not essential for living processes, it can positively affect plant growth and yield. The explicit role of Si in plant growth comes out, especially under stress conditions, such as, drought stress (Kleiber, 2018). Sommer *et al*. (2006) reported that the amount of Si in the soil could range from 1% to 45%. It is present in the soil in different forms, but plants can easily absorb orthosilicic acid Si $(OH)_4$ from the soil. Despite Si deposition on cell walls, its active participation in a plurality of metabolic and physiological processes occurs (Epstein, 1999; Moussa, 2006). Generally, plants belonging to the family Poaceae accumulate much more silicon than other plants belonging to different families (Akram *et al*., 2010).

Studies on water deficit stress showed that Si reduces the transpiration rate (Agarie *et al*., 1998), increases photosynthetic capacity, or stimulates antioxidant superoxide dismutase activity (Schmidt *et al*., 1999). Gunes *et al*. (2007) and Sacała (2009) also reported positive indications of Si application in connection with such physiological parameters as photosynthesis or stomatal conductance. The Si treatment significantly influences the plant water status (relative water content, RWC) (Kleiber *et al.,* 2015) and reduces transpiration rates compared with combinations without Si treatment. In addition, silicon application to drought-stressed maize plants enhanced the growth and yield, which could be attributed to an improved photosynthetic rate and lowered transpiration rate (Amin *et al*., 2018). Furthermore, Si lessened the damage caused by severe water deficits in maize plants because it kept the relative leaf water content, decreased the cell leakage index, and preserved the content of photosynthetic pigment, which increased the quantum efficiency of photosystem II, content, and use efficiency of macronutrients, thus leading to greater growth and biomass (Teixeira *et al*., 2022). Therefore, the objectives of the recent investigation were to (1) study the effect of water stress at flowering on some maize single- crosses, (2) determine the effect of silicon on maize and its relation to water stress tolerance, and (3) evaluate the most tolerant single crosses to each condition.

MATERIALS AND METHODS

Two field experiments took place at the Agricultural Research and Experiment Station of the Faculty of Agriculture, Cairo University, Giza, Egypt (30°02′ N and 31°13′ E, with an altitude of 30 m) during the two successive seasons of 2019 and 2020. The climatic variables in the two successive seasons are presented in Table 1. Soil properties of the 2019 and 2020 seasons (Table 2) underwent analysis at the Soils, Water and Environment Research Institute (SWERI), Agricultural Research Center (ARC), Giza, Egypt.

Table 1. Climatic variables recorded at Giza, Egypt in the 2019 and 2020 seasons.

Months	2019		2020	
	Temperature (°C)	Relative humidity (%)	Temperature (°C)	Relative humidity (%)
May	30.23	25.83	29.27	29.33
June	32.10	41.00	31.87	32.33
July	33.13	42.67	32.37	40.67
August	32.70	46.00	31.87	39.67
September	29.93	51.33	32.30	40.00

* Data obtained by the Central Laboratory for Agricultural Climate (CLAC), Agricultural Research Center (ARC), Egypt. Precipitation was not detected in both seasons.

Table 2. Physical and chemical properties of the soil at the experimental site in the 2019 and 2020 seasons.

Soil analysis	2019	2020
Physical properties		
Sand (%)	33.2	33.3
Silt (%)	30.3	31.4
Clay (%)	36.5	35.3
Texture class	Clay loam	Clay loam
Chemical properties		
pH $_{(1:1)}$	7.65	7.71
Ec$_{(1:1)}$ (dS m^{-1})	1.9	1.9
Organic matter (%)	2.3	2.2
Total Ca Co_3 (%)	3.4	3.5
Available N (mg kg^{-1})	36.4	37.9
Available P (mg kg^{-1})	8.85	9.2
Available K (mg kg^{-1})	235.0	237.0
Available Si (mg kg^{-1})	13.2	13.0
Total Si (mg kg^{-1})	346.0	342.7
Irrigation water analysis		
Ec of Irrigation water (ds/m)	0.82	0.85
pH of Irrigation water	7.42	7.50
Irrigation system	Flooding	Flooding

Factors of the study

The following factors were applied:

Irrigation (Factor A)

The study included two water treatments, i.e., non-stress (NS), by giving all recommended irrigations, applied every 12 days, and water deficit (WS) at the flowering stage by withholding the 4^{th} and 5^{th} irrigations.

Silicon (Factor B)

Silicon (Si), in the form of sodium silicate (Na_2SiO_3), was added by using three concentrations, *i.e*., zero (by spraying only water), 3, and 6 mM L^{-1}. Afterward, the genotypes received foliar spraying of silicon before the second and third irrigations. The concentrations of 3 and 6 mM L^{-1} resulted from calculating the mass of sodium silicate added per liter of water and were found to be at 0.367 and 0.733 g L^{-1}, respectively. In addition to these mentioned concentrations, the silicon available in the soil, as shown in Table 2, underwent evaluation. Therefore, silicon applications included foliar spraying with sodium silicate at the concentrations mentioned above, plus the silicon available in the soil. Determining the available silicon in the soil used the silicon content averages across the 2019 and 2020 seasons, which resulted in 13.1 mg kg^{-1}.

Genotypes (Factor C)

Five maize single-cross (SC) hybrids, namely, SC-3433, SC-3444, SC-30N11, SC-168, and SC-178, received experimentation. Hybrids Sc-3433, Sc-3444, and Sc-30N11 were obtained from Pioneer Company (Pioneer International Company in Egypt), while the Agricultural Research Center (ARC), Giza, Egypt, provided the hybrids SC-168 and SC-178. All the single crosses in the study have yellow endosperm.

Experimental design

A split-split plot design in a randomized complete block arrangement proceeded with three replications. The main plots received the two irrigation treatments (NS and WS), while the sub-main plots received the three concentrations of sodium silicate (0, 3, and 6 mM L^{-1}). The sub-sub plots focused on the five single crosses. Each experimental plot consisted of four ridges of 3.5 m long and 0.7 m in width, with an area of 9.8 m^2. Each main plot was bordered by a wide alley (4 m in width) to elude interference of the two water treatments.

Cultural practices

The preceding crop in both seasons was wheat (*Triticum aestivum* L.). Sowing dates comprised 20 May and 26 May in 2019 and 2020, respectively. The sown seeds underwent hills 25 cm apart by hand, after that (before the 1st irrigation) got thinned to one plant per hill. Calcium super phosphate fertilizer (15.5% P_2O_5) application at the rate of 238 kg ha^{-1} ensued uniformly before sowing. Likewise, ammonium nitrate (33.5% N) application at the rate of 286 kg N ha^{-1} continued in two equal doses before the first and second irrigations. Other traditional practices progressed by recommendation of ARC, Ministry of Agriculture, Giza, Egypt.

Data recorded

The following data were recorded on 10 secured plants from each plot: plant height (cm), measured from the soil surface up to the point of the flag leaf; ear height (cm), measured from the soil surface to the base of the topmost ear; leaf area (cm^2) of the uppermost ear, calculated by multiplying the leaf length by the maximum leaf width, then multiplying it by 0.75 (Francis *et al*., 1969). Also, logging of the following data continued on 10 random ears from each plot, namely, the number of rows ear^{-1} (rows ear^{-1}), number of kernels row^{-1} (kernels row^{-1}), 100-kernel weight (wt.) (g) and shelling % calculated by dividing grain weight by ear weight and multiplying by 100.

Grain yield in kg was weighed from the whole area of each experimental unit and then adjusted into ton $hectare^{-1}$ (t ha^{-1}). The grain yield per hectare was adjusted based on the 15.5% grain moisture content. Carbohydrate %, protein %, and oil % analysis proceeded at the Gene Bank, ARC, Giza, Egypt. Carbohydrate yield t ha^{-1}, protein yield t ha^{-1}, and oil yield t ha^{-1} were calculated by multiplying the percentage of each trait by grain yield ha^{-1}.

Statistical analysis

The test of normality distribution proceeded, according to Shapiro and Wilk (1965), using SPSS v. 17.0 (2008) software package. Also, data testing took place for violation of assumptions underlying the combined analysis of variance by separately analyzing a split-split plot design of each season. Then combined analysis across two seasons took place if homogeneity (Bartlet test) revealed insignificant. LSD estimates ensued to test the significance of differences among means, according to Snedecor and Cochran (1994).

The stress tolerance index (STI) was calculated according to Fernandez (1992) as follows:

$$STI = (Y_S)\ (Y_N)\ /\ (\overline{Y}_N)^2$$

where: Y_S = grain yield of a given hybrid under water stress; Y_N = grain yield of a given hybrid under non-stress; and $\overline{Y}_N$ = average grain yield of all hybrids under non-stress. When the STI is ≥ 1, it indicates genotype tolerance (T) to stress. If the STI is ≥ 0.5 to < 1, the genotype is moderately tolerant (M), and if the STI is < 0.5, the genotype is sensitive (S). The change percentage was calculated as follows:

$$Change\ (\%) = \left(\frac{Control - Stress}{Control}\right) \times 100$$

RESULTS AND DISCUSSION

Analysis of variance

Mean squares of combined analysis of variance (Table 3) showed that significant (P≤0.05/P≤0.01) differences existed among years for nine out of studied 14 traits, namely, the plant height, leaf area, ear height, rows ear^{-1}, kernels row^{-1}, 100-kernel wt., shelling %, carbohydrate %, and oil yield ha^{-1}, indicating that climatic conditions had a significant effect on such traits. Also, mean squares due to irrigation treatments revealed significant (P≤0.05 or P≤0.01) for kernels row^{-1}, 100-kernel wt., grain yield ha^{-1}, carbohydrate %, carbohydrate yield ha^{-1}, protein %, protein yield ha^{-1}, oil %, and oil yield ha^{-1}, signifying irrigation regime positively

Table 3. Combined analysis of variance across 2019 and 2020 seasons for all the studied traits in single-cross maize hybrids.

S.O.V.	d.f.	Plant height	Leaf area	Ear height	Rows/ear	Kernels/row	100-kernel weight.	Shelling %	Grain yield (ha^{-1})	Carbohydrate (%)	Carbohydrate yield (ha^{-1})	Protein (%)	Protein yield (ha^{-1})	Oil (%)	Oil yield (ha^{-1})
Years (Y)	1	48979.26*	3365008.1*	14007.62**	38.61**	1593.64**	576.201**	1056.234*	78.236	110.121**	51.232	7.025	0.189	0.195	0.048**
Reps /Y	2	910.353	24731.11	871.263	0.026	12.83	1.202*	413.512	6.865	0.620	3.719	2.048	0.081	0.408	0.000
Error	2	1411.84	59004.70	65.151	0.36	4.30	0.006	34.163	5.263	0.716	2.799	0.388	0.046	0.560	0.000
Irrigation (I)	1	632.44	10239.32	311.57	0.04	540.83**	303.706**	88.158	15.991**	559.576**	21.945**	8.252**	0.003*	2.547**	0.001*
I × Y	1	0.370	2651.13	381.29	0.00	161.67*	23.479	72.619	0.165	0.012	0.013	0.043	0.004*	0.004	0.000
Error	4	3279.08	8081.88	613.19	0.49	12.52	4.382	132.205	0.147	1.029	0.141	0.136	0.000	0.002	0.000
Silicon (Si)	2	15121.4*	73026.36**	1947.51**	1.780	27.83**	19.622**	193.015	2.831*	4.493**	1.402*	0.353	0.007	2.189**	0.012**
Si × Y	2	2279.64	4637.63	1009.25	0.271	41.44**	6.734	39.626	0.715	0.808	0.464	0.074	0.006	0.003	0.000
Si × I	2	10104.29	5776.28	77.82	0.77	31.53**	42.736**	221.312	8.435**	6.466**	5.350**	0.158	0.053**	0.426**	0.005**
Si × I × Y	2	494.144	106.549	111.900	0.026	4.944	0.441	21.617	0.233	0.307	0.195	0.039	0.000	0.000	0.000
Error	16	2904.270	2774.238	303.451	0.705	2.509	2.736	69.331	0.698	0.673	0.359	0.163	0.005	0.006	0.000
Genotypes (G)	4	6810.14	67676.73**	1998.87**	21.40**	157.82**	180.012**	411.085**	24.749**	72.273**	16.843**	5.211**	0.061**	14.013**	0.051**
G × Y	4	447.41	2934.83	31.56	0.04	4.19	1.231	44.293	0.429	0.287	0.234	0.052	0.003	0.006	0.001*
G × I	4	7087.89	2330.55	30.24	0.74*	44.62**	17.492**	145.952	1.899**	5.212**	0.619*	2.129**	0.038**	0.094**	0.004**
G × I× Y	4	325.55	926.54	5.508	0.065	2.09	1.056	43.898	1.599**	0.177	0.844**	0.096	0.009*	0.006	0.001**
G × Si	8	6372.42	15965.10**	259.77**	1.727**	14.29**	7.091**	314.707**	2.327**	5.007**	1.213**	0.877**	0.012**	0.254**	0.003**
G × Si × Y	8	352.08	2045.45	13.36	0.066	0.64	0.183	38.898	0.589	0.399	0.314	0.053	0.003	0.005	0.000
G × Si × I	8	6070.99	6444.48*	129.06*	0.887**	22.81**	13.460**	178.892	2.376**	1.731	1.374**	0.678**	0.014**	0.067**	0.001**
G × Si × I × Y	8	381.02	1398.17	11.27	0.18	0.67	0.424	43.821	0.445	0.397	0.250	0.063	0.003	0.007	0.000
Error	96	3344.95	2557.29	54.35	0.24	3.94	1.645	88.854	0.410	1.083	0.231	0.204	0.003	0.013	0.000

*and ** indicate significance at 0.05 and 0.01 levels of probability, respectively.

influences these traits. Mean squares from silicon treatments showed significance ($P \leq 0.05$/$P \leq 0.01$) for all studied traits, except rows ear^{-1}, shelling %, protein %, and protein yield ha^{-1}, indicating positive impacts of silicon on most of the traits. In addition, mean squares from genotype effects showed significance ($P \leq 0.01$) for all studied traits except plant height. These results indicate genotype effects significantly influenced most studied traits.

Mean squares from silicon × irrigation interaction revealed significant ($P \leq 0.05$/$P \leq 0.01$) for eight of the 14 traits, namely, kernels row^{-1}, 100-kernel wt., grain yield ha^{-1}, carbohydrate %, carbohydrate yield ha^{-1}, protein yield ha^{-1}, oil %, and oil yield ha^{-1}. Also, mean squares from genotype × irrigation interaction showed significantly ($P \leq 0.05$/$P \leq 0.01$) for all studied traits, except plant height, leaf area, ear height, and shelling %. The significance of genotype × irrigation leads to the conclusion that the performance of studied genotypes varies with irrigation treatments for most studied traits. Therefore, these results agree with previous findings of many studies (Classen and Shaw, 1970; Westgate and Boyer, 1985; Westgate and Grant, 1989; Chapman *et al.,* 1996; Ribaut *et al.,* 1997; Salih *et al.,* 2014; Atta and Masri, 2015; Atta *et al.,* 2017; Al-Naggar *et al*., 2000, 2018). Furthermore, mean squares due to genotype × silicon interaction proved significant ($P \leq 0.01$) for all studied traits except plant height, indicating that silicon treatments significantly affected the performance of studied genotypes for most studied traits.

Significant ($P \leq 0.05$/$P \leq 0.01$) mean squares were also detected for genotype × irrigation × silicon for all studied traits, except plant height, shelling %, and carbohydrate %. These results agree with previous findings that silicon application to drought-stressed maize plants improved the growth (Kleiber, 2018) and yield, which could be attributed to improved photosynthetic rate and lowered transpiration rate (Amin *et al*., 2018).

Effect of irrigation treatments

The water deficit imposed at flowering caused a significant grain yield ha^{-1} reduction of 7.41% (Table 4). Yield reduction due to water deficit at the flowering stage resulted from significant reductions in kernels row^{-1} (8.52%), 100-kernel weight (7.16%), carbohydrate % (4.79%), and carbohydrate yield ha^{-1} (11.88%). Thus, the water deficit at the flowering stage in maize decreased yield, as well as, the most important yield component traits, *i.e*., kernels row^{-1} and 100-kernel weight. It confirms other previous studies

Table 4. Mean performance of the single-cross maize hybrids for various traits across silicon treatments under non-stress (NS) and water stress (WS) conditions, and change from NS to WS (combined data across 2019 and 2020).

Stress	Plant height (cm)	Leaf area (cm^2)	Ear height (cm)	Rows/ear	Kernels/row
Non-stress	243.84	637.55	99.83	14.26	40.59^a
Water stress	240.09	652.63	102.46	14.29	37.13^b
Change %	1.54	-2.37	-2.63	-0.21	8.52**
$LSD_{0.05}$	18.20	28.57	7.87	0.22	1.13
$LSD_{0.01}$	31.99	50.22	13.83	0.39	1.98
Stress	100-kernel weight (g)	Shelling (%)	Grain yield (t ha^{-1})	Carbohydrate (%)	Carbohydrate yield (t ha^{-1})
Non-stress	36.33^a	80.63	7.96^a	73.65^a	5.877^a
Water stress	33.73^b	82.03	7.37^b	70.12^b	5.179^b
Change %	7.16**	-1.74	7.41**	4.79**	11.88**
$LSD_{0.05}$	0.67	6.67	0.12	0.32	0.12
$LSD_{0.01}$	1.67	6.42	0.22	0.57	0.21
Stress	Protein (%)	Protein yield (t ha^{-1})	Oil (%)	Oil yield (t ha^{-1})	
Non-stress	6.94^b	0.549	2.01^b	0.158	
Water stress	7.37^a	0.54	2.25^a	0.162	
Change %	-6.20**	1.64	-11.94**	-2.53	
$LSD_{0.05}$	0.12	6.03	0.01	3.32	
$LSD_{0.01}$	0.21	0.01	0.02	5.83	

Means in the same column followed by the same letter are not statistically different at a 0.05 level of probability. * and ** indicate significance at a 0.05 and 0.01 levels of probability, respectively.

Table 5. Mean performance of the single-cross maize hybrids for various traits under silicon treatments and change % (data combined across hybrids, irrigation treatments, and years [2019 and 2020]).

Silicon	Plant height (cm)	Leaf area (cm^2)	Ear height (cm)	Rows/ear	Kernels/row
0	257.87	685.05	105.92	14.43	38.49
3 mM/L	226.12	620.68	94.84	14.09	38.44
6 mM/L	241.9	629.54	102.67	14.31	39.65
Change % 0 vs. 3 mM/L	12.31**	9.40**	10.46**	2.36*	0.13
Change % 0 vs. 6 mM/L	6.19**	8.10**	3.07	0.83	-3.01**
$LSD_{0.05}$	20.86	20.38	6.74	0.33	0.61
$LSD_{0.01}$	2.89	28.08	9.28	0.44	0.84
Silicon	100-kernel weight (g)	Shelling (%)	Grain yield (t ha^{-1})	Carbohydrate (%)	Carbohydrate yield (t ha^{-1})
0	34.6	82.15	7.9	71.58	5.688
3 mM/L	34.82	79.27	7.47	71.99	5.384
6 mM/L	35.68	82.56	7.63	72.09	5.511
Change % 0 vs. 3 mM/L	-0.64	3.51	5.44*	-0.57*	5.34*
Change % 0 vs. 6 mM/L	-3.12**	-0.50	3.42	-0.71 **	3.11
$LSD_{0.05}$	0.64	3.22	0.32	0.32	0.23
$LSD_{0.01}$	0.88	4.44	0.44	0.44	0.32
Silicon	Protein (%)	Protein yield (t ha^{-1})	Oil (%)	Oil yield (t ha^{-1})	
0	7.12	0.557	1.95	0.149	
3 mM/L	7.24	0.54	2.1	0.155	
6 mM/L	7.09	0.537	2.33	0.176	
Change % 0 vs. 3 mM/L	-1.69**	3.05	-7.69**	-4.03	
Change % 0 vs. 6 mM/L	0.42	3.59	-19.49**	-18.12**	
$LSD_{0.05}$	0.16	0.03	0.03	0.01	
$LSD_{0.01}$	0.21	0.04	0.04	0.02	

* and ** indicate significance at 0.05 and 0.01 levels of probability, respectively.

(Classen and Shaw, 1970; Westgate and Boyer, 1985; Westgate and Grant, 1989; Chapman *et al.,* 1996; Ribaut *et al.,* 1997; Salih *et al.,* 2014; Atta and Masri, 2015; Atta *et al.,* 2017; Al-Naggar *et al*., 2000, 2018).

Additionally, water deficit decreased carbohydrate % and carbohydrate yield confirming the previous results of Al-Naggar *et al*. (2016), who observed that water deficit imposed at flowering decreased starch yield ha^{-1} by 25.0%, 17.03%, and 23.7% for parents, F_1 crosses, and checks, respectively. On the other hand, water stress caused a slight increase in grain protein % by 4.17% and 7.07% for F_1s and checks, respectively. The maize grain contains approximately 73% starch, 9% protein, 4% oil, and 14% other constituents, mostly fiber. The starch and protein are found primarily in the endosperm, while the oil is stored mainly in the germ (Tan and Marrison, 1979). Monotti (2003) and Ali *et al*. (2009) pointed out that lack of water during all stages of growth and development serves as the limiting factor for seed growth that can influence its composition. Water deficit can affect seed chemical composition by reducing CO_2 assimilation (Yang *et al*., 2004) or changing the metabolic processes (Xing *et al*., 2001; Zhou *et al*., 2001).

Effect of silicon treatments

Results in Table 5 showed that silicon treatments caused significant increases in carbohydrate % by 0.57% and 0.71% and oil % by 7.69% and 19.49% due to the sodium silicate concentrations of 3 and 6 mM L^{-1}, respectively. In addition, significant increases in kernels row^{-1} (3.01%), 100-kernel weight (3.12%), and oil yield ha^{-1} (18.12%) showed under the concentration of 6 mM L^{-1}. On the other hand, the control (water spray only) displayed significantly superior to silicon spraying in plant height, leaf area, ear height, grain yield ha^{-1}, and carbohydrate yield ha^{-1}. Notably, the change % in grain yield ha^{-1}, due to the application of the 6 mM L^{-1} concentration, showed no significance compared with the control. These results indicate that silicon treatments significantly affected the most important traits of yield components (kernels row^{-1} and 100-kernel weight), as well as, grain quality, especially carbohydrate % and oil %, in addition to oil yield ha^{-1}. These results showed more distinctly under the concentration of 6 mM L^{-1} than under 3 mM L^{-1}.

Concerning oil percentage and oil yield ha^{-1}, the latest results concur with the findings of Seleiman *et al*. (2019) in sunflower grown under water stress treatments. They observed that silicon treatments caused significant increases in oil % and oil yield ha^{-1} under water stress treatments compared with non-stress. These results could be attributed to silicon, which can mitigate the damage caused by water deficit through increasing nutritional efficiencies (Bonder *et al*., 2015) and by stimulating greater efficiency in nutrient use for transformation into biomass, which benefits the growth of plants under water stress (Teixeira *et al*., 2022). Furthermore, silicon alleviates water stress by decreasing stomatal transpiration (Gao *et al*., 2006).

Effect of genotypes

Table 6 presents the means of all studied traits of each single-cross hybrid across irrigation and silicon treatments in the 2019 and 2020 seasons. Data in Table 6 showed SC-30N11 as the highest single-cross hybrid for grain yield ha^{-1} (8.73 ton ha^{-1}), followed by SC-3433 (7.99 ton ha^{-1}) and SC-3444 (7.94 ton ha^{-1}). The superiority of SC-30N11 in grain yield ha^{-1} also is exuded in kernels row^{-1}, carbohydrate %, carbohydrate yield ha^{-1}, protein yield ha^{-1}, shelling %, 100-kernel weight, rows ear^{-1}, plant height, and leaf area.

Table 6. Mean performance of the single-cross maize hybrids for various traits across irrigation and silicon treatments (Data combined across 2019 and 2020).

Genotypes	Plant height (cm)	Leaf area (cm^2)	Ear height (cm)	Rows/ear	Kernels/row
SC-3433	235.2^a	584.98^c	108.54^a	13.03^d	37.27^c
SC-3444	247.58^a	613.89^b	106.33^a	14.13^c	40.5^b
SC-30N11	260.34^a	678.79^a	89.39^c	14.63^b	41.66^a
SC-168	223.52^a	665.57^a	99.74^b	15.05^a	37.9^c
SC-178	243.18^a	682.21^a	101.73^b	14.55^b	36.97^c
$LSD_{0.05}$	Ns	23.66	3.44	0.23	0.93
$LSD_{0.01}$	Ns	31.32	4.55	0.29	1.22
Genotypes	100-kernel weight (g)	Shelling (%)	Grain yield (t ha^{-1})	Carbohydrate (%)	Carbohydrate yield (t ha^{-1})
SC-3433	37.16^a	84.48^a	7.99^b	71.32^c	5.72^b
SC-3444	36.15^b	82.64^a	7.94^b	72.99^a	5.81^b
SC-30N11	36.5^b	81.52^a	8.73^a	73.42^a	6.41^a
SC-168	32^d	82.39^a	6.95^c	71.86^b	5^c
SC-178	33.33^c	75.6^b	6.7^c	69.85^d	4.69^d
$LSD_{0.05}$	0.60	4.41	0.30	0.49	0.22
$LSD_{0.01}$	0.80	5.81	0.40	0.64	0.30
Genotypes	Protein (%)	Protein yield (t ha^{-1})	Oil (%)	Oil yield (t ha^{-1})	
SC-3433	6.69^d	0.54^{bc}	2.41^b	0.19^b	
SC-3444	7.03^c	0.55^b	1.91^c	0.15^c	
SC-30N11	7^c	0.61^a	1.56^e	0.14^c	
SC-168	7.33^b	0.51^d	1.68^d	0.12^d	
SC-178	7.7^a	0.52^{cd}	3.08^a	0.21^a	
$LSD_{0.05}$	0.21	0.03	0.53	0.02	
$LSD_{0.01}$	0.28	0.03	0.06	0.01	

Means in the same column followed by the same letter are not statistically different at a 0.05 level of probability.

Effect of genotype by irrigation regime interaction

The studied maize hybrids showed significant differences in the absolute means under water deficit imposed at the flowering stage compared with those observed under non-stress for all studied traits except plant height, leaf area, ear height, and shelling % (Table 7). Therefore, the ranks of all studied single-crosses under water deficit at the flowering stage differed from those under non-stress conditions for most traits. Under non-stress, SC-30N11 achieved the highest mean values for grain yield ha^{-1}, followed by SC-3433 and SC-3444. The highest mean values for grain yield ha^{-1} were also achieved by SC-30N11, followed by SC-3444 and SC-3433 under water deficit conditions. Thus, the study concludes the best high-yielding hybrids consist of the

Table 7. Mean performance of the single-cross maize hybrids for various traits under non-stress (NS) and water stress (WS) conditions across silicon treatments (data combined across 2019 and 2020).

Genotype	Kernels row^{-1}			100-kernel weight (g)			Rows ear^{-1}		
	NS	WS	Change (%)	NS	WS	Change (%)	NS	WS	Change (%)
SC-3433	37.6	36.95	1.73	39.58	34.75	12.20**	13.12	12.94	1.37
SC-3444	43.36	37.65	13.17**	37.6	34.7	7.71**	14.06	14.20	-1.00
SC-30N11	44.55	38.77	12.97**	37.07	35.93	3.08**	14.72	14.55	1.16
SC-168	39.27	36.53	6.98**	33.01	31	6.09**	14.80	15.29	-3.31**
SC-178	38.2	35.74	6.44**	34.39	32.27	6.17**	14.61	14.50	0.75
$LSD_{0.05}$ (I × G)	1.31			0.85			0.32		
$LSD_{0.01}$ (I × G)	1.73			1.13			0.42		
Genotype	Grain yield (t ha^{-1})			Carbohydrate (%)			Protein (%)		
	NS	WS	Change (%)	NS	WS	Change (%)	NS	WS	Change (%)
SC-3433	8.49	7.5	11.66**	72.96	69.68	4.50**	6.42	6.97	-8.57**
SC-3444	8.26	7.61	7.87**	74.79	71.19	4.81**	6.69	7.38	-10.31**
SC-30N11	8.68	8.78	-1.15	75.82	71.01	6.34**	6.62	7.39	-11.63**
SC-168	7.16	6.74	5.87*	73.35	70.37	4.06**	7.05	7.6	-7.80**
SC-178	7.21	6.19	14.15**	71.33	68.37	4.15**	7.92	7.49	5.43**
$LSD_{0.05}$ (I × G)	0.42			0.69			0.30		
$LSD_{0.01}$ (I × G)	0.44			0.91			0.40		
Genotype	Protein yield (t ha^{-1})			Oil (%)			Oil yield (t ha^{-1})		
	NS	WS	Change (%)	NS	WS	Change (%)	NS	WS	Change (%)
SC-3433	0.55	0.52	5.46	2.28	2.53	-10.97**	0.19	0.19	0
SC-3444	0.55	0.56	-1.82	1.74	2.08	-19.54**	0.14	0.16	-14.29**
SC-30N11	0.57	0.65	-14.04**	1.42	1.7	-19.72**	0.12	0.15	-25**
SC-168	0.5	0.51	-2	1.55	1.8	-16.13**	0.11	0.12	-9.10**
SC-178	0.57	0.46	19.30**	3.05	3.11	-1.97**	0.22	0.19	13.64**
$LSD_{0.05}$ (I × G)	0.05			0.07			0.02		
$LSD_{0.01}$ (I × G)	0.05			0.09			0.01		

* and** indicate significance at 0.05 and 0.01 levels of probability, respectively.

single crosses SC-30N11, followed by SC-3444 and SC-3433 across studied irrigation treatments. The superiority of SC-30N11 and SC-3444, particularly in grain yield ha^{-1} in different irrigation treatments across the 2019 and 2020 seasons also displayed in kernels row^{-1}, 100-kernel weight, carbohydrate %, and carbohydrate yield ha^{-1}.

Effect of genotype by silicon interaction

Data of genotype by silicon interaction emanate in Table 8. The studied maize hybrids showed significant differences in absolute means under the concentrations of 3 and 6 mM L^{-1} of sodium silicate compared with those observed under control treatment (0 mM L^{-1} or water spray only). Therefore, the ranks of all studied hybrids differed under each concentration from that under control for most studied traits. Data showed the single-cross hybrid SC-178 significantly increases in grain yield ha^{-1} by 17.57% and 12.64% under the 3 and 6 mM L^{-1} concentrations, respectively. The yield increase for SC-178 also reflected a significant increase in carbohydrate yield ha^{-1} (17.61% and 13.50%, respectively) and oil yield ha^{-1} (27.78% and 16.67%, respectively).

Moreover, the increase in yield ha^{-1} for SC-178 exhibited a significant increase in kernels row^{-1} (6.23%) and protein yield ha^{-1} (14.58%) under a concentration of 3 mM L^{-1} of sodium silicate. The application of 3 mM L^{-1} concentration significantly increased the 100-kernel weight by 3.86% for SC-30N11. Furthermore, the concentration of 6 mM L^{-1} of sodium silicate showed significant increases in kernels row^{-1} by 5.98% for SC-3444, 100-kernel weight by 7.47% and 4.80% for SC-3444 and SC-3433, respectively.

The most interesting observation in the study resulted in the significant increase in oil yield ha^{-1} for all studied hybrids, which ranged from 13.33% (SC-3444) to 29.41% (SC-3433) due to applying the concentration of 6 mM L^{-1} of sodium silicate. The increase in the oil yield ha^{-1} with the previous concentration's application also affected the increase in oil % (not presented) and grain yield ha^{-1}. These results correspond with the findings of Seleiman *et al*. (2019) in sunflowers, reporting that silicon treatments increased oil % and oil yield ha^{-1} under water-deficit stress conditions compared with non-stress.

Table 8. Mean performance of the single-cross maize hybrids for various traits under silicon treatments across irrigation treatments and years (2019 and 2020).

Genotype	Leaf area (cm^2)				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	616.09	581.79	557.05	5.57	9.58**
SC-3444	627.28	618.78	595.62	1.36	5.05
SC-30N11	680.88	661.2	694.29	2.9	-1.97
SC-168	760.72	592.53	643.46	22.11**	15.41**
SC-178	740.26	649.09	657.28	12.36**	11.21**
$LSD_{0.05}$ (Si × G)	40.98				
$LSD_{0.01}$ (Si × G)	54.25				
Genotype	Ear height (cm)				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	111.15	102.68	111.79	7.62**	-0.58
SC-3444	112.44	101.23	105.32	9.97**	6.33*
SC-30N11	92.41	83.88	91.87	9.23**	0.58
SC-168	107.08	85.66	106.47	20.00**	0.57
SC-178	106.54	100.75	97.91	5.44	8.10**
$LSD_{0.05}$ (Si × G)	5.95				
$LSD_{0.01}$ (Si × G)	7.88				
Genotype	Rows ear^{-1}				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	13.49	12.81	12.78	5.04**	5.26**
SC-3444	14.2	13.82	14.36	2.68*	-1.13
SC-30N11	14.54	14.92	14.44	-2.61*	0.69
SC-168	15.53	14.33	15.28	7.73**	1.61
SC-178	14.4	14.57	14.69	-1.18	-2.01
$LSD_{0.05}$ (Si × G)	0.4				
$LSD_{0.01}$ (Si × G)	0.52				
Genotype	Kernels row^{-1}				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	36.55	37.27	37.99	-1.97	-3.94
SC-3444	39.61	39.92	41.98	-0.78	-5.98**
SC-30N11	41.93	39.74	43.3	5.22**	-3.27
SC-168	38.54	37.24	37.92	3.37	1.61
SC-178	35.82	38.05	37.04	-6.23**	-3.41
$LSD_{0.05}$ (Si × G)	1.61				
$LSD_{0.01}$ (Si × G)	2.12				
Genotype	100-kernel weight (g)				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	36.74	36.25	38.5	1.33	-4.80**
SC-3444	35.08	35.66	37.7	-1.65	-7.47**
SC-30N11	35.73	37.11	36.66	-3.86**	-2.6
SC-168	32.09	31.54	32.38	1.71	-0.9
SC-178	33.33	33.52	33.15	-0.57	0.54
$LSD_{0.05}$ (Si × G)	1.04				
$LSD_{0.01}$ (Si × G)	1.38				
Genotype	Shelling (%)				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	84.55	84.63	84.28	-0.1	0.32
SC-3444	84.05	81.34	82.53	3.22	1.81
SC-30N11	78.72	83.1	82.74	-5.56	-5.11
SC-168	81.7	83.88	81.6	-2.67	0.12
SC-178	81.72	63.4	81.67	22.42**	0.06
$LSD_{0.05}$ (Si × G)	7.64				
$LSD_{0.01}$ (Si × G)	10.06				

*and **indicate significance at 0.05 and 0.01 levels of probability, respectively.

Table 8 (cont'd).

Genotype	Grain yield (t ha^{-1})				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	8.46	7.62	7.9	9.93**	6.62*
SC-3444	8.3	7.49	8.03	9.76**	3.25
SC-30N11	9.23	8.38	8.58	9.20**	7.04*
SC-168	7.4	6.7	6.76	9.46**	8.65*
SC-178	6.09	7.16	6.86	-17.57**	-12.64**
$LSD_{0.05}$ (Si × G)	0.52				
$LSD_{0.01}$ (Si × G)	0.69				
Genotype	Carbohydrate (%)				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	70.33	71.74	71.88	-2.00**	-2.20**
SC-3444	72.79	72.77	73.41	0.03	-0.85
SC-30N11	73.63	72.8	73.82	1.13	-0.26
SC-168	71.35	72.92	71.31	-2.20**	0.06
SC-178	69.78	69.73	70.04	0.07	-0.37
$LSD_{0.05}$ (Si × G)	0.84				
$LSD_{0.01}$ (Si × G)	1.12				
Genotype	Carbohydrate yield (t ha^{-1})				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	5.98	5.48	5.68	8.36*	5.02
SC-3444	6.07	5.47	5.9	9.85**	2.8
SC-30N11	6.83	6.08	6.33	10.98**	7.32*
SC-168	5.3	4.88	4.83	7.93*	8.87*
SC-178	4.26	5.01	4.82	-17.61**	-13.15**
$LSD_{0.05}$ (Si × G)	0.39				
$LSD_{0.01}$ (Si × G)	0.51				
Genotype	Protein (%)				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	6.89	6.6	6.6	4.21	4.21
SC-3444	6.97	7.49	6.64	-7.46**	4.74
SC-30N11	6.75	7.21	7.05	-6.82*	-4.44
SC-168	7.2	7.21	7.57	-0.14	-5.14*
SC-178	7.81	7.69	7.61	1.54	2.56
$LSD_{0.05}$ (Si × G)	0.36				
$LSD_{0.01}$ (Si × G)	0.48				
Genotype	Protein yield (t ha^{-1})				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	0.58	0.5	0.52	13.79**	10.35*
SC-3444	0.58	0.55	0.53	5.17	8.62
SC-30N11	0.62	0.61	0.61	1.61	1.61
SC-168	0.53	0.48	0.51	9.43	3.77
SC-178	0.48	0.55	0.52	-14.58*	-8.33
$LSD_{0.05}$ (Si × G)	0.06				
$LSD_{0.01}$ (Si × G)	0.08				
Genotype	Oil (%)				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	2	2.38	2.83	-19**	-41.5**
SC-3444	1.82	1.81	2.09	0.55	-14.84**
SC-30N11	1.44	1.5	1.74	-4.17	-20.83
SC-168	1.56	1.61	1.87	-3.21	-19.87**
SC-178	2.95	3.18	3.12	-7.80**	-5.76**
$LSD_{0.05}$ (Si × G)	0.09				
$LSD_{0.01}$ (Si × G)	0.11				

*and** indicate significance at 0.05 and 0.01 levels of probability, respectively.

Table 8 (cont'd).

Genotype	Oil yield (t ha^{-1})				
	0	Si 3mM\L	Si 6mM\L	Change% 0 vs. 3mM/L	Change% 0 vs. 6mM/L
SC-3433	0.17	0.18	0.22	-5.88*	-29.41**
SC-3444	0.15	0.13	0.17	13.33*	-13.33*
SC-30N11	0.13	0.13	0.15	0	-15.39*
SC-168	0.11	0.11	0.13	0	-18.18*
SC-178	0.18	0.23	0.21	-27.78**	-16.67**
$LSD_{0.05}$ (Si × G)	0.01				
$LSD_{0.01}$ (Si × G)	0.03				

*and** indicate significance at 0.05 and 0.01 levels of probability, respectively.

Effect of genotype by irrigation by silicon interaction

The data on the interaction of genotype × irrigation × silicon are presented in Figure 1. Data showed the SC-30N11 exhibited the highest mean values for grain yield ha^{-1}, followed by SC-168 and SC-3433 at the concentration of 3 mM L^{-1} of sodium silicate under water deficit. On the other hand, SC-30N11 had a high mean value for grain yield ha^{-1} at the concentration of 6 mM L^{-1}, followed by SC-3444 and SC-3433 under water deficit conditions. In general, all the studied hybrids

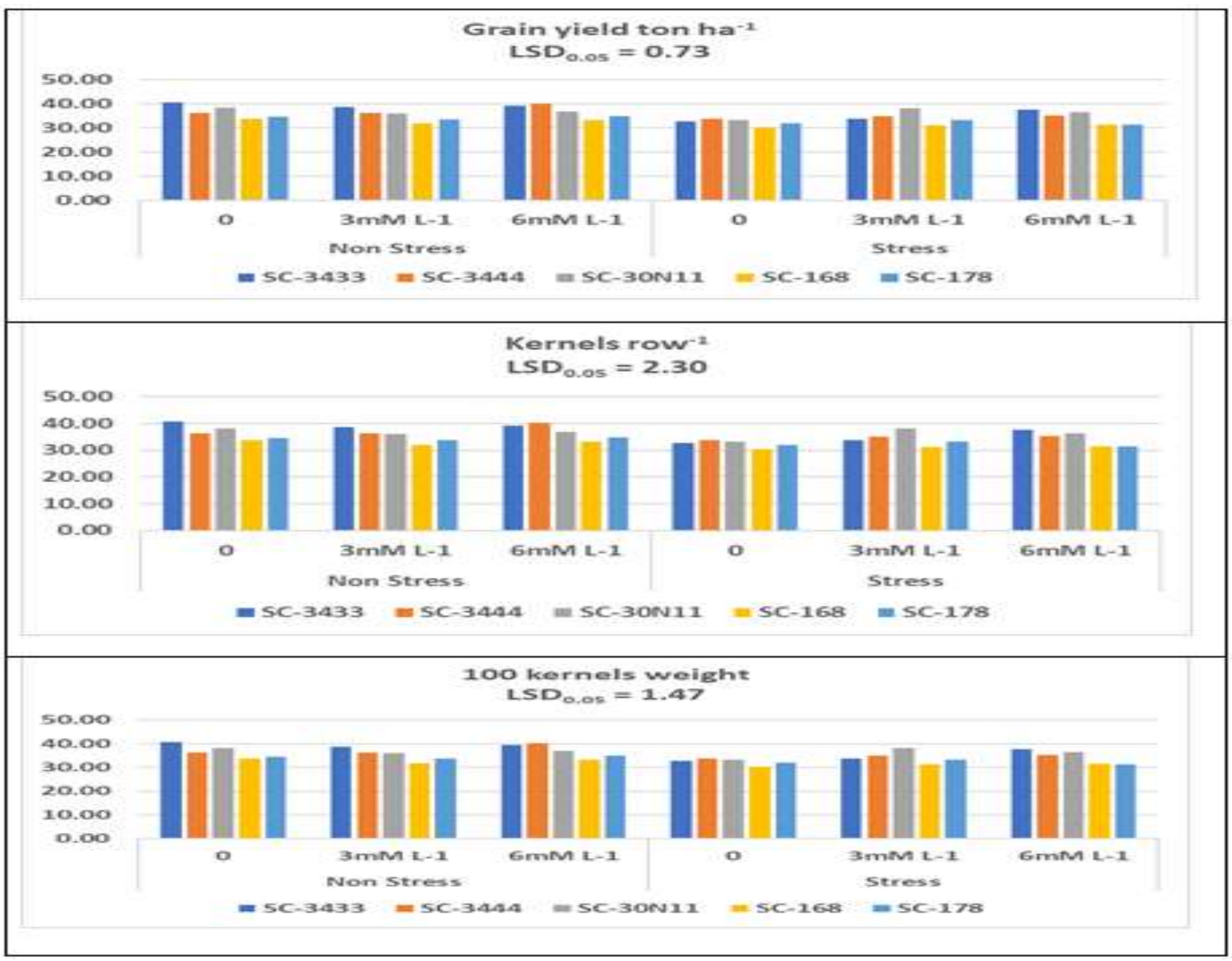

Figure 1. Effect of genotype × irrigation × silicon interaction for grain yield ha^{-1}, Kernels row^{-1}, and 100 kernels weight across 2019 and 2020 seasons.

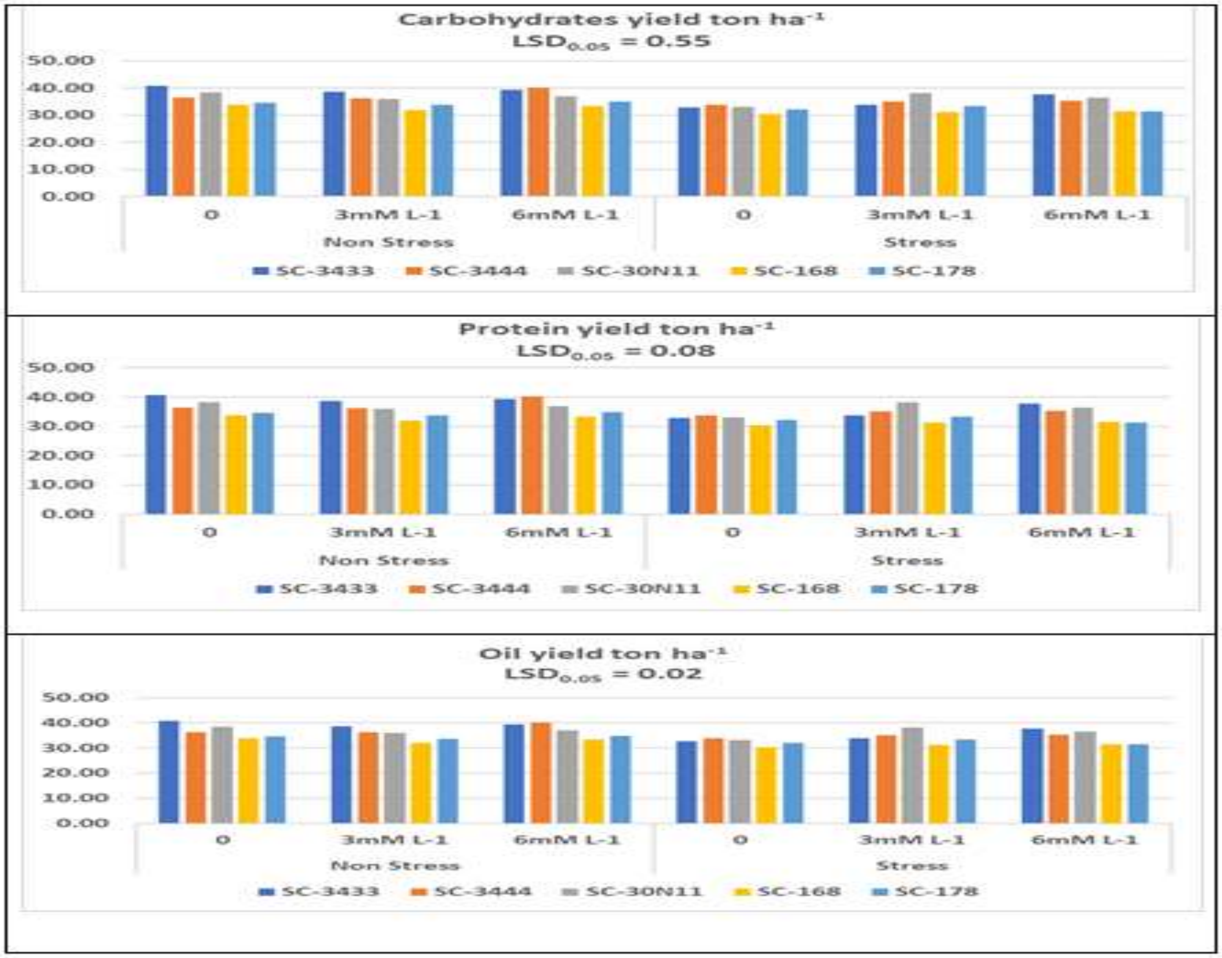

Figure 2. Effect of genotype × irrigation × silicon interaction for carbohydrates yield ton ha^{-1}, protein yield ton ha^{-1}, and oil yield ton ha^{-1} across 2019 and 2020 seasons.

showed high mean values for grain yield ha^{-1} at the control (0 mM L^{-1}) under non-stress conditions. The single-cross hybrid SC-30N11 showed the highest for grain yield ha^{-1}, followed by SC-3433 and SC-3444 under non-stress conditions. On the other hand, SC-178 showed high mean values for grain yield ha^{-1} at 3 and 6 mM L^{-1} under non-stress conditions. The increases in yield ha^{-1} under such conditions also reflected increases in 100-kernel weight, carbohydrate yield ha^{-1}, and protein yield ha^{-1} (Figures 1 and 2). The trait kernels row^{-1} showed the highest mean values at the concentrations of 3 and 6 mM L^{-1} under non-stress and water stress, respectively.

On oil yield ha^{-1}, the most studied hybrids showed the highest mean values at the concentration of 6 mM L^{-1} under non-stress and water stress at flowering, except SC-168 and SC-178. The single cross SC-168 showed high mean values of oil yield ha^{-1} at the 3 and 6 mM L^{-1} under non-stress and water stress, respectively (Figure 2). Meantime, SC-178 showed high mean values for oil yield ha^{-1} at the concentrations of 3 mM L^{-1} under non-stress and water deficit at flowering. These results indicate silicon`s ability to induce water-stressed maize and to increase yield and the most important yield components (kernels row^{-1} and 100-kernel weight) and improve carbohydrate yield ha^{-1}, protein yield ha^{-1}, and oil yield ha^{-1}. These results confirm the previous results of Gao *et al*. (2006), Bonder *et al*. (2015), Amin *et al*. (2018), Seleiman *et al*. (2019), and Teixeira *et al*. (2022).

Stress tolerance index

The stress tolerance index (STI) displays in Table 9. From the agronomic point of view, the tolerant genotype to water deficit should have the highest absolute mean yield under stress

Table 9. Mean grain yield of the single-cross maize hybrids (tons ha^{-1}) under non-stress and water stress conditions, change %, and stress tolerance index (STI) (Data combined across silicon treatments and years).

Hybrids	Means		Change (%)	STI
	Non-stress	Water stress		
SC-3433	8.49	7.5	11.66	1.00 (T)
SC-3444	8.26	7.61	7.87	0.99 (M)
SC-30N11	8.68	8.78	-1.15	1.20 (T)
SC-168	7.16	6.74	5.87	0.76 (M)
SC-178	7.21	6.19	14.15	0.70 (M)
Average	7.96	7.36	7.68	0.93 (M)

T and M indicate tolerance and moderately tolerant, respectively.

and the lowest reduction in yield under stress relative to non-stress conditions (Blum 1988). Based on this point of view, SC-30N11 proved the best maize hybrid in this experiment for tolerance to water deficit at flowering, followed by SC-3433 and SC-3444. Similarly, the single-cross hybrids SC-168 and SC-178 exhibited moderate tolerance to water deficit imposed at flowering.

CONCLUSIONS

In conclusion, the best maize hybrids for tolerance to water deficit at flowering consist of SC-30N11, SC-3433, and SC-3444. The sodium silicate concentration of 6 mM L^{-1} increased oil yield ha^{-1} for all studied hybrids, ranging from 13.33% (SC-3444) to 29.41% (SC-3433). Silicon can induce water-stressed maize to improve its ability to increase yield and the most important yield components.

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